



High-strength steel columns in steel structures – Establishment of reference slenderness ratios to select the appropriate steel grade

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Abstract

In the context of structural optimisation, high-strength steels represent the highest strength-to-weight ratio of the existing steels, thereby contributing to the optimisation of steel structures by reaching the same level of resistance with a reduced material quantity and resulting in lighter buildings requiring less extensive and costly foundations. New production technologies are already available for the manufacture of hot-rolled steel sections with a yield strength up to 500 MPa in Europe and 80 ksi (550 MPa) in the United States, which comply with the product norms for civil engineering applications. The selection of the right steel at the right place may result in further investments by manufacturers in the future to develop the optimal material solution for each application. Nevertheless, the use of mild steels is still often preferred for hot-rolled sections due to a lack of information regarding the existing high-performance products and the advantages they offer, as well as a scarcity of availability due to the current low demand. Furthermore, using a higher steel grade is often associated with an increase in the unitary cost of steel, accompanied by an increased carbon factor, a reduced weldability and ductility as well as an increased risk of local and global buckling instabilities. This paper demonstrates the considerable weight, cost and carbon savings that can be attained through the selection of an appropriate steel grade for multi-storey building columns and propose reference slenderness ratios to facilitate the selection of the steel grade.

Keywords

High-strength steels, Flexural buckling, Hot-rolled sections, Relative prices, Sustainable design

1 Introduction

The development of new steel production techniques has led to a notable advancement of steel products, facilitating the fabrication of steels with enhanced mechanical and chemical properties [1], [2], [3], [4], [5], [6], [7], [8], [9]. In 2022, according to the WorldSteel Association [10], the steel industry invested 6.3% of its revenue in research and process improvement, so the development of new production technologies is in constant evolution. Indeed, about 75% of the 3500 steel grades in use today did not exist 20 years ago. High-strength steels are generally defined as steels with a yield strength in excess of 460 MPa). New production technologies are already available to produce hot-rolled steel sections up to 500 MPa that meet the European construction requirements and the consideration of the right material at the right place may lead to further

investments by manufacturers in the future to develop the best material solution for each application. Nevertheless, the use of mild steel is still preferred for heavy hot-rolled sections in steel structures. This may result from a lack of information on existing high-performance products and their resulting benefits as well as a lack of availability. This paper aims at providing reference slenderness ratios to determine the benefit in using high-strength steels in columns.

2 Sustainability assessment

To assess the sustainability of a new material or construction technique, it is necessary to adopt a holistic approach accounting for the scarcity of resources, the need to reduce and eliminate inequalities and the need to ensure the economic viability of this improvement [11], [12], [13].

The use of a higher steel grade is often associated with an increase in the carbon footprint as well as an increase of the unitary material cost, so while using high-strength steels enables saving material resources by reducing the weight, the designer is sometimes reluctant to use them as he does not know in which cases the use of such high-performance grades is economically and environmentally justified.

2.1 Material price

In the report of the European RFCS project RUOSTE [8], the authors compare two papers published by Johansson [14] and Stroetmann [15] which derive relative material prices for high-strength steel heavy plates. As stated in [8], [14], [16], the price is highly dependent on changes in the production process, e.g. a change from a quenched and tempered (QT) to a thermomechanical (TM) production process, which may explain the discrepancy between the two references. Face to this observation, a deeper analysis based on price lists available online in the past and on the history of steel base prices considering three relevant levels (low: 500€/t, medium: 750€/t and high: 1000€/t) has been realised by the present authors [17]. The relevant relative prices are reported in Table 1. The low level of the relative price, indicated in Table 1, corresponds to the high level of base price and vice versa.

Table 1 Relative price levels for the economic assessment.

Level	S235	S355	S460	S500	S600	S700
Low	1.00	1.05	1.07	1.08	1.11	1.14
Medium	1.00	1.08	1.13	1.15	1.21	1.32
High	1.00	1.12	1.20	1.23	1.31	1.50

These relative prices, listed in Table 1, allow for the consideration of both the multiplicity of production techniques and the variability of the base price associated with the market demand, which has a significant impact on the economic advantage of using a higher specific grade. Indeed, the higher the material base price, the less the relative price and so the higher the economic advantage in considering higher steel grades.

