Parameter studies on imperfections for the LTB-design of members based on EN 1993-1-1

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The stability design of members and structures based on a geometrically nonlinear analysis with equivalent initial geometric imperfections (GNIA) is a commonly used method. In the case of lateral torsional buckling (LTB) of members, the regulations in EN 1993-1-1 are unsatisfactory. With the current code, but also with the new draft prEN 1993-1-1 results are achieved, some of which are significantly too conservative as well as lacking in terms of safety. The reasons for this are the specified shape of imperfection as bow imperfections \( \epsilon_0 \) out of plane, an inappropriate differentiation related to the cross-section shape and yield strength, as well as neglecting the influence of the moment distribution over the member lengths. Parameter studies have shown that a distinction is required due to the different structural behaviours of members loaded with pure bending, pure compression, or a combination of bending and compression. This article presents current research results that consider the case of pure bending of I- and H-profiles. The dependencies of the profile shape, the cross-sectional resistance model and the influence of steel grades are analysed with respect to the height of the equivalent geometric imperfection to be applied.

Keywords: Imperfections; lateral torsional buckling; geometrically nonlinear analysis; parametric study; EN 1993-1-1

1 Introduction

The design process using a geometrically nonlinear analysis using equivalent initial imperfections (GNIA) will be carried out in three steps by applying equivalent initial geometric imperfections, determination of internal forces using geometrically nonlinear analysis and verification of the cross-section resistance at the most unfavourable position. The LTB-resistance according to this design method depends on the size and shape of the geometrical imperfection, the moment distribution and possible additional compression forces, the cross-sectional shape, the resistance model and the steel grade. In EN 1993-1-1 [1] imperfections for the LTB-design of members are defined in chapter 5.4.3, where the shape is specified as an initial bow imperfection out of plane. The amplitude is given as \( k \cdot \epsilon_0 \), the recommended value for \( k \) is 0.5, the basic values \( \epsilon_0 \) are defined in Tables 5.1 and 6.2 of EN 1993-1-1.

For rolled I-sections the relevant buckling curve for flexural buckling depends on the \( h/b \)-ratio, the plate thickness and steel grade. For slender cross-sections with \( h/b > 1.2 \) this results in smaller imperfection amplitudes than for stocky cross-sections with \( h/b \leq 1.2 \). Kindmann & Beier-Tertel [2] have shown that this assumption is not suitable for LTB. Sections with \( h/b \leq 2.0 \) are more favourable than those with \( h/b > 2.0 \). This is also considered in the selection of the LTB-curves according to Table 6.5 of EN 1993-1-1. In the German National Annex of EN 1993-1-1 [3] other imperfection amplitudes are specified which are derived from the assignment to the LTB-buckling-curves. The \( k \)-factor is given as 1.0 in the medium range of slenderness (0.7 \( \leq \lambda_{LT} \leq 1.3 \)). These rules are adopted and modified in the latest version of prEN 1993-1-1 [4] by considering the material parameter \( \epsilon \) as an amplifier. The shape of the equivalent initial geometrical imperfection is still specified as a bow-imperfection out of plane (Table 1).

Investigations by Ebel [5] on various structural systems and loads have shown, that the structural behaviour may be better reflected by considering the shape of the first LTB-buckling mode for the equivalent geometrical imperfection. Snijder, van der Aa, Hofmeyer & van Hove [6] also considered shapes of imperfections based on LTB-modes and developed a proposal for geometrically and materially nonlinear analysis. In Hajdú, Papp & Rubert [7] a proposal is presented, which considers the combination of compression and bending. The imperfection shape is also based on the relevant LTB-mode.

