

Full paper

Optimizing the Imperfection Factor for Flexural Buckling Resistance of Equal-Leg Hot-Rolled Angles

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Abstract

In recent years, the construction of ever taller and more efficient structures, especially in the field of towers and masts, has required the development of high-performance steel profiles that can withstand new loads. In response to this growing demand, high-strength hot-rolled angles up to S460 have been introduced to the steel market. However, despite the existence of evidence demonstrating that the detrimental influence of geometrical and material imperfections decreases with increasing yield strength, the same buckling curve is frequently recommended for different steel grades. For instance, in the forthcoming design specifications for hot-rolled sections in the next generation of Eurocodes, only the S460 grade benefits from a higher buckling curve while the same buckling curve is recommended for grades from S235 up to S420. In a first step, this paper illustrates the beneficial effect of the yield strength on the stability of steel angles subjected to pure compression and criticizes the current stepwise evolution of the imperfection factor in the design rules, based on a review of existing buckling tests and a series of numerical simulations on hot-rolled equal-leg angle members. In a second step, a new modified imperfection factor evolving with the steel grade is proposed and validated, in order to better reflect the beneficial effect of the yield strength on buckling resistance, for both existing and future emerging steel grades.

Keywords

Angle sections, imperfection factor, buckling resistance, flexural buckling, EN1993-1-1.

1 Introduction

Angle sections are extensively used in the field of structural engineering in a wide range of applications such as buildings, bridges, lattice towers and masts. The ease with which these profiles can be produced and transported, as well as the ability to assemble them on site through bolted connections, renders them a high attractive solution for practitioners. Although angles sections are already available in the steel market in a wide range of dimensions and steel grades, including high-strength steel up to S460, there is continuously witnessing the emergence of new, ever-stronger steel [1]. The development of high-strength steels, which exhibit the highest strength-to-weight ratio among existing steel grades, contributes to the optimisation of structural designs with the potential for substantial weight, cost and carbon savings as shown by many authors in the literature [2–10].

A series of experimental studies have been conducted to

investigate the buckling behaviour of angle sections and members composed of both mild and high-strength steels [11–15]. In addition to the experimental studies, a substantial amount of analytical research has also been performed. Vayas et al. [16] provide a comprehensive analysis of the inelastic capacity of angle sections subjected to combined axial forces and biaxial bending. In their study, both Schillo et al. [17] and Farhoud et al. [18] examined the design rules of hot-rolled angle members subjected to compression according to the European and International standards, respectively. Finally, the influence of the residual stresses, which have been experimentally measured in order to ascertain their effect on the buckling resistance of the members, is studied by both Zhang et al. [19] and Moze et al [20]. Despite the fact that the recent European project [21] encompassed high-strength steel grades such as S460 and that the validity of current recommendations for this grade has been validated, the assessment of the existing rules for the buckling resistance of intermediate grades has not been conducted. The re-establishment of

continuity of current standards, as well as the establishment of rules depending on the yield strength, has the potential to result in substantial material, cost and carbon savings. Furthermore, it has been experimentally and numerically observed by various researchers [14,18,22–27] that the dominant failure mode of a pinned compressed equal-leg angle member is weak axis buckling, sometimes combined with local failure modes. In this context, the present study aims to examine the flexural buckling of hot-rolled equal-leg angles subjected to concentric loading, with the objective of deriving a modified imperfection factor as a function of the yield strength of the material, covering existing and future emerging steel grades.

2 Research background

2.1 Current design recommendations

The European design standard EN1993-1-1 [28,29] provides the Ayrton-Perry formulation for the resistance of a member subjected to pure compression, as expressed in Eq. (1).

$$N_{b,Rd} = \frac{\chi \cdot \beta \cdot A \cdot f_y}{\gamma_{M1}} \geq N_{Ed} \quad (1)$$

where:

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \quad (2)$$

$$\phi = 0.5 \cdot [1 + \alpha \cdot (\bar{\lambda} - 0.2) + \bar{\lambda}^2] \quad (3)$$