2.2 Carbon footprint

In terms of relative CO₂ emissions, specific information on building materials or products is disseminated through Environmental Product Declarations (EPDs). Currently, the EPDs available on the market do not provide Global Warming Potential (GWP) values depending on the yield strength. In the Steel Eco-Cycle project (2004-2012) [18], [19], [20], [21], the Swedish steel industry in collaboration with the Swedish Environmental Research Institute, carried out a series of cradle-to-gate analyses and provided carbon emission trends as a function of yield strength and steel typology. In addition, Stroetmann provided in 2011 [15] reference relative GWP values for heavy thermomechanical steels that were seen as constant up to S500 grade. Based on those results, an approach was proposed in [13], [22], allowing evaluating, for a given steel category, the relative GWP of high-strength steels based on their chemical compositions. In-

deed, it appears that differences in carbon footprint between steel grades result from the production emissions of additional alloying elements. For steels produced by the quenching and self-tempering process (QST), the increase in carbon emissions is likely to be negligible up to 500 MPa, similarly to steels complying with EN10149-2 [23] and EN10025-2 [24]. This demonstrates that the reduction in carbon emissions can be estimated as equal to the percentage of weight savings for the existing steel grades for hot-rolled sections. By conservatively using the established reference values listed in Table 1, it is possible to derive recommendations for developing and selecting appropriate steel grades, resulting in both cost and carbon savings thereby contributing to sustainable designs.

3 Establishment of reference slenderness ratios

The elastic buckling resistance is independent of the material strength; therefore, the relative slenderness increases with the yield strength. Consequently, high-strength steel members are more susceptible to being affected by buckling instability if the cross-sectional geometry of the member is identical to that of a member made from a lower steel grade. In addition, for the same cross-sectional resistance, the member made of a high-strength steel grade will exhibit a smaller cross-section, which is generally associated with smaller inertia, so to a lower critical load and so to higher relative slenderness. This observation could compromise the benefit of high-strength steels for stability-governed members as the higher the slenderness, the closer to the Euler's resistance and the less the advantage in using high-strength steels. In the framework of this publication, the focus is made on local buckling and flexural buckling as the latter are the most prevalent instability modes for doubly symmetric cross-sections subjected to pure compression. The relevant slenderness ratio for local buckling is provided in Eq. (1) while the slenderness ratio for flexural buckling is in Eq. (2).

$$\text{Local buckling: } \bar{\lambda} = \frac{\lambda_{LB}}{28.4 \cdot \varepsilon \cdot \sqrt{k_\sigma}} \text{ with } \lambda_{LB} = \frac{c}{t} \quad (1)$$

$$\text{Flexural buckling: } \bar{\lambda} = \sqrt{\frac{N_{Rk}}{N_{cr}}} = \frac{\lambda_{FB}}{\lambda_1} \cdot \sqrt{\beta} \text{ with } \lambda_{FB} = \frac{L_{cr}}{i} \quad (2)$$

With $\bar{\lambda}$ the relative slenderness, λ_{LB} the local buckling slenderness, ε the material parameter, k_σ the local buckling coefficient, c the appropriate plate width, t the plate thickness, N_{Rk} the characteristic axial resistance, N_{cr} the Euler's critical load, λ_{FB} the flexural buckling slenderness, λ_1 the reference slenderness, β the local buckling reduction factor, L_{cr} the buckling length and i the radius of gyration.