2 Parameter studies for pure bending

2.1 GMNIA- and GNIA-calculations

For the calibration of equivalent geometric imperfections, reference solutions are required with the help of which the amplitudes can be determined. Possibilities exist in the consideration of test results (if available), the buckling curves from prEN 1993-1-1 or the results from GMNIA-calculations. For reasons of practicability and to achieve higher accuracy, extensive parameter studies were carried out on hot-rolled I-sections using GMNIA. The nonlinear simulations were performed using the finite element analysis software ANSYS [8]. For this purpose, a hybrid shell-beam model was created modelling the I-section as a combination of shell and beam elements. The shell elements were located in the middle plane of the flanges and...
For the residual stress patterns, the ECCS recommendations [9] were considered. The magnitudes of the stress patterns depend on the height-to-width-ratio of the cross-section and are independent of the yield stress. The values of $0.5 \cdot 235 \, \text{N/mm}^2$ for $h/b < 1.2$ and $0.3 \cdot 235 \, \text{N/mm}^2$ for $h/b > 1.2$ were assumed with a linear distribution over the width of the flanges and the web.

The parametric study was performed using a multi-linear stress-strain behaviour considering isotropic strain hardening. The selected material model is based on the von Mises yield criterion. The accuracy of the numerical model for reproducing reference LTB-resistances with GMNIA was verified by comparison with analytical solutions (benchmark cases) and validated by simulation of several experiments. Figure 1 shows the FE model, the material law and the imperfection assumptions made.

Initial geometric imperfections were implemented in the FE-models using the first buckling mode from an elastic buckling analysis. The amplitude was scaled to $L/1000$.

| $h/b \leq 1.2$ | $h/b > 1.2$ |
|----------------|-------------|
| $1/400$         | $1/500$     |
| $1/300$         | $1/400$     |

The scope of the parameter studies

The aim of the present investigations is to derive imperfection assumptions for the LTB-design by GNIA calcula-
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The main influences of the cross-sectional shape, the yield strength, the moment distribution and the model for the cross-sectional resistance shall be considered. For the comparative calculations, single span beams of rolled I- and H-sections with fork end conditions were used (Fig. 2). Different moment distributions for bending about the major axis have been analysed, see Table 2. The investigations included 52 rolled I- and H-sections listed in Table 3.

![Fig. 2. Structural system and loads](image)

**Table 2. Investigated load cases for bending about the major axis**

| Load case | LC 1 | LC 2 | LC 3 | LC 4 | LC 5 |
|-----------|------|------|------|------|------|
| Moment distribution | $M$ = const. | $M$ | $-0.5M$ | $-M$ | $-M$ |

| Load case | LC 6 | LC 7 | LC 8 | LC 9 | LC 10 |
|-----------|------|------|------|------|-------|
| Moment distribution | $M_b$ | $M_b - M_t$ | $M_b$ | $M_b$ | $M_b - M_t$ |

**Table 3. Investigated I- and H-sections with ratios $h/b$, $I_y/I_T$, $I_y/I_z$ and $\sqrt{(A \cdot b)/(2 \cdot W_y)}$**

