

## HIGH-STRENGTH STEELS IN STEEL STRUCTURES: HOW TO SELECT THE APPROPRIATE STEEL GRADE?

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### **KEYWORDS :**

High-strength steels, Column slenderness, Hot-rolled sections, Hollow sections, Economic design

### **ABSTRACT :**

Among the existing solutions to reduce material consumption in the construction sector, the steel market is continuously witnessing the emergence of new, ever-stronger steels. The recent improvements of the steelmaking process have indeed enabled to manufacture wide flange sections with improved material properties, with good toughness and weldability performance. The development of high-strength steels contributes to the optimisation of structural designs with the potential for substantial weight, cost and carbon savings. Hot-rolled sections with a yield strength of up to 500 MPa in Europe and 80 ksi (550 MPa) in the United States already exist and comply with the product standards for structural applications. Although research has shown an insignificant increase in carbon footprint with rising yield strength, demonstrating the environmental benefit of developing and using higher steel grades, their adoption remains quite marginal. This can be explained by a lack of information on existing high-performance products and the advantages they offer, as well as a lack of availability resulting from the current low demand for these grades. In addition, higher steel grades are often associated with increased unit material costs, reduced weldability and ductility, and a greater tendency to both local and global buckling instabilities. Consequently, designers are often reluctant to incorporate these innovative materials in their designs and manufacturers hesitant to develop them, particularly in the absence of clear guidelines for assessing their economic viability in specific structural applications. This paper consists of a comparative study on the use of the appropriate steel grade for members under pure compression. In particular, reference member slenderness ratios are established allowing the identification of the relevant field of application for the different considered grades.

## 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 [1-4]. In 2022, according to the WorldSteel Association [5], 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. Over the last twenty years, markets have seen the emergence of high-strength steels (HSS). Indeed, about 75 % of the 3500 steel grades in use today did not exist 20 years ago. Although there is no universal consensus on the definition of these steels, since a steel grade can be classified as "standard" or "high-strength" depending on its field of application, high-strength steels are generally characterised as steels with a yield strength of at least 460 MPa.

For hot-rolled sections, new production technologies are already available to produce steel grades up to S500 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 structural application. By comparison, welded I-shaped columns and hot-finished and cold-formed hollow sections have already been studied in steel grades up to S960 in the literature [6-12], reflecting the growing demand for efficient, lightweight structural solutions capable of withstanding higher loads while minimizing material usage. It is therefore likely that hot-rolled sections will be developed in grades beyond S500 in the upcoming years. European design standards support these developments by adapting the existing design rules; the forthcoming EN1993-1-1:2022 [13] will cover grades up to S700 while the new upcoming version of EN1993-1-12 will include additional rules for steel grades up to S960.

In the United States, the transition from S235 to S355 as the standard steel grade was completed in the early 2000s. In Germany, the S355J2 grade has emerged as the most prevalent steel grade [14,15]. In the United Kingdom, twenty-five years ago, S275 was the preferred steel choice of structural engineers. Today, the prevailing preference is for S355 as the default structural grade so that an extra cost is charged to lower grades like S235 or S275 as they are no more routinely produced [16-18]. A slight trend towards S355 as the basis grade can be observed in most of the European steel market, which indicates that the construction industry is gradually adopting higher steel grades. The use of mild steel is still preferred for heavy hot-rolled sections in steel structures, the market share of S420/S460 is relatively modest but is nevertheless experiencing growth, particularly in the context of applications such as columns in high-rise buildings, long-span structures and/or bridges. However, contemporary challenges emerge when designing steel structures, including considerations of resilience, sustainability and material efficiency. It seems reasonable to assume that interest in high-strength steel grades will increase in the coming years in light of these considerations. Indeed, in the forthcoming years, the global steel market is witnessing an expansion in the availability of high-strength steel products, with the objective of building more efficiently with less material in order to respect the Paris Agreement [19] and achieve carbon neutrality by 2050.

Recent studies [20-25] have demonstrated that the increase in carbon footprint associated with higher yield strength is negligible. Based on those results, an approach was proposed in [26,27], allowing evaluating, for a given steel category, the relative global warming potential (GWP) of high-strength steels based on their chemical compositions as it appears that differences in emissions between steel grades result from the production emissions of additional alloying elements. It has been demonstrated that, for hot-rolled steel sections, the increase in carbon emissions is likely to be negligible up to 500 MPa. 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. Consequently, the use of high-strength steel grades presents a promising strategy for reducing the environmental impact of structural projects across a wide range of structural applications. However, ensuring the sustainability of a structural project is not only related to environmental concerns. 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 [27-29]. The use of a higher steel grade is often associated with an increase of the unit material cost, so while using high-strength steels enables saving material resources and reducing the carbon footprint 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 justified.

The increase in relative material cost of high-strength steels is generally offset by the reduction in self-weight. For instance, for weightsensitive members, the use of S460 instead of S355 represents a 30 % increase in strength, while the relative material cost is approximately 10-15 % higher, assuming that the fabrication costs are not unduly affected by the material yield strength [14,28,30-32]. The advantage of using high-strength steels may be found in various structural applications such as in compression members with low to medium slenderness [33,34], for lower-storey columns in multi-storey frames as these members are often highly loaded [24,25,28,30,35,36] or in long-span structures [22,37,38]. The literature review on the economic benefit indicates that high-strength steels have an advantage in certain applications, but not everywhere. The high-strength steel guide [31] mentions that the weight savings can range from 10 % to 40 % but regrets that there is a lack of reliable data on the economic and environmental savings achievable using high-strength steels. Given the limited availability of high-strength sections and the lack of clear guidance on the selection of the appropriate steel grade, some recommendations should be written to help designers in optimising their designs [1]. Consequently, this paper pursues two main goals, i.e., providing guidelines to practitioners as well as proving to steelmakers the benefit of pursuing the development of ever-stronger steel grades for hot-rolled sections for a more sustainable construction sector.