3.1 Resistance to local buckling

The presence of local buckling can strongly affect material efficiency. The increase in terms of axial resistance as a function of the yield strength and accounting for the presence of local buckling is derived for a plate under pure compression, which is the worst scenario, as computed in Eq. (3) with S235 as reference.

$$\frac{N_{rd,HSS}}{N_{rd,S235}} = \frac{\rho_{HSS} \cdot A \cdot f_y}{\rho_{S235} \cdot A \cdot 235} = \left(\frac{\rho_{HSS}}{\rho_{S235}} \right) \cdot \left(\frac{f_y}{235} \right) \quad (3)$$

with $N_{Rd,HSS}$ the design value of the high-strength axial resistance, $N_{Rd,S235}$ the design value of the axial resistance for S235, ρ_{HSS} the reduction coefficient for the cross-section made of the high-strength steel grade, ρ_{S235} the one for the S235 grade, A the cross-sectional area and f_y the yield strength of the high-strength steel grade. The resistance ratios for internal elements of hot-rolled H-shaped and SHS profiles are reported in Figure 1.

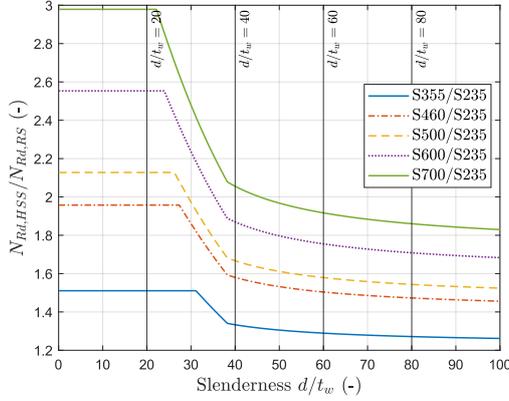


Figure 1 Relative resistance to local buckling for internal compression elements under pure compression (S235 as reference).

Increasing the wall width leads to an increase in plate slenderness associated with a higher reduction factor, which may counterbalance the increase in terms of cross-sectional area. The practical guide for sustainable steel buildings [11] states that for SHS 260x8, increasing the width of this section without adapting the wall thickness (e.g. increasing to SHS 300x8) results in a negligible increase in axial resistance for high-strength steel grades due to the presence of local buckling. Indeed, the slenderness of SHS 260x8 is equal to 32.5 which is on the decreasing slope for high-strength steels (see Figure 1).

3.2 Resistance to flexural buckling

The relative importance of residual stresses decreases as the yield strength increases, which can have a positive effect on the flexural buckling resistance. Regarding the current design recommendations [25], [26], the same buckling curve is assigned to grades included between S235 and S420 and an increase of one buckling curve is allowed for grades equal to or higher than S460. The gain of buckling resistance resulting from the use of a higher yield strength can be computed by evaluating the ratio of buckling resistances for a given column (same cross-sectional area for both compared grades) as given in Eq. (4), considering a Class 1, 2 or 3 column, one buckling axis and S235 as the reference grade.

$$\frac{N_{b,HSS}}{N_{b,S235}} = \frac{\chi_{HSS} \cdot A \cdot f_y}{\chi_{S235} \cdot A \cdot 235} = \left(\frac{\chi_{HSS}}{\chi_{S235}} \right) \cdot \left(\frac{f_y}{235} \right) \quad (4)$$

with $N_{b,HSS}$ the design buckling resistance of the high-strength member, $N_{b,S235}$ the design buckling resistance for the S235 member, χ_{HSS} the reduction coefficient for the high-strength steel member, χ_{S235} the reduction coefficient for the S235 member, A the cross-sectional area of the member and f_y the yield strength for the steel grade.

If H-shaped hot-rolled members with height-to-width ratios above 1.2, flange thickness below 40 mm and flexural buckling about the major axis or for hot-finished hollow sections are considered, buckling curve "a" is recommended in FprEN1993-1-1:2022 [25] for mild steels while curve "a0" is recommended for grades from S460 [43]. This case has been evaluated as the worst scenario regarding the benefit of using higher grades [13], so it will be considered as the reference case study in this paper. In such a case, the results in terms of buckling resistance ratios are given in Figure 2. The importance of the flexural buckling slenderness ratio ($\lambda_{FB} = L_{cr}/i$) on the benefit of using high-strength steels is demonstrated by plotting the relative resistances for 4 relevant actual column slenderness ratios between the two boundaries already cited by Johansson in 2005 [14], [16], i.e. $\lambda_{FB} = 40$ and 100, as a function of the yield strength in Figure 2.