| Section | $h/b$ | $I_y/I_T$ | $I_y/I_z$ | $\sqrt{(A \cdot b)/(2 \cdot W_y)}$ | Section | $h/b$ | $I_y/I_T$ | $I_y/I_z$ | $\sqrt{(A \cdot b)/(2 \cdot W_y)}$ |
|---------|-------|-----------|-----------|-------------------------------|---------|-------|-----------|-----------|-------------------------------|
| IPE80   | 1.739 | 9.43      | 114.8     | 0.937                         | HEB550  | 1.833 | 10.45     | 227.8     | 0.875                         |
| IPE100  | 1.818 | 10.75     | 142.5     | 0.910                         | HEB650  | 2.167 | 15.06     | 285.0     | 0.814                         |
| IPE200  | 2.000 | 13.66     | 277.9     | 0.857                         | HEB700  | 2.533 | 17.79     | 309.1     | 0.791                         |
| IPE300  | 2.000 | 13.84     | 415.9     | 0.851                         | HEB800  | 2.667 | 24.10     | 379.6     | 0.747                         |
| IPE400  | 2.222 | 17.52     | 452.6     | 0.811                         | HEB1000 | 3.333 | 39.60     | 515.8     | 0.682                         |
| IPE450  | 2.368 | 20.08     | 504.3     | 0.791                         | HEM200  | 1.068 | 2.92      | 41.1      | 1.181                         |
| IPE500  | 2.500 | 22.52     | 539.8     | 0.776                         | HEM240  | 1.089 | 2.98      | 38.7      | 1.174                         |
| IPE600  | 2.727 | 27.16     | 581.8     | 0.748                         | HEM260  | 1.082 | 3.00      | 43.5      | 1.168                         |
| HEA100  | 0.960 | 2.60      | 66.6      | 1.207                         | HEM320  | 1.162 | 3.48      | 45.4      | 1.127                         |
| HEA200  | 0.950 | 2.75      | 175.7     | 1.177                         | HEM350  | 1.220 | 3.87      | 50.6      | 1.098                         |
| HEA300  | 0.967 | 2.89      | 214.3     | 1.160                         | HEM400  | 1.407 | 5.38      | 68.9      | 1.019                         |
| HEA320  | 1.033 | 3.28      | 212.3     | 1.121                         | HEM500  | 1.712 | 8.45      | 105.1     | 0.923                         |
| HEA360  | 1.167 | 4.19      | 222.1     | 1.065                         | HEM550  | 1.869 | 10.33     | 127.7     | 0.884                         |
| HEA400  | 1.300 | 5.27      | 238.5     | 1.016                         | HEM650  | 2.190 | 14.84     | 178.3     | 0.822                         |
| HEA500  | 1.633 | 8.39      | 281.5     | 0.915                         | HEM700  | 2.355 | 17.52     | 207.1     | 0.796                         |
| HEA550  | 1.800 | 10.34     | 317.9     | 0.876                         | HEM800  | 2.686 | 23.76     | 268.2     | 0.750                         |
| HEA650  | 2.133 | 14.95     | 391.1     | 0.814                         | HEM1000 | 3.338 | 39.13     | 424.9     | 0.684                         |
| HEA700  | 2.300 | 17.68     | 418.9     | 0.791                         | HEA100  | 0.910 | 2.57      | 94.1      | 1.225                         |
| HEA800  | 2.633 | 24.00     | 508.2     | 0.747                         | HEA360  | 1.130 | 4.26      | 324.5     | 1.085                         |
| HEA1000 | 3.300 | 38.13     | 649.4     | 0.695                         | HEA400  | 1.260 | 5.33      | 369.0     | 1.035                         |
| HEB200  | 1.000 | 2.85      | 96.1      | 1.171                         | HEA500  | 1.573 | 8.65      | 507.3     | 0.942                         |
| HEB300  | 1.000 | 2.94      | 136.1     | 1.154                         | HEA550  | 1.740 | 10.77     | 545.1     | 0.906                         |
| HEB320  | 1.067 | 3.34      | 137.0     | 1.120                         | HEA600  | 1.903 | 13.14     | 613.3     | 0.874                         |
| HEB360  | 1.200 | 4.26      | 147.9     | 1.064                         | HEA700  | 2.233 | 18.60     | 731.3     | 0.820                         |
| HEB400  | 1.333 | 5.33      | 162.0     | 1.015                         | HEA800  | 2.567 | 25.68     | 813.4     | 0.777                         |
| HEB500  | 1.667 | 8.49      | 199.3     | 0.914                         | HEA1000 | 3.233 | 42.78     | 1007.5    | 0.711                         |
The table provides additional information on the different aspect ratios, which are explained in more detail in Section 3.2.