The research questions can therefore be formulated as follows: Is there an economic benefit to developing and using hot-rolled sections in S460 grade instead of S355? What about grades above S500 as a prospective study? Is there a benefit in developing them? What are the application fields for such sections? The objective of this paper is therefore to identify the fields of application for which the utilisation of high-strength steels is economically advantageous through comparative studies. This process involves the adaptation and/or the validation of the extant recommendations

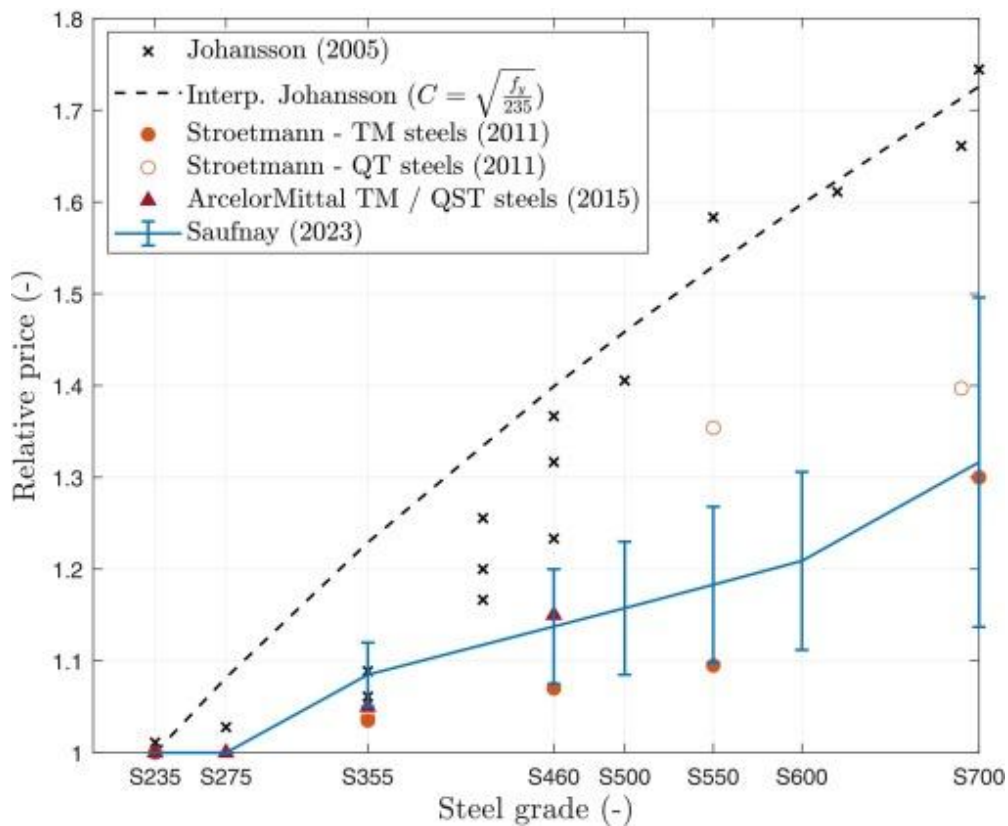
referring to updated design rules and reference prices. The initial step in this research is a literature review about the relative material cost of higher grades. Subsequently, comparative studies are performed with the aim of providing up-to-date recommendations and answering to the formulated research questions.

## 2. Relative material cost

To conduct a comparative study and draw conclusions on the economic benefit of using high-strength steels, it is necessary to have a reliable estimate of relative prices, i.e. the price of a steel grade compared to another. In the report of the European RFCS project RUOSTE [39], the authors compare two papers published by Johansson [34] and Stroetmann [25] which derive relative material prices for high-strength steel heavy plates. Although these two references are regularly cited when analysing the economic benefits of using high-strength steels [16,28,40-43], the two trends are significantly different. Indeed, in 2005, Johansson [34] proposed that the relative price trend follows the square root of the yield strength, while in 2011, Stroetmann [25] provided lower relative values based on the average prices of several producers on the German market, as shown in Figure 1. As stated in [33,34,39], 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 in [26,44]. Realistic relative price ranges have been established and validated based on the existing values and models from the literature, as reported in Figure 1.

These relative prices, represented in Figure 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, during periods of base price peaks, such as those experienced during the pandemic crisis or the energy crisis in the previous years, the extra costs associated with a particular grade, which have been assessed as constant values in [44], become relatively insignificant, thereby increasing the economic gains generated by using high-strength steels.

**Figure 1.** Establishment of reliable relative price intervals for steel grades up to S700.



### 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 these are the most prevalent instability modes for doubly symmetric cross-sections subjected to pure compression. According to EN1993-1-1 [13] and EN1993-1-5 [45], the relevant slenderness ratio for local buckling is provided in Eq. (1) while the slenderness ratio for flexural buckling is expressed in Eq. (2).

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

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

With  $\bar{\lambda}_p$  the relative slenderness for local buckling,  $\bar{\lambda}$  the relative slenderness for flexural buckling,  $\lambda_{LB}$  the local buckling slenderness ratio,  $\varepsilon$  the material parameter,  $k_\sigma$  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,  $\lambda_{FB}$  the flexural buckling slenderness ratio,  $\lambda_1$  the reference slenderness,  $\beta$  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. To account for local buckling, design standards recommend either evaluating an effective width or evaluating an effective stress. The method prescribed in EN1993-1-5 [45] consists of determining an effective area obtained by virtually removing the part of the plate which is prone to local buckling ( $A_{c,eff} = \rho \cdot A$  where  $\rho$  is the reduction coefficient to account for the risk of local buckling).