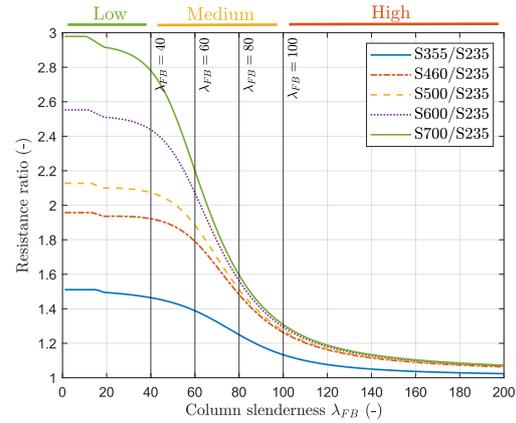


Figure 2 Relative resistance to flexural buckling for hot-rolled sections (curve "a" up to S420 and curve "a0" for S460 and above) and hot-finished hollow sections considering grade S235 as reference.

It can be seen in Figure 2 that, for column slenderness ratios $\lambda_{FB} < 40$ (Low slenderness), the resistance ratio is close to the yield strength ratio, i.e. the resistance is almost proportional to the yield strength. This slenderness limit was already cited by Johansson in 2005 [16] as it corresponds to the slenderness of stocky columns that are typical in non-sway structures where high-strength steels can lead to significant savings. On the contrary, for slender columns $\lambda_{FB} > 100$ (High slenderness), the increase of resistance for grades higher than S460 becomes insignificant, and the flexural buckling phenomenon drastically reduces the benefit of considering higher yield strengths for such applications. This is the typical column slenderness ratios met in sway structures as identified by Johansson [16]. This conclusion applies to any pair of buckling curves, i.e. any geometrical limit and buckling axis. To summarize, for slender columns ($\lambda_{FB} > 100$), there is no benefit in using a yield strength above the practical range (presently limited to 460-500 MPa) while for $\lambda_{FB} < 40$, there is an advantage in developing the highest considered grade regardless of the buckling axis. For Intermediate slendernesses, the optimum yield strengths are included between 500 MPa and 700 MPa and the benefit for high-strength steels should be assessed depending on the application. The aforementioned conclusions are illustrated by plotting the slenderness limits of each steel grade, which define the field of application for a steel grade. For example, the ratio between the flexural buckling resistance of a given column made from steel grade S355

and the one from S235 is shown in Figure 3 (a). Based on the relative prices defined in Table 1, it is feasible to derive the slenderness limit below which there is an economic advantage in using the S355 grade instead of S235, and this for the three relative cost levels as depicted in Figure 3 (a) ($\lambda_{lim,H}$ being the slenderness limit for the high cost level, $\lambda_{lim,M}$ for the medium cost level and $\lambda_{lim,L}$ for the low cost level). The three limits for all steel grades are presented in a single graph in Figure 3 (b), facilitating the comparison of these relevant parameters for existing grades, as well as for future emerging grades up to S700, for the purpose of a prospective study. The figures have been plotted for the case study, i.e., curve “a” for mild steels and “a₀” for grades above S420. It should be noted, however, that the remaining charts for all the other cases are gathered in the annexes of the free-access PhD thesis of the first author [13]. The purpose of these charts is twofold: firstly, they serve as graphical tools to assist designers in determining the benefit of a higher grade; and secondly, to assist steelmakers in the development of new products that are appropriate for different structural applications.