The model for determining the cross-sectional resistance has a significant influence on the size of the initial imperfection. In addition to the elastic resistance model, several plastic interaction formulas were investigated. As a result of this study, which for reasons of scope is not presented in this article, the linear plastic interaction has proven to be particularly suitable for members with cross-section classes 1 and 2, which are prone to lateral torsional buckling. On the other hand, the linear plastic interaction is easy to handle. On the other hand, plastic cross-section reserves can usually only be partially exploited until the load-bearing capacity is reached. Due to the propagation of plastic zones during LTB, there is a considerable loss of stiffness, which excludes fully plastic cross-section utilization in the medium and high slenderness range. Since the size $e_0$ of the equivalent geometric imperfection is adapted to the model of the cross-section resistance, the linear plastic interaction is not to be evaluated as particularly conservative either. Only in the compact slenderness range, in which torsional bending is no longer important, can underestimations of the load-bearing capacity occur.

- Linear elastic interaction formula 1 (I-1)

Elastic verification of the cross-sectional resistance. The limit criterion is achieved when the von Mises stress $\sigma_v$ (Eq. 1) reaches the yield strength $f_y$ at the most critical point of the cross-section.

$$\sigma_v = \sqrt{\sigma_x^2 + 3 \cdot \tau^2}$$  \hspace{1cm} (1)

Simplified, the linear elastic interaction formula (Eq. 2) can be used if shear stresses are negligible.

$$\frac{N}{N_{el}} + \frac{M_y}{M_{el,y}} + \frac{M_z}{M_{el,z}} + B \cdot \frac{B_y}{B_{el}} \leq 1.0$$  \hspace{1cm} (2)

- Linear plastic interaction formula 2 (I-2)

The plastic cross-section resistance is reached when the sum of the degrees of utilisation from the internal forces involved reaches the value of 1 (Eq. 3). The influence of shear may lead to a reduction of the full plastic cross-section resistances (see EN 1993-1-1).

$$\frac{N}{N_{pl}} + \frac{M_y}{M_{pl,y}} + \frac{M_z}{M_{pl,z}} + B \cdot \frac{B_y}{B_{pl}} \leq 1.0$$  \hspace{1cm} (3)

The shape of the initial imperfection strongly influences the spatial structural behaviour of beams loaded by in-plane bending moments. Two common shapes of imperfection, the sinusoidal bow-imperfection out of plane (IMP 1) and the first elastic buckling mode for LTB (mode imperfection, IMP 2), were investigated. For both imperfection shapes, the amplitude $e_0$ corresponds to the maximum deflection of a flange, see Fig. 3.

For a large number of rolled sections, it was found that the minimum imperfection ratio $j = L/e_0$ is only achieved with member lengths that are unrealistic in terms of construction practice. For example, a compact HE100M loaded with constant bending moments requires the largest imperfection size at a relative slenderness of $\lambda_{LT} = 0.9$ (Fig. 4). The corresponding member length is 99.0 m and the $L/h$ ratio is 82.5. In order to exclude the possibility that such cases are used to calibrate the imperfection measures, the ratio of member length to cross-section height was limited to $L/h = 50$. For very slender sections, the limit was set to $L/h = 40$.

Short members subjected to transverse loads have a reduced bending resistance due to the influence of shear force. For slender cross-sections, the local buckling effect due to shear and compression stresses also influences the member resistance. All these local effects are considered in a GMNIA analysis using shell elements. By interacting with the global stability effects, lower LTB-resistances are achieved. The derivation of the required equivalent imperfections according to GNIA is usually carried out using beam theory, where these local effects due to shear stress are not considered. For this reason, local checks such as buckling according to EN 1993-1-5 should be performed in addition to the verification of member buckling. When calibrating the imperfection measures $e_0$, failure due to shear from transverse forces and local buckling were excluded since the objective was to calibrate imperfection measures for failure due to lateral torsional bending.
The calculation of the required amplitude of imperfection \( e_0 \) is an iterative process with the aim of achieving the same LTB-resistance as with GMNIA. They are defined in relation to the member length \( L \) as a non-dimensional \( j \)-value (Eq. 4).

\[
j = \frac{L}{e_0}
\]  

(4)