As given in EN1993-1-5 [45], the reduction factor due to local buckling is provided in Eq. (3) for internal plated elements and Eq. (4) for outstand plated elements.

$$\rho = \begin{cases} \bar{\lambda}_p^{-0.055 \cdot (3+\psi)} & 1.0, \bar{\lambda}_p \leq 0.673 \\ \frac{1.0}{\bar{\lambda}_p^2} & \bar{\lambda}_p > 0.673 \end{cases} \quad (3)$$

$$\rho = \begin{cases} \bar{\lambda}_p^{-0.188} & 1.0, \bar{\lambda}_p \leq 0.748 \\ \frac{1.0}{\bar{\lambda}_p^2} & \bar{\lambda}_p > 0.748 \end{cases} \quad (4)$$

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. (5) with S235 as reference.

$$\frac{N_{Rd,HSS}}{N_{Rd,S235}} = \frac{\rho_{HSS} \cdot A \cdot f_y}{\rho_{S235} \cdot A \cdot 235} = \left( \frac{\rho_{HSS}}{\rho_{S235}} \right) \cdot \left( \frac{f_y}{235} \right) \quad (5)$$

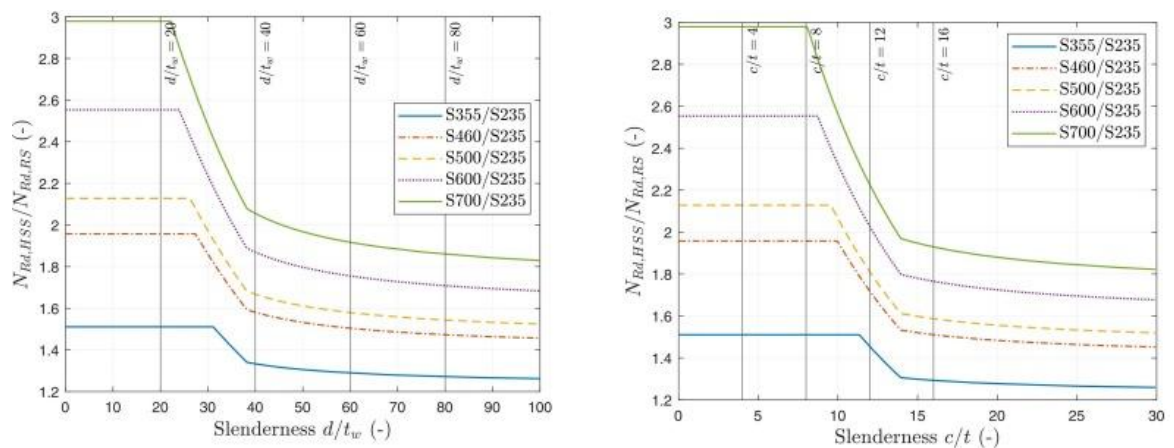
with  $N_{Rd,HSS}$  the design value of the high-strength axial resistance,  $N_{Rd,S235}$  the design value of the axial resistance for S235,  $\rho_{HSS}$  the reduction coefficient for the cross-section made of the high-strength steel grade,  $\rho_{S235}$  the one for the S235 grade,  $A$  the cross-sectional area and  $f_y$  the yield strength of the high-strength steel grade.

The resistance ratios for outstand and internal elements covering various constitutive parts of hot-rolled H-shaped and SHS profiles as well as for circular hollow sections are reported in Figure 2.

Figure 2 shows that, even for slender plates, there is still a gain in resistance resulting from the use of a higher yield strength but in a lower proportion than for stocky plates. Most of the European profiles respect the slenderness limit of outstand elements as stocky plate. The practical guide for sustainable steel buildings [28] states that for SHS 260 × 8, increasing the width of this section

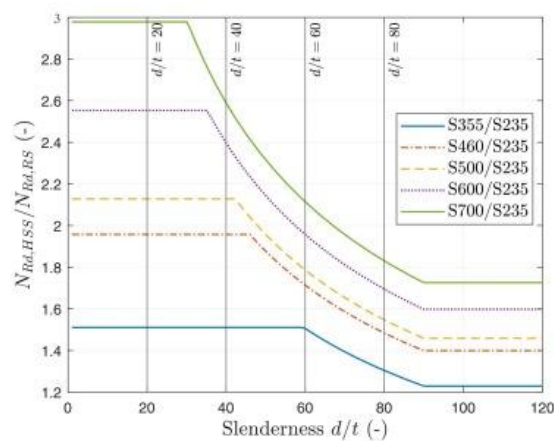
without adapting the wall thickness (e.g. increasing to SHS 300 × 8) results in a negligible increase in axial resistance for high-strength steel grades due to the presence of local buckling. Indeed, the slenderness of SHS 260 × 8 is equal to 32.5 which is on the decreasing slope for high-strength steels (see Figure 2b). Therefore, increasing the wall width leads to an increase in plate slenderness associated with a lower reduction factor, which may counterbalance the increase in terms of cross-sectional area. In contrast to hot-rolled H-shaped and I-shaped sections, which typically have reasonable thicknesses, the walls in compression of hollow sections are generally slender. According to manufacturers' catalogues available on the steel market, the diameter-to-thickness ratio for CHS varies between 7 and 127, while the width-to-thickness ratio for SHS varies between 8 and 50. This feature may particularly affect the benefit of using high-strength steels. Figure 2 demonstrates that, if in the future, new steels with higher yield strengths than the practical range become available, the existing catalogue of sections should be reviewed to limit the slenderness of the walls to levels that allow to take benefit from the increased yield strength without any reductions that alter the material efficiency.

**Figure 2.** Relative resistance to local buckling for hot-rolled sections under pure compression (S235 as reference).



(a) Internal compression element (web)

(b) Outward compression element (flanges)



(c) Circular hollow section

### 3.2. RESISTANCE TO FLEXURAL BUCKLING

According to the European procedure for the design of steel members under compression, geometrical and material imperfections are accounted for through an imperfection parameter  $\alpha$ , which defines the well-known European buckling curves. The European buckling curves provide the reduction factor as a function of the relative slenderness  $\chi = f(\bar{\lambda})$  the analytical expression of those curves is expressed in Eq. (6).