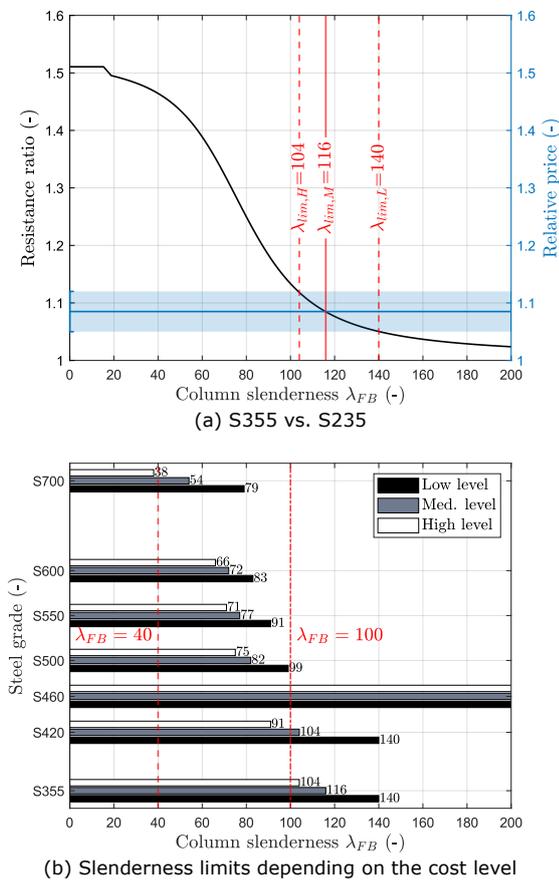


Figure 3 Slenderness limits to justify the benefit of a higher grade for hot-rolled sections respecting $h/b > 1.2 / t_f \leq 40$ mm / major axis as well as for hot-finished hollow sections.

Figure 3 (a) confirms that, while the slenderness ratio remains below 100, there is always a benefit in substituting the S235 grade by the S355 grade, regardless of the relative cost level (noted $\lambda_{lim,H}$) is 104. Furthermore, there is a benefit in considering the highest grade, i.e. S700, if the column slenderness ratio does not exceed 40. For intermediate grades, the benefit should be evaluated in the slenderness

range $\lambda_{FB} \in [40; 100]$ depending on the relative material cost, i.e. the following limits could be safely written $\lambda_{FB} \leq 75$ for S500, $\lambda_{FB} \leq 70$ for S550, $\lambda_{FB} \leq 65$ for S600. Nevertheless, based on Figure 3, it should be conservatively concluded that it is relevant to investigate the possibility of using grades above the practical range from column slenderness ratios respecting $\lambda_{FB} < 80$ as this is the limit obtained for S700 considering the low material cost level.

However, based on the current unphysical stepwise evolution in FprEn1993-1-1:2022 [25], there is always a benefit in considering the S460 grade instead of S420, as shown in Figure 3 (b) with slenderness limits exceeding the upper boundary of 200 in the chart. This can be explained by the stepwise evolution of the imperfection factor in current design rules. A modified version of the imperfection factor to more appropriately account of the beneficial effect of the yield strength has been proposed in [13], [27] for hot-rolled sections and hot-finished hollow sections. Indeed, as the yield strength increases, the relative influence of residual stresses on the buckling resistance reduces. The proposed modified imperfection factor is reported in Eq. (5) and the influence of such parameter is illustrated in Figure 4.

$$\alpha^* = \alpha \cdot \left(\frac{235}{f_y} \right)^{0.7} \quad (5)$$

With α^* the modified imperfection factor, α the reference imperfection factor prescribed for the S235 grade and f_y the yield strength.

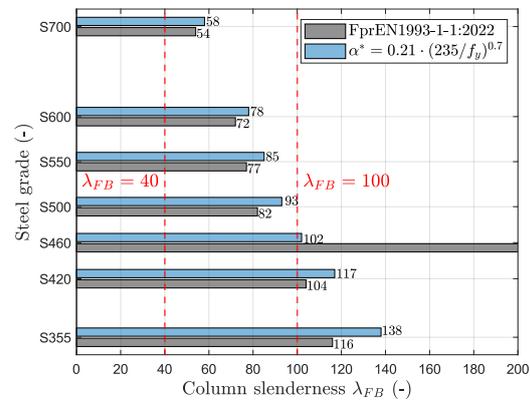


Figure 4 Influence of a modified imperfection factor on relative buckling resistances and slenderness limits.