$N_{b,Rd}$ is the design buckling resistance, N_{Ed} is the design applied compression load, χ is the reduction factor to account for the relevant global buckling mode, β is the reduction factor to account for local buckling according to EN1993-1-5 [30], A is the cross-section area, f_y is the material yield strength, γ_{M1} is the partial safety coefficient, $\bar{\lambda}$ is the relative slenderness, and α is the imperfection factor. Regarding hot-rolled steel angles, the recommendations change between the two versions EN1993-1-1:2005 [28] and EN1993-1-1:2022 [29]. For mild steel grades (S235 to S420), a buckling curve “b” is recommended whatever the standard version. On the contrary, for high-strength steel grades (S460 up to S700), a buckling curve “b” is recommended in EN1993-1-1:2005 [28] while a buckling curve “a” is now prescribed in EN1993-1-1:2022 [29]. This can be attributed to the fact that the detrimental influence of initial imperfections on the buckling resistance reduces as the yield strength increases. A state-of-the-art overview of the existing modified imperfection factors for other cross-sectional shapes is presented as the basis for the developments set out in this publication. Indeed, according to the design recommendations for the intermediate steel grades (S275 to S420), the buckling curve “b” initially specified for S235 must be considered for these intermediate grades, but a progressively decreasing imperfection factor value could be suggested so as to recognise the fact that the detrimental effect of the residual stresses on the actual buckling load reduces when the steel grade increases.

2.2 Existing experimental data

A review of existing GMNIA simulations and experimental investigations on the column buckling capacity is presented in Figure 1 [14,22,26,31–35].

As can be seen in Figure 1, the numerical simulations as well as the buckling tests for the S420 grade are closely aligned with the buckling curve that has been prescribed for the S460. Also, the 96 Q345 tests from the research of Chen et al. [24] on similar angle sections demonstrate analogous results for this grade too.

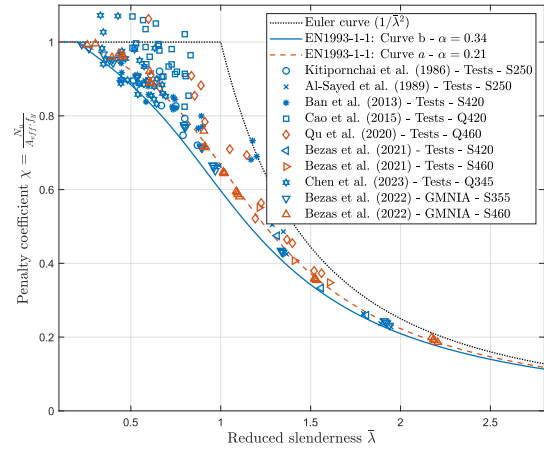


Figure 1 Comparison between experimental test results and column buckling resistances according to EN1993-1-1

Bezas et al [22,27] confirm this trend through experimental and numerical evidence on large-section angles made of S420 and S460 grades. Consequently, this comparison demonstrates the optimisation potential of developing a buckling curve selection which is continuously function of the yield strength instead of having a stepwise evolution of the imperfection factor as currently recommended in design guidelines.

2.3 Existing modified imperfection factors

In previous years, a number of modified imperfection factors that continuously account for the material strength were proposed. Maquoi [36] was the first author to propose a modified imperfection factor α^* , see Eq. (4):

$$\alpha^* = \alpha \cdot \left(\frac{235}{f_y} \right)^n \quad (4)$$

With α the coefficient recommended for the S235 steel grade. The exponent $n = 0.8$ was proposed to keep the gap of one buckling curve between the curve recommended for S235 and the one for the former high-strength steel grade, S430 as proposed in the normative documents of that period. Indeed, for instance, if a curve “b” is recommended for S235 ($\alpha = 0.34$) and a curve “a” ($\alpha = 0.21$) for S430, the modified imperfection factor with the exponent $n = 0.8$, i.e. $\alpha^* = 0.34 \cdot \left(\frac{235}{430} \right)^{0.8} = 0.21$, respects the gap of one buckling curve between the two reference grades. As an alternative, Johansson [37] proposed to consider an exponent $n = 1.0$. In the framework of the European project RUOSTE [38], Somodi et al. [39,40] proposed the same expression