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \quad (6)$$

with  $\phi = 0.5 \cdot (1 + \eta + \bar{\lambda}^2)$  and  $\eta = \alpha \cdot (\bar{\lambda} - 0.2)$

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 [13], [46], 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. (7), considering a Class 1, 2 or 3 column, one buckling axis and S235 as the reference grade.

$$\frac{N_{b,HSS}}{N_{b,S235}} = \frac{\chi_{HSS} \cdot A \cdot f_y}{\chi_{S235} \cdot A \cdot 235} = \left( \frac{\chi_{HSS}}{\chi_{S235}} \right) \cdot \left( \frac{f_y}{235} \right) \quad (7)$$

with  $N_{b,HSS}$  the design buckling resistance of the high-strength member,  $N_{b,S235}$  the design buckling resistance for the S235 member,  $\chi_{HSS}$  the reduction coefficient for the high-strength steel member,  $\chi_{S235}$  the reduction coefficient for the S235 member,  $A$  the cross-sectional area of the member and  $f_y$  the yield strength for the considered 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 [13] for mild steels while curve "a<sub>0</sub>" is recommended for grades above S420 [42]. This case has been evaluated as the worst scenario regarding the benefit of using higher grades [27], 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 3. The importance of the 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 slenderness ratios between the two boundaries already cited by Johansson in 2005 [33,34], i.e.  $\lambda_{FB} = 40$  for stocky columns and  $\lambda_{FB} = 100$  for slender columns, as a function of the yield strength in Figure 3.

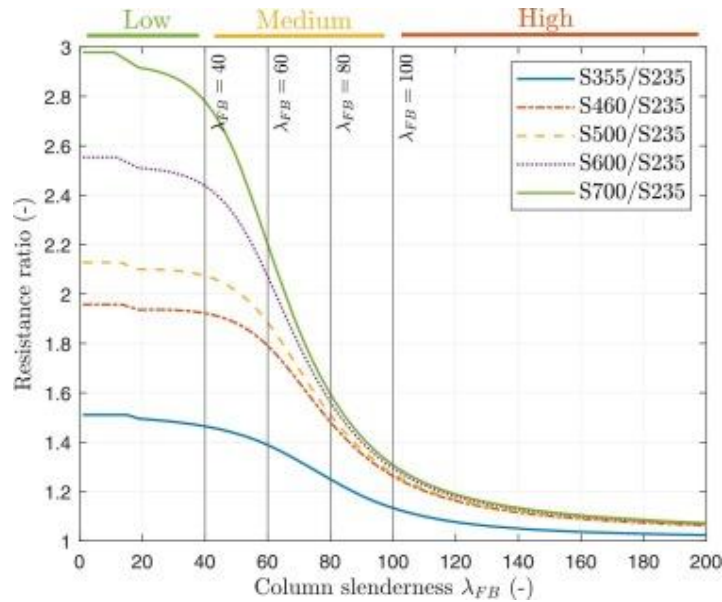
It can be seen in Figure 3 that, for column slendernesses  $\lambda_{FB} < 40$  (**Low slenderness**), the resistance ratio is close to the yield strength ratio, i.e. the resistance is almost proportional to the yield strength. This slenderness limit was already cited by Johansson in 2005 [33] as it corresponds to the slenderness of stocky columns that are typical in multi-storey buildings 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 met in sway structures as identified by Johansson [33]. 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 (medium) 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.

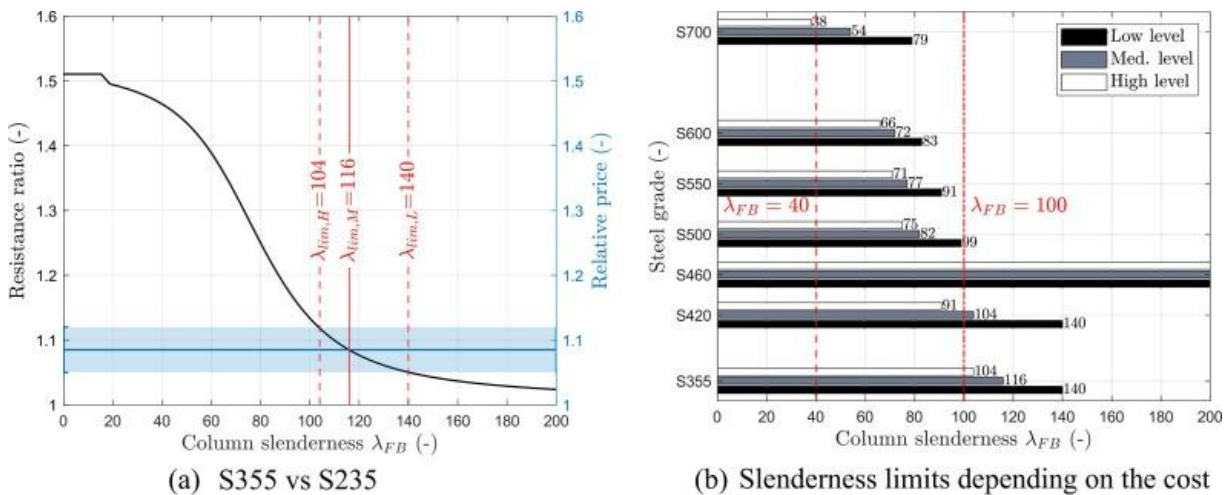
The aforementioned conclusions are illustrated by plotting the slenderness limits of each steel grade, which define the field of application for a steel grade. For example, the ratio between the flexural buckling resistance of a given column made from steel grade S355 and the one from S235 is shown in Figure 4a. Based on the relative prices defined in Figure 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 material cost levels as depicted in Figure 4a ( $\lambda_{lim,H}$  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 4b, 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 "a<sub>0</sub>" 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 [27]. 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 4a confirms that, while the column slenderness remains below 100, there is always a benefit in substituting the S235 grade by the S355 grade, regardless of the relative cost level as the slenderness limit for the higher cost level (noted  $\lambda_{lim,H}$ ) is 104. Based on the current unphysical stepwise evolution, i.e., the step of one buckling curve between S420 and S460 in current design provisions, there is always a benefit in considering the S460 grade instead of S420, as shown in Figure 4b with slenderness limits exceeding the upper boundary of 200 in the chart. Furthermore, there is a benefit in considering the highest grade, i.e. S700, if the column slenderness 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 4, it should be conservatively concluded that it is relevant to investigate the possibility of using grades above the practical range from column slendernesses respecting  $\lambda_{FB} < 80$  as this is the limit obtained for S700 considering the low material cost level.