3 Equivalent geometrical imperfections for bending

3.1 General

The required imperfection amplitudes \( e_0 \) of beams loaded by in-plane bending moments are significantly influenced by the shape of the equivalent geometric imperfections, the model for the cross-section resistance, the cross-sectional shape, yield strength and moment distribution. The shape of the imperfection also has a fundamental effect on the load-bearing behaviour, and the dependencies of the other previously listed influencing parameters are therefore always valid in the context of the applied imperfection shape. Figure 5 shows typical curves of the \( j \)-values as a function of the related slenderness and imperfection shape for three different sections. The curves are comparable, but have different amplitudes. The smallest \( j \)-values and thus the largest related amplitudes occur in the range of medium slenderness \((0.7 < \lambda_{LT} < 1.3)\).

3.2 Required bow-imperfections (IMP-1)

The main advantage of using bow-imperfection is the simple handling during the design process. In contrast to the assumption of mode imperfections, no prior linear buckling analysis is required to obtain the imperfection shape. This standard EN 1993-1-1 defines bow-imperfections as a function of the cross-sectional shape, the manufacturing method (rolled or welded profile) and the \( h/b \)-ratio. For the future standard prEN 1993-1-1, the influence of the yield strength is added (Table 1).

The influence of the cross-sectional shape on the magnitude of the \( j \)-value is shown in Figure 6. Due to the different residual stress assumptions below and above the limit \( h/b = 1.2 \) in GMNIA discontinuities in the \( j \)-values occur. The course of the \( j \)-values depends on the moment diagram (Fig. 6 and 7). For slender sections with \( h/b > 1.2 \), the required \( j \)-values are almost at the same level for constant moment (LC 1), whereas for the triangular moment diagram (LC 2) the \( j \)-values become higher with increasing cross-section height. For moment distributions caused by transverse loads (LC 7 and LC 10), the \( j \)-values decrease with increasing section height. Bending moment diagrams with maximum values at the mid-span of the beams (LC 5 and LC 8) require comparatively low imperfection values \( e_0 \) (large \( j \)-values) in order to achieve the same LTB-resistance as from GMNIA-calculations. Antimetric moment diagrams (LC4) require very small \( j \)-values, since the symmetrical imperfection shape in the form of a sinusoidal half-wave is unsuitable for this purpose (Fig. 7).

Figure 8 shows the course of the required \( j \)-values for a stocky section HE200B and a slender section HE400A in the steel grades S 235, S 355 and S 460 considering the elastic and the plastic cross-sectional resistance. Beams of S 235 require slightly lower \( j \)-values than those from higher steel grades. Furthermore, if the cross-sectional resistance is determined elastically, significantly lower amplitudes are required with respect to the linear plastic interaction formula.

3.3 Required mode imperfections (IMP-2)

If mode imperfections are used, a pronounced cross-section dependency is recognizable, see Fig. 9. Similar to
bow-imperfection, a discontinuity of the $j$-values occurs at the $h/b$-ratio 1.2. Slender cross-sections require larger imperfections than stocky ones, the sensitivity of the $j$-values is much higher.

In the following, the $j$-values are evaluated according to different ratios of cross-section values in order to determine the dependencies. Possible ratios are $I_y/I_z$, $I_y/I_T$, and $\sqrt{(A \cdot b)/(2 \cdot W_y)}$. The latter ratio results from buckling curves for lateral torsion buckling according to prEN 1993-1-1. The analytical formulation of the buckling curves (Ayrton-Perry-formulation) is based on the mechanical model of a single span member with fork end conditions subjected to constant bending moment and mode imperfection. The cross-sectional resistance was determined by a linear interaction formula, see [11], [12]. The imperfection size was calibrated to GMNIA results and can be expressed by the Equation (5).