but with an exponent $n = 0.5$ for cold-formed hollow sections and $n = 0.6$ for welded I-sections. Subsequently, Saufnay et al. [2,41] proposed to consider an exponent $n = 0.7$ for hot-rolled I- or H-sections as well as for hot-rolled hollow sections. Indeed, for all types of hot-rolled sections, the forthcoming EN1993-1-1:2022 [29] suggests a gap of one buckling curve between grades below S460 and grades equal or higher than S460. Therefore, an exponent $n = 0.7$ was proposed to fit with the current recommendation for the high-strength steel grade S460 ($\alpha^* = 0.34 \cdot \left(\frac{235}{460}\right)^{0.7} = 0.21$).

As an alternative to the above-mentioned formulation, in the framework of the European project STROBE [42], a reduction in the length of the plastic plateau from 0.2 to 0.1 and a modified imperfection factor function of the “ $\varepsilon = \sqrt{235/f_y}$ ” coefficient for hot-rolled and cold-formed hollow sections [43] as well as for welded I-sections [44] were proposed [56]. Finally, the last proposal that can be found in the literature consists of applying this “ ε ” coefficient to the relative slenderness, thereby rendering the length of the plastic plateau a function of the yield strength. This approach has been proposed by Jönsson et al. [45] for hot-rolled I- and H-shaped sections and by Fang et al. [46] for cold-formed hollow sections.

The above-mentioned literature does not address the subject of hot-rolled equal-leg angles yet. The objective of the present paper is therefore to derive an expression of the modified imperfection factor for this profile typology based on parametric numerical studies.

3 Methodology

3.1 Research scope

This paper focuses on the flexural buckling behaviour of pin-ended members consisting of hot-rolled equal-leg angles made of mild or high-strength steel grades (up to S460), as well as possible future emerging steel grades (from S500 to S690) as a prospective study, when subjected to concentric axial loading. The studied profiles i.e., L70x70x7 and L150x150x18, have been selected to focus on compact cross-sections. Indeed, these profiles remain Class 3 as $c/t \leq 14\varepsilon$ up to S690, following the recommendations established in the ANGELHY project [21].

3.2 Description of the numerical model

Geometrical and non-linear analyses with imperfections (GMNIA) have been realised to simulate the selected cross-sections. The FineLg software [47] with beam finite elements has been used as the considered column cross-sections are not prone to local buckling. The use of FineLg to simulate member instability problem has been validated in many studies [48–50], including some dealing with the flexural buckling behaviour of angle profiles [22,27,51]. Ten beam elements were assessed as suitable for evaluating the buckling resistance of a member subjected to pure compression; the same assumption was validated in [41]. The GMNIA analyses were solved by the arc-length method in order to capture the decreasing slope after the occurrence of the instability phenomenon. The loading is realised by an imposed load at the gravity centre in the end-section of the angle member.

To model a buckling curve, 13 simply supported elements corresponding to 13 different relative slendernesses from $\bar{\lambda} = 0.2$ to $\bar{\lambda} = 2.6$ were selected for each considered cross-section. The buckling lengths L_{cr} associated with those relative slendernesses are computed as expressed in Eq. (5).

$$\bar{\lambda} = \sqrt{\frac{\beta \cdot A \cdot f_y}{N_{cr}}} \rightarrow L = L_{cr} = \frac{i \cdot \pi \cdot \bar{\lambda}}{\sqrt{\frac{\beta \cdot f_y}{E}}} \quad (5)$$

The Euler’s load N_{cr} is analytically computed considering the geometrical properties of the selected gross cross-sections. In the buckling procedure, the β coefficient reduces the plastic resistance to account for the risk of local buckling according to EN1993-1-5 [30], this coefficient is equal to 1.0 here as this study focuses on compact sections (classes 1 to 3).

For each relative slenderness, the reduction factor χ obtained through numerical simulations is evaluated as expressed in Eq. (6) in such a way to draw the numerical buckling curve.

$$\chi = \frac{N_u}{A \cdot f_y} \quad (6)$$

with N_u the peak axial load obtained through GMNIA simulations, A the cross-sectional area, and f_y the material strength.