**Figure 3.** Relative resistance to flexural buckling for hot-rolled sections (curve "a<sub>0</sub>" up to S420 and curve "a<sub>0</sub>" for S460 and above) and hot-finished tubes considering grade S235 as reference.



**Figure 4.** 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 tubes.



## 4. Methodology

As a reminder, the conclusions expressed in Section 3.2 are for Class 1, 2 or 3 columns with a fixed slenderness for which the cross-section area decreases as the yield strength increases. But, in reality, the column slenderness increases with decreasing cross-sectional area, which is less favourable for high-strength steels. Furthermore, 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 global 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 [47] are carried out using the MATLAB software [48]; the objective is to define the cheapest structural element, i.e. the optimum design, respecting the new version of Eurocode 3 part 1-1 [13]. The flowchart of the developed optimisation routine is reported in Figure 5.

The flowchart in Figure 5 has been developed to address various loading situations; however, in this study focusing exclusively on steel columns under pure compression, Ultimate Limit States (ULS) encompasses yielding, local buckling and flexural buckling while Serviceability Limit States (SLS) are useless. For each case study, the benefit assessment is based on the comparison of the optimum designs at room temperatures of different grades. An optimum design for a specific steel grade is defined as a design that returns the lightest profile, in a specific series of profiles (HEA, HEB, ...), thereby achieving the best material use. Then, a cost comparison between the optimum profiles for the different considered steel grades is performed to determine whether there is an economic benefit in using a high-strength steel grade or not. When the applied load is such that the optimised profiles are the same for the compared steel grades, there is no economic benefit in using the high-strength steel grade instead of the mild steel grade because the latter is cheaper.

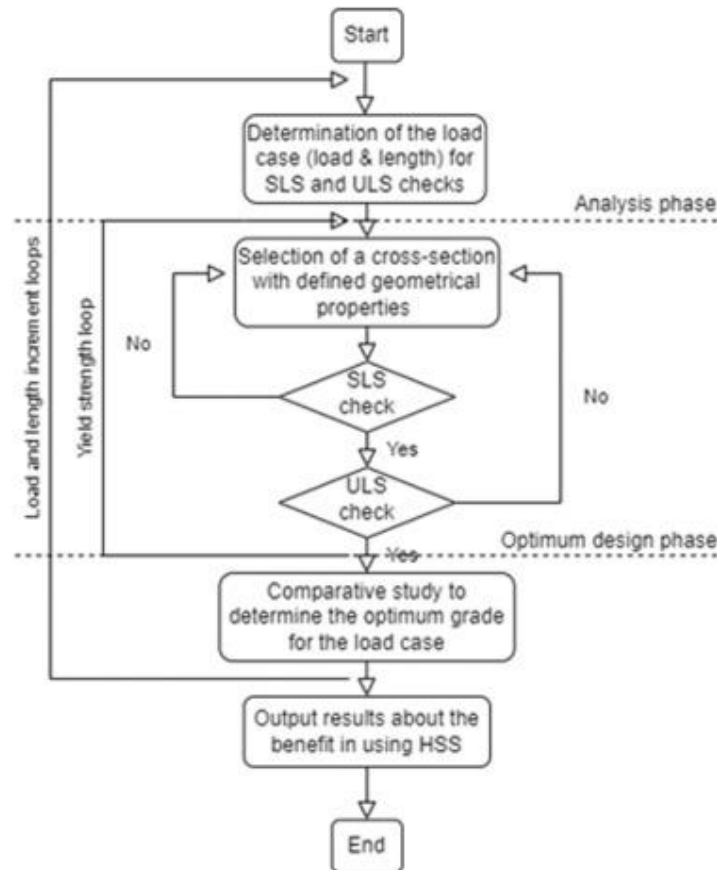
The buckling lengths for columns are included in  $L_{cr} \in [1; 12]m$  to cover non-sway and sway structural systems. Regarding the internal forces, an axial force of  $N_{Ed} \in [500; 10000]kN$  is considered for columns in compression (up to 30000 kN for HD profile series) to cover multistorey buildings. For instance, in the Mapfre tower (40-storey building) which is analysed in Section 6.1, the compression load reaches about 14000 kN for the highest loaded columns in the first floors. These loads are factored and can be directly used for the ULS checks.

Only European hot-rolled steel sections are considered in the scope of this study including H-sections (comprising HEA, HEB, HEM and HD), and hollow sections (CHS, SHS and RHS). These sections are available in a wide variety of sizes through European suppliers. It has been demonstrated that the profile range has an impact on the result as the radius of gyration differs, as represented in Figure 6.