3.3 Optimisation routine

As neglected in Section 3.2, the consideration of a higher grade implies that some sections in the manufacturers' catalogues fall into the class 4 category, which means that they are sensitive to local buckling phenomena. It is therefore essential to consider both instability phenomena in order to draw final conclusions. To compare different steel grades and account for all instability modes that column may be prone to, analytical comparative studies following the approach described in [28] are carried out using the MATLAB software [29]; the objective is to define the cheapest structural element, i.e. the optimum design, respecting the new version of Eurocode 3 part 1-1 [25]. Only European hot-rolled steel sections are considered in the scope of this study including H-sections (HD profiles), and hollow sections (SHS profiles). Each geometrical property

has been interpolated through a spline interpolation in MATLAB [29] to neglect the effect of profile discretisation on the so-obtained results. The yield strength is assumed to be equal to the reference nominal values prescribed in the forthcoming standard version FprEN1993-1-1:2022 [25]. The MATLAB routine developed in the framework of the present thesis was validated through comparisons with the existing ATTEL algorithm [30] and it perfectly reproduced the former results. The optimisations have been carried out according to the procedure considering the medium relative cost represented in Table 1 and the continuous quantities for HD and SHS catalogues and the results are shown in Figure 5. The flexural buckling slenderness ratios $\lambda_{FB,z}$ (weak axis buckling) of the optimum profiles are also reported in order to identify the column slenderness ratios for which there is an advantage in developing new steel grades. In addition, the Class 3 slenderness limits in S700 are included, i.e., $38 \cdot \sqrt{\frac{235}{700}} = 22.0$ for SHS to demonstrate the impact of local buckling on the benefit of considering high-strength steels.

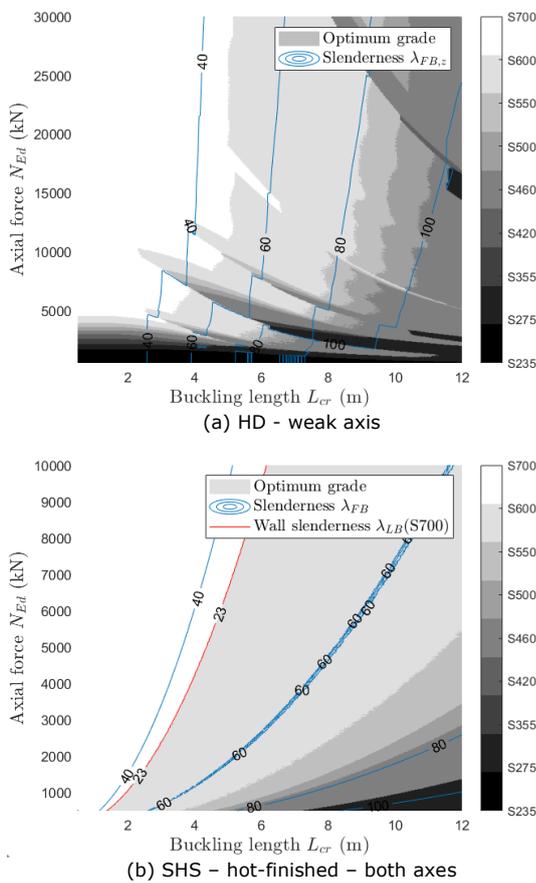


Figure 5 Optimisation results for continuous hot-rolled sections (HD and SHS profile series) under pure compression and medium cost level.

Figure 5 confirms the previous conclusion that, there is a benefit in considering grades above the practical range when $\lambda_{FB} < 80$. In addition, for SHS made of S700 grade, the benefit starts to be limited by the local buckling. Further results may be found in the PhD thesis of the corresponding author [13].