The yield strengths f_y considered in the numerical models are the nominal values provided in Table 5.1 of EN1993-1-1:2022 [29]. However, the latter specifications for the nominal yield strength only consider a reduction of the yield strength for thicknesses above 40 mm, while the corresponding product standards prescribe a reduction from 16 mm. Therefore, it has been decided to realize some numerical simulations considering the yield strength reduction prescribed in products standards, in order to ensure that similar conclusions could also apply to steels complying with the relevant product standards, i.e., EN10025-2 [52] and EN10025-4 [53] for hot-rolled steel angles. The results related to this yield strength are indicated with the index EN10025 hereafter.

In each numerical model, a linear elastic – perfectly plastic material model with a nominal plateau slope for numerical stability has been chosen, similarly to what was already done in previous research works [2,22,27,41,54,55].

3.3 Geometrical and material imperfections

According to the modelling recommendations from prEN1993-1-14:2025 [56], an initial bow imperfection with a magnitude equal to $L/1000$ with a deformation shape similar to the first pure weak-axis flexural buckling mode has been implemented in the numerical models. The selection of the initial geometrical imperfection shape is justified by the outcomes of the ANGELHY project [21], where it has been demonstrated that the dominant failure mode of a pinned compressed equal-leg angle member is weak axis buckling, even if, at the first steps of loading, the member tends to buckle in a flexural-torsional mode. Similar observations have been made by other researchers [14,24–26].

The magnitude of the residual stresses is often discussed in the literature based on experimental measurements [19,20,32,57–59] when evaluating the bearing capacity of steel angle members under compression, as the measurements generally present large scatter. Sometimes, even the shape of the residual stress pattern is discussed to have a better agreement with the experimental measurements, for instance a trilinear model instead of a bilinear one [20]. It however appears that, the compression residual stresses at flange tips are always lower than the recommended pattern scaled for 235 MPa, meaning that the same distribution can be conservatively considered whatever the steel grade under concern. Consequently, the ECCS pattern scaled by 235 MPa has been used in the parametric study for each considered steel grade (see Figure 2). This residual stress pattern is predefined in the FINELG software for this section typology. It is also assumed to be appropriate for non-existing grades (grades above S460) as a prospective study.

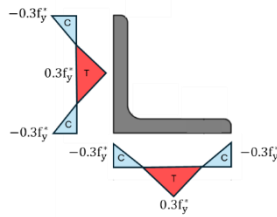


Figure 2 Residual stress distribution

4 Numerical validation

In the framework of the ANGELHY project [21], experimental buckling tests were performed to evaluate the resistance of S460 steel angles. In particular, in this framework, Bezas et al. [22] realised experimental tests on L150x150x18 and L200x200x16 profiles made of S420 and S460 steel grades. Within this study, they successfully reproduced the observed structural behaviour by using the FineLg software with beam finite elements, considering again both material and geometrical non-linearities. This demonstrates that the finite element software is adequate for simulating the flexural buckling of high-strength steel angle profiles, validating also the considerations made in section 3 regarding the initial geometrical imperfections, the residual stresses and the material law. Consequently, based on the literature review and the experience of the present authors in the use of the numerical tool, it appears that the Finelg software with beam elements is suitable to accurately reproduce the buckling behaviour of steel angles made of regular and high-strength steel grades.

5 Numerical results

5.1 Assessment of the design rules for reference grades

EN1993-1-1:2022 [29] specifies a gap of one buckling curve between mild steel grades (up to S420) and high-strength steel grades (from S460), whereas the same buckling curve is specified for both in the current EN1993-1-1:2005 [28]. Consequently, the first step of the parametric study consisted of validating the new prescription for the reference grades, i.e., S235 and S460. Comparisons between the Eurocode design rules and the numerical simulations are reported in Figure 3.

The statistical evaluation reported in Figure 3 indicates a good correspondence between numerical simulations and design rules. A buckling curve is assumed to be suitable when the mean value, noted $\bar{\chi}$ is above 1.0, this limit corresponds to the partial safety coefficient for stability design calculations ($\gamma_{M1} = 1.0$). To complete the statistical evaluation, the standard deviation s , the coefficient of variation COV and the maximum and minimum values are also provided.