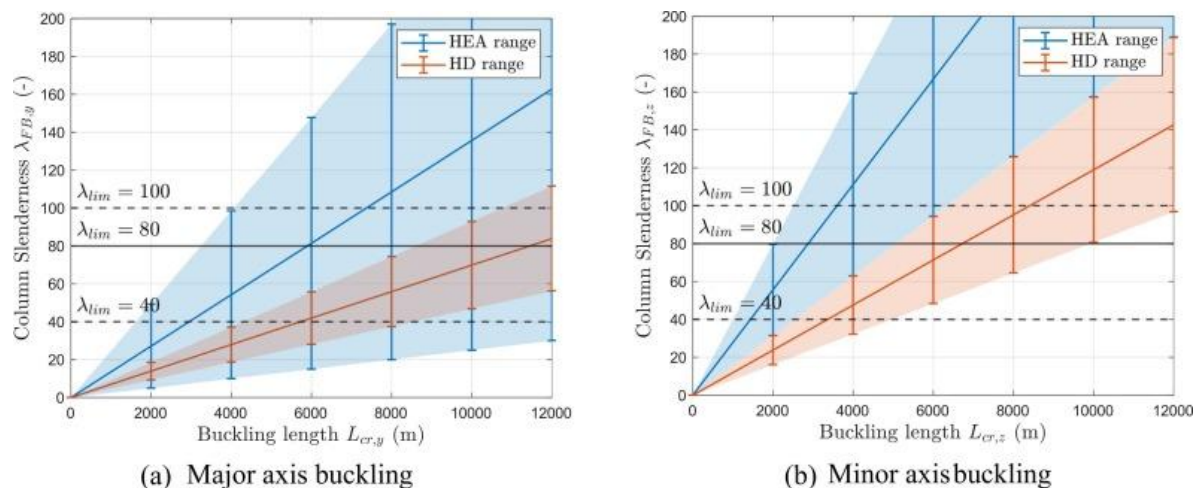
Figure 6 illustrates that, for massive cross-sections like HD profiles, the column slenderness is below the slenderness limit  $\lambda_{lim} = 80$  for typical multi-storey buckling lengths (between 3 and 5 m) and regardless of the buckling axis. On the contrary, lighter cross-sections like HEA profiles exhibit greater column slenderness for both buckling axes, meaning that the benefit of high-strength steel grades for such sections is likely to be limited. It has therefore been decided to consider these two profile categories to draw conclusions, as well as CHS and SHS profiles to extend the conclusions to hollow sections. Each geometrical property has been interpolated through a spline interpolation in MATLAB [48] to evaluate 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 [13]. Consequently, a yield strength reduction is applied for flange thicknesses greater than 40 mm. Finally, the medium base price level is considered for the

comparative studies presented in this paper. The MATLAB routine developed in this paper to compare the various steel grades has been validated on circular hollow steel sections based on comparisons with the algorithm developed within the ATTEL project [36].

**Figure 5.** Flowchart of the developed optimisation routines.



**Figure 6.** Column slenderness depending on the buckling length and the profile range.



## 5. Analysis of the results

The results of optimisations carried out according to the procedure described in Section 4, considering the medium relative cost represented in Figure 1 and the continuous quantities for HEA, HD, CHS and SHS catalogues are shown in Figure 7. The flexural buckling slenderness ratios  $\lambda_{FB,y}$  (strong axis buckling) and  $\lambda_{FB,z}$  (weak axis buckling) of the optimum profiles are reported in order to identify the column slenderness ranges for which there is an advantage in developing new steel grades. In addition, the local buckling slenderness ratios are also represented in Figure 7e for CHS and Figure 7f for SHS as well as the limits from which the resistance of the S700 designs is affected by the local buckling (see Figure 2), i.e.,  $90 \cdot \frac{235}{700} = 30.2$  for CHS and  $38 \cdot \sqrt{\left(\frac{235}{700}\right)} = 22.0$  for SHS.

These slenderness ratios and limits demonstrate the impact of local buckling on the benefit of considering high-strength steels. It should be noted that the load range for HD profiles has been extended up to 30000 kN as this profile range is more adapted for highly loaded columns.

As stated in reference [28], for HD profiles with a weight greater than 134 kg/m (HD360x134), the radius of gyration about the weak axis  $i_z$  becomes significantly higher than for HEA profiles. Indeed, HD sections offer the best weak axis buckling resistance among the rolled sections available on the steel market. Given that the larger the radius of gyration, the smaller the slenderness and the greater the benefit of increased yield strengths, this explains why the benefit of high-strength steels for HD profiles is greater than for HEA profiles in Figure 7. This Figure 7 also confirms the conclusions expressed in Section 3.2 regarding the slenderness limits, i.e. benefit in using the maximum grade for  $\lambda_{FB} < 40$ , no benefit for grades above the practical range when  $\lambda_{FB} > 100$  and a benefit for grades above the practical range when  $\lambda_{FB} < 80$ . The discontinuities observed in Figure 7a and Figure 7b, are caused by the sudden change of buckling curve prescribed in the Eurocode recommendations. Indeed, from a profile weight of 125 kg/m in the HEA profile series, the height-to-width ratio becomes greater than 1.2, leading to a change in the buckling curve. On the other hand, for the case of HD profiles, the two discontinuities are caused by the sudden increases in inertia between the HD320 and the HD400 profile series, which explains why there are two specific transition zones in Figure 7c and Figure 7d. Indeed, in these zones, the lower grades change from one series to the other, resulting in a reduction of the cross-sectional area for the same radius of gyration which gives them an advantage in these specific areas. Finally, for the highly stressed columns in Figure 7d, the flange thickness is greater than 40 mm and therefore the yield strength is reduced according to FprEN1993-1-1:2022 [13]. Furthermore, as the optimum designs are performed for each steel grade and load case, such figures provide information on the domains  $(N_{Ed}, L_{cr})$  for which there is a benefit in using higher yield strengths. For example, for storey columns characterised by buckling lengths between 3 m and 5 m, there is a benefit in considering higher yield strengths regardless of the buckling axis. In contrast, for lighter profiles (HEA) and sway frames corresponding to higher buckling lengths, there is less benefit in considering new yield strengths for such applications. However, these figures were obtained by considering a medium relative cost level and fictitious continuous quantities for profile ranges.

To assess the impact of discrete quantities, Figure 8 represents the same results as in Figure 7 by considering the discrete HEA and HD profile series. As can be seen, the general trends based on the column slenderness are still valid for the discrete catalogues, but the profile availability affects the results. To illustrate the impact of profile discretization, let's consider a column with a buckling length of 3.0 m subjected to a compression load of 5500 kN. Based on the results presented in Figure 7b, designers might initially conclude that using S600 grade is economically justified for this loading scenario. However, the developed routine with the existing discrete catalogue reveals that there is no weight reduction when passing from a S550 grade to a S600 grade as the optimum profile (HEA320) remains unchanged between both designs. Details about the designs for both steel grades are provided in Table 1.