$$e_0 = \frac{W_y}{A} \cdot \alpha_{LT} \cdot (\bar{X}_z - \bar{X}_0)$$  

\[ (5) \]
with \( \alpha_{LT} = 0.16 \sqrt{\frac{W_y}{W_z}} \) for \( h/b \leq 1.2 \),
\( \alpha_{LT} = 0.12 \sqrt{\frac{W_y}{W_z}} \) for \( h/b > 1.2 \)
and
\( \lambda_z = \frac{L/I_z}{\lambda_1} \)  
\( \lambda_1 = \pi \cdot \sqrt{E/f_y} \)

Neglecting the term \( \lambda_0 \) in Equation (5) the following expression can be derived:

\[
j = \frac{L}{e_0} = \frac{\lambda_1}{\delta} \cdot \sqrt{\frac{A \cdot b}{2 \cdot W_y}}
\]

with \( \delta = 0.16 \) for \( h/b \leq 1.2 \) and \( \delta = 0.12 \) for \( h/b > 1.2 \).

The term \( \lambda_1 \) depends on the material properties, the other term on the cross-sectional properties. Figure 10 shows the required minimum \( j \)-values as functions of ratios \( I_y/I_z \), \( I_y/I_T \), and \( \sqrt{(A \cdot b)/(2 \cdot W_y)} \). Due to the reasons men-
shape decrease. This allows definition of the \( j \)-values in relation to this parameter.

Fig. 11 shows the investigation of further moment distributions. The constant moment distribution requires, with few exceptions, the lowest \( j \)-values. None of the investigated moment distributions require lower \( j \)-values than 400. In contrast to bow-imperfection, the mode imperfection is an adaptable imperfection shape whose effectiveness on the LTB-resistance determined with GNIA is always present.

The ratios \( I_y/I_z \) and \( I_y/I_T \) represent the stiffness proportions with respect to bending about the strong axis in relation to bending about the minor axis or torsion. The higher the ratio, the more sensitive a beam reacts to lateral displacements or rotations. Thus, the \( j \)-values decrease with increasing ratios \( I_y/I_z \) and \( I_y/I_T \). A good correlation was found between the \( j \)-values and the ratio \( \sqrt{(A \cdot b)/(2 \cdot W_y)} \). As the value increases, the \( j \)-value also increases and the scattering through the cross-sectional shape decrease. This allows definition of the \( j \)-values in relation to this parameter.

Fig. 10: Minimum \( j \)-values as a function of ratios \( I_y/I_z \), \( I_y/I_T \) and \( (A \cdot b)/(2 \cdot W_y) \) for mode imperfections IMP-2, sections according to Table 3, linear plastic interaction formula (I-2), steel grade S 235 and various moment distributions.
The parameter studies show that the mode imperfection approach leads to significant smaller imperfection amplitudes $e_0$ than the approach of sinusoidal bow-imperfections. If mode imperfections are applied, the value $((A \cdot b)/(2 \cdot W_y))$ better describes the tendency for the imperfection size $e_0$ than the ratio $h/b$. Using bow-imperfections, however, no dependence on different cross-sectional ratios could be determined. The shape of the moment diagram has a very strong influence on the required imperfection amplitude $e_0$. For moment diagrams with a low proportion of bending moment (first order) at mid-span, the approach of sinusoidal bow-imperfections is unsuitable. The assumption of mode imperfections is suitable for all moment diagrams and boundary conditions, since the eigenmodes adapt to them.

Discontinuities occur because the assumed residual stresses for rolled sections with $h/b > 1.2$ decreases from $0.5 \cdot f_y,S235$ to $0.3 \cdot f_y,S235$. The investigations on the effect of the yield strength in relation to the value $e_0$ show that this influence is only small and is overestimated with the current draft prEN 1993-1-1.

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In this article, parameter studies are presented in which imperfection magnitudes $e_0$ for the LTB-design of members with I- and H-sections under bending $M_y$ were derived. The values are based on the results of more detailed structural analysis according to the GMNIA and were derived by a comparison of the results of a linear elastic calculation of internal forces and the assessment of the sectional resistance with two different interaction formulas.
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