4 Case study

In a promotional paper [28], ArcelorMittal promoted its HISTAR® 460 trademark steel by giving an example of its

use in the Mapfre Tower in Barcelona. The weight saving calculated by reproducing the design of each column through the developed optimisation routine is 26%. It should be noted that the column's slenderness ratio $\lambda_{FB,z}$ significantly varies between floors, ranging from 30 at the ground floor to 70 at the top floor. So, the benefit for high-strength steels may decrease with height according to Figure 3. An optimisation routine has been developed to evaluate the potential benefit of developing high-strength steels, i.e. grades above S460, within the context of the present practical case study. The weight savings and relative costs as a function of yield strength are shown in Figure 6, with S235 as a reference for the sake of continuity with the preceding presented results. Continuous quantities for the profile catalogues have been used to establish the results.

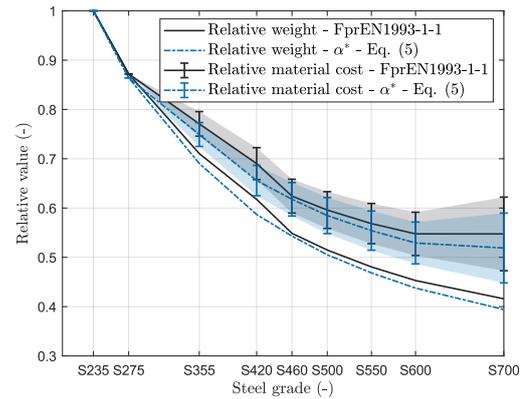


Figure 6 Benefit in increasing the material yield strength for columns in the Mapfre Tower.

As can be seen in Figure 6, passing from an S235 to an S460 grade represents a weight gain of 45% (which is seen as equal to the environmental advantage) while the economic benefit is between, 35% and 40% depending on the level of material cost. Similarly, for the S700 grade, a weight gain of 60% is contemplated but the economic benefit of using this grade instead of the S600 grade is limited to a low level of relative material cost. Nonetheless, it should be remembered that the aforementioned results assume that the same grade is used for all columns in the building, which is unlikely to be the optimum design. As observed in Figure 3, the benefit for possible future emerging steel grades is highly sensitive to both the material cost level and the column slenderness ratio. The advantage of utilising the maximum grade, specifically S700, is restricted to column slenderness ratios below 54 (see Figure 3 (b)), corresponding to columns of the bottom half of the structure. As the column slenderness ratios are included between 40 and 70, they respect the criterion of $\lambda_{FB} < 80$, so there is an advantage in considering grades above the practical range and it is even more pronounced when considering the modified imperfection factor - see Eq. (5). Therefore, this case study corroborates the suitability of the slenderness limits in providing an initial indication of the potential benefits of considering and developing higher steel grades.

5 Conclusions

Comparative studies have been carried out between the various existing and future possible emerging grades for

hot-rolled sections, based on the realistic ranges of relative prices and carbon emissions. The analysis revealed several factors that either limit or increase the advantages of using higher steel grades. In the case of members that are sensitive to instability, reference slenderness ratios, denoted λ_{LB} (for local buckling) and λ_{FB} (for flexural buckling), were discussed. It appears that there is always a benefit to be gained from using the highest grade (under consideration within the present study) for slenderness ratios $\lambda_{FB} < 40$. Conversely, for slenderness ratios $\lambda_{FB} > 100$, the advantage of developing grades above the practical range becomes very limited. To ascertain the advantage of producing a specific profile with higher yield strength, a series of reference figures were plotted, delineating the various dimension limits with the associated costs and establishing reference slenderness limits. It has been safely concluded that it is relevant to investigate the possibility of using grades above the practical range from column slenderness ratios respecting $\lambda_{FB} < 80$. The research also highlights the necessity of having appropriate design rules to take benefit from the material strength ("build clever"). The selection of the right steel at the right place may result in significant weight, carbon and cost savings by building "less" but it requires effective communication and collaboration between the designer and the supply chain to ensure the efficiency of the performed designs. As a perspective, it would be prudent to incorporate fire design into the existing routines to address this aspect as well. It is believed that the methodology employed in this study can be applied to other problems, such as those involving partially or fully encased steel-concrete composite sections. It may be feasible to also undertake comparative studies with welded members, given enhanced flexibility in terms of dimensions, which may lead to efficient designs.

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