As shown in Table 1, the unity check of the HEA320, also called the utilisation ratio, is 0.99 for S550 and 0.93 for S600. This indicates that the design is fully optimised for S550, whereas approximately 7 % of the cross-sectional area in the S600 design is not contributing to withstand the load. In this case, the geometrical properties of the previous profile in the range (HEA300) are insufficient to support the applied load, despite the higher strength of S600 (unity check of 1.028 in Table 1).

However, if a continuous catalogue was available with intermediary cross-sections between HEA300 and HEA320, a more efficient design could be achieved for S600 grade with a unity check closer to the unit, i. e., the profile HEA\*\*\* as reported in Table 1. This explains why there is a benefit for S600 grade in Figure 7b whereas there is no benefit in Figure 8a. The unity check constitutes a good indicator for assessing material efficiency, and this example underscores how both material efficiency and profile discretization significantly influence the benefit of using higher steel grades and why designers should check profile availability before concluding about the benefit.

Regarding hot-finished hollow sections, there is a significant benefit for high-strength steels in steel tubes under pure compression, but the presence of local buckling strongly affects the results. Indeed, as demonstrated in Figure 7e and Figure 7f with the slenderness ratios for local buckling, the benefit for S700 is reduced due to local buckling. A small loss of resistance due to the presence of local buckling, from the reported "limits for local buckling", is sufficient to limit the benefit for the S700 grade. Figure 9 displays the same charts as Figure 7e and Figure 7f but without considering the reduction of resistance due to local buckling. The conclusions drawn from this example apply to both CHS and SHS, and a significant benefit is expected for characteristic buckling lengths of storey columns ( $L_{cr} \in [3; 5]m$ ).

Figure 9 and Figure 7 demonstrate the importance of local buckling on the advantage of using high-strength steels, and the necessity of reducing the importance of this buckling phenomenon by adapting the existing profile catalogues. Besides, some authors already proposed in the past to develop innovative cross-sections to take better advantage of the increased yield strength [49], rather than simply using classical cross-sections. Various methods can be used to limit the width-to-thickness ratio of compression elements including the use of polygonal cross-sections, stiffeners (e.g. cold-formed folds) or corrugated webs [31,42]. Nevertheless, such solutions can be costly and may offset the economic benefit of using high-strength steels. Despite the detrimental impact of local buckling, the overall benefit for high-strength steels remains significant within the defined

domain, especially for buckling lengths corresponding to non-sway structures and the criterion expressed in Section 3.2 i.e.,  $\lambda_{FB} < 80$ , remains a reference to justify for the benefit in using grades above the practical range in any case. Solutions may be found to reduce the column slenderness by reducing the buckling length, for example by using pre-stressed stayed columns [31,49]. Nonetheless, the practical application of such a system is rare, and it is difficult to imagine such a concept in a building; in addition, the cost associated with the placement of such a system would strongly compromise the economic advantage in using higher steel grades. On the contrary, an adequate consideration of the end fixity of the columns could reduce both the applied load and the buckling length. It should be remembered that these results have been plotted for the medium relative cost level and two specific profile categories, but the above-mentioned discussions apply regardless of the profile category and the relative cost of the grades as reflected in [27].

Selecting an appropriate range of profiles is therefore critical for achieving substantial weight savings. Figure 7 offers designers valuable insights into the potential advantages of high-strength steel grades when considering fictitious continuous catalogues. At the same time, the study emphasizes to producers the need to adapt existing catalogues to enhance material efficiency by multiplying the number of profiles available in high-strength steel grades, by providing more flexibility in terms of profile dimensions and by reducing the plate slenderness to avoid reductions due to local buckling, thus enabling designers to perform more effective structural designs.