It can be seen in Figure 3 that the numerical data for a relative slenderness $\bar{\lambda} = 0.2$ are below the plastic plateau. This feature has already been observed in many studies and led to some modified imperfection factors with a different length for the plastic plateau [43,44], which is even sometimes different depending on the steel grade [45,46] as previously mentioned. However, this limit has been fixed in the past based on a statistical evaluation of the wide experimental campaign, including angles; so it has been decided to keep the 0.2 boundary value for the plateau.

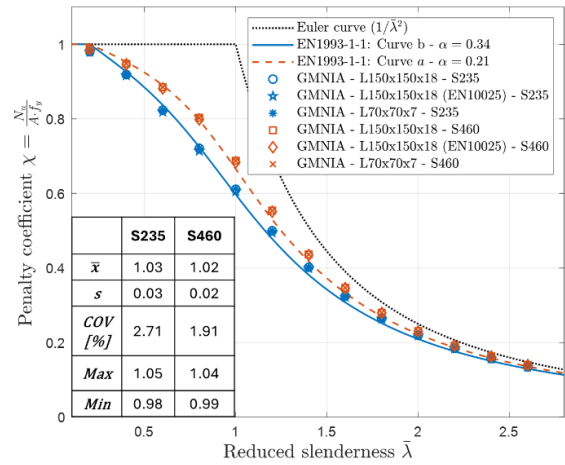


Figure 3 Assessment of the existing rules for reference grades

In addition, the numerical simulations realised considering the nominal yield strength from product standards are slightly below the values obtained by considering the yield strength from design standard, as expected. Indeed, for the S235 steel grade for instance, the design rule EN1993-1-1:2022 [29] recommends the use of a yield strength of 235 MPa for thicknesses up to 40 mm while the associated EN10025-2 & -4 [52,53] recommends a reduction to 225 MPa from 16mm. The profile L150x150x18 is concerned by this particular aspect as reported in Figure 3. Nevertheless, according to the statistical evaluations made in Figure 3, there is a perfect agreement between the recommended curves in EN1993-1-1:2022 [29] and the numerical simulations, meaning that it is appropriate to conserve these recommendations for those grades.

5.2 Assessment of the design rules for intermediate grades

The previous subsection illustrates how the impact of initial imperfections is reduced when moving from the S235 grade to the S460 grade. However, intermediate grades such as S355 and S420 are gathered in the same category as the S235 grade while it is likely that the detrimental impact of initial imperfections is gradually reduced for

these grades too. The same applies to the S500 grade, which has the same prescribed buckling curve as the S460 grade. The comparison between numerical simulations and the currently prescribed buckling curves for intermediate grades is shown in Figure 4.

The current design recommendations for the flexural buckling of intermediate grades are too conservative. Indeed, as it can be observed in Figure 4, the buckling resistance of intermediate grades are clearly underestimated when considering buckling curve “b” while the consideration of curve “a” would be unconservative for most of the cases.

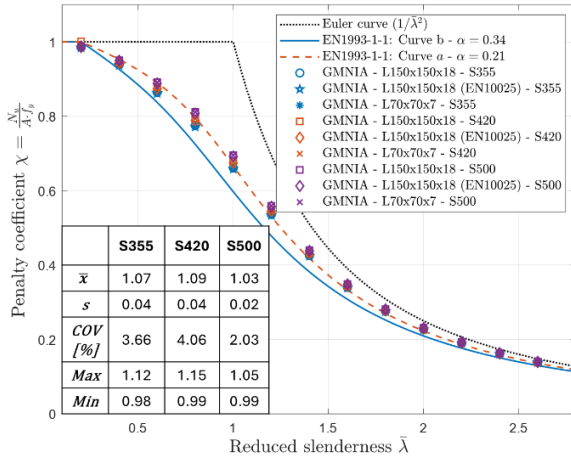


Figure 4 Assessment of the existing rules for reference grades

5.3 Proposal for a new modified imperfection factor

Based on the literature review presented in Section 2.2 and the numerical conclusions reported in Section 5.1 and 5.2, the objective is to derive a modified imperfection factor that respects the gap of one buckling curve between the reference grades, i.e. S235 and S460, and continuously accounts for the beneficial impact of the yield strength. The modified imperfection factor which was already proposed for hot-rolled H-shaped and hollow sections [2,41] is reported in Eq. (7).