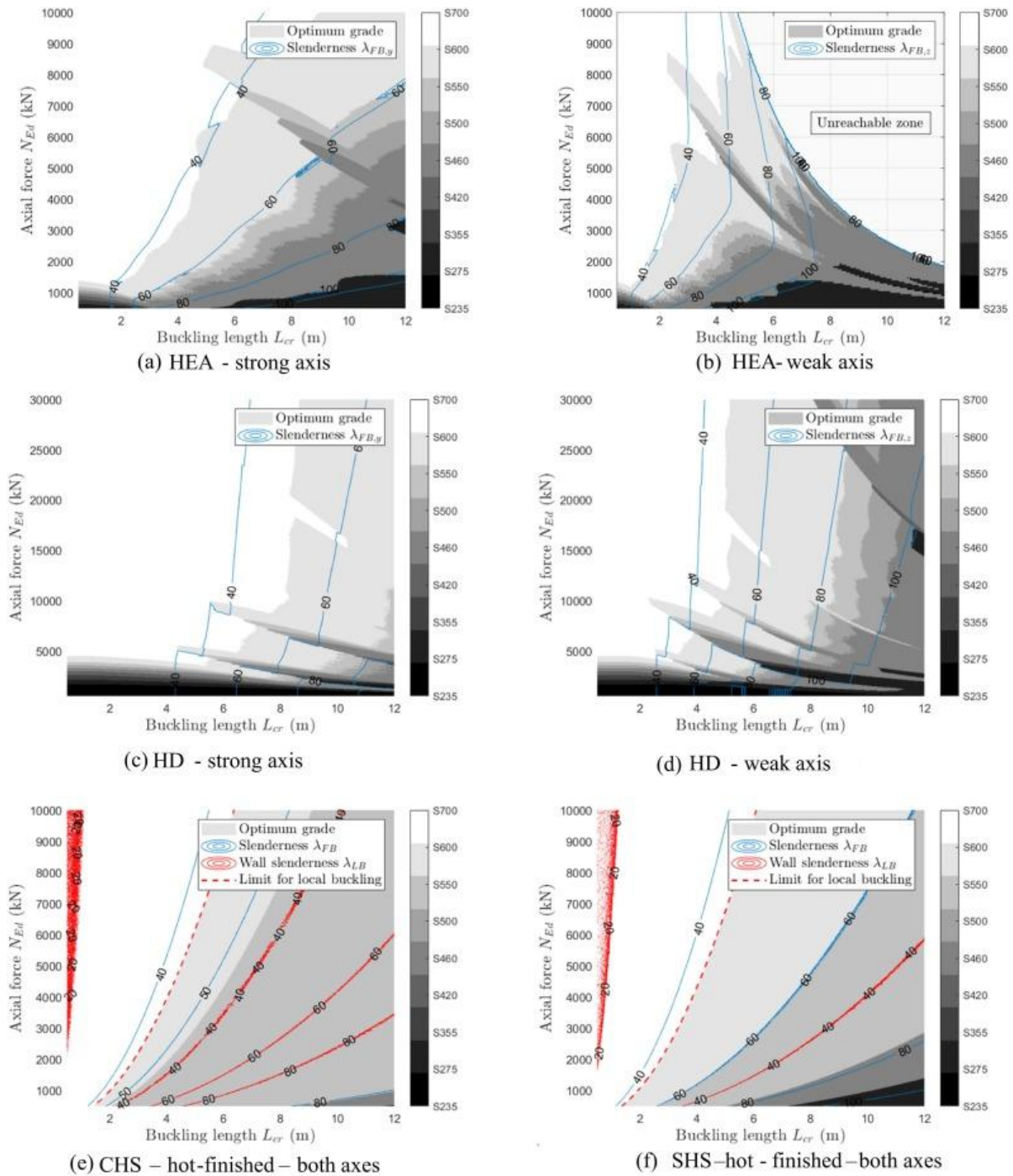
Finally, the study has been made consistent with the recommendations of the FprEN1993-1-1:2022 [13]. However, some improvements have already been proposed in the literature [50-56], i.e., a modified version of the imperfection factor to more appropriately account of the beneficial effect of the yield strength on the column stability. Indeed, as the yield strength increases, the relative detrimental influence of residual stresses on the buckling resistance reduces. The proposed modified imperfection factor for hot-rolled sections and hot-finished hollow sections defined in [27,56] is reported in Eq. (8) and the influence of such parameter is illustrated in Figure 10.

$$\alpha^* = \alpha \cdot \left(\frac{235}{f_y}\right)^{0.7} \quad (8)$$

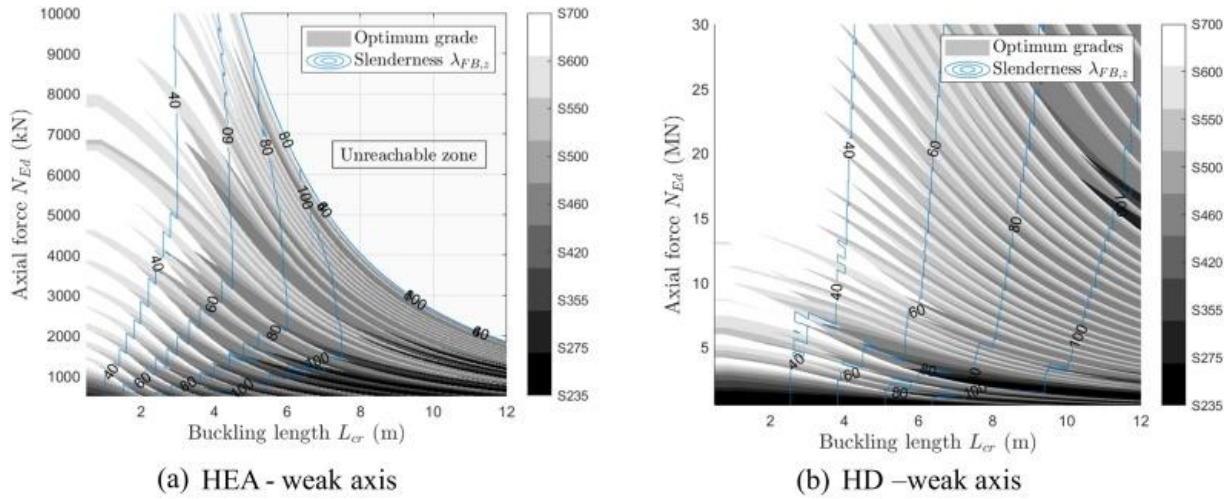
With  $\alpha^*$  the modified imperfection factor,  $\alpha$  the reference imperfection factor prescribed for the S235 grade and  $f_y$  the yield strength.

As illustrated in Figure 10, the modified imperfection factor  $\alpha^*$  increases the benefit of using a higher steel grade to larger column slenderness as the curve representing the resistance ratio in Figure 10a is shifted to the right. This is particularly the case for intermediate grades between S235 and S420 and future emerging grades (above S460-S500). This last comparison with the literature demonstrates the necessity of having appropriate design rules to benefit from material strength and thus contributing to a more sustainable building environment.

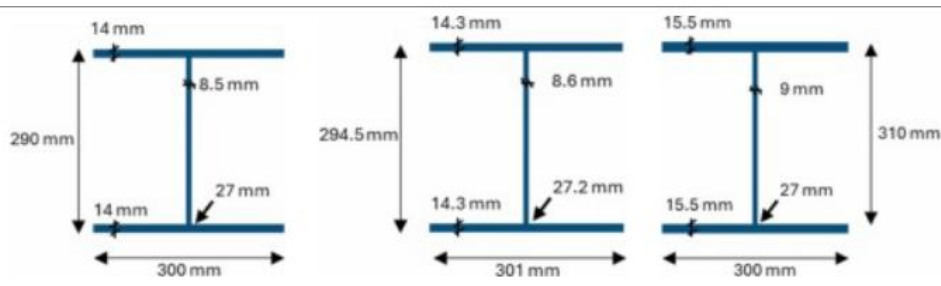