$$\alpha^* = \alpha \cdot \left(\frac{235}{f_y} \right)^{0.7} \quad (7)$$

This proposal offers the advantage of conserving the current buckling curves for S235 and S460 as they were evaluated as suitable in Section 5.1. Indeed, for S235, $\alpha^* = 0.34 \cdot \left(\frac{235}{235} \right)^{0.7} = 0.34$ corresponding to a buckling curve “b” while for S460, $\alpha^* = 0.34 \cdot \left(\frac{235}{460} \right)^{0.7} = 0.21$ corresponding to buckling curve “a” as currently prescribed. Consequently, an extensive parametric study covering grades from S235 up to S700 was carried out by means of the FineLg software for Class 1 to 3 cross-sections which consists of 300 numerical simulations. For each numerically produced buckling curve, an imperfection factor α has been calculated to fit with the numerical curve. The so-obtained imperfection factor α is evaluated as appropriate when the mean value is above 1.0 while arbitrarily limiting the maximum overestimation of the load-bearing capacity to 2%. Those numerically obtained imperfection factors, the current recommendations of the two versions of EN1993-1-1

[28,29] as well as the proposed modified imperfection factor are represented in Figure 5.

Figure 5 confirms the reliability of the proposal expressed in Eq. (7) for hot-rolled equal-leg angles.

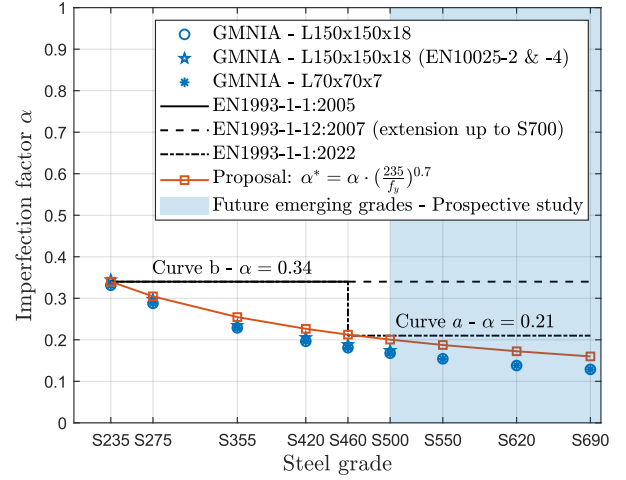


Figure 5 Proposal for a new modified imperfection factor

6 Conclusions

The study shows that higher yield stress reduces the negative influence of initial imperfections, that the upcoming EN1993-1-1:2022 recommendations for S460 align well with numerical predictions, and that current rules significantly underestimate the buckling resistance of intermediate grades between S235 and S460 as well as future higher-strength steels. The scope of the modified imperfection factor proposed by Saufnay et al. [2,41], initially developed for hot-rolled H-shaped and hollow sections, has been extended to include hot-rolled angle sections.

This new proposal is particularly advantageous for intermediate steel grades such as S355 and S420 grades, which are the most underestimated grades despite S355 is seen as the standard steel grade in contemporary design. In the context of the “build clever” strategy within the hierarchy to net-zero [60,61], the implementation of appropriate design rules is essential not only to enable designers to efficiently exploit material performance and achieve weight savings, but also to embed sustainability at the core of the design process. By optimizing structural efficiency and minimizing resource use, designers contribute to reducing embodied carbon and environmental impact, aligning engineering decisions with broader sustainability goals like achieving net-zero by 2050.

As a perspective, a full statistical approach based on a Monte Carlo analysis should be realised to assess the reliability of this new modified imperfection factor with a unitary partial safety coefficient $\gamma_{M1} = 1.0$. The reliability of the proposal should be evaluated for unequal-leg as well as welded angles to generalize. In addition, there are different formulations in the literature for this modified imperfection factor; it would be of great interest to generalize and choose one single form for all types of elements so as to propose a consistent amendment of the design rules.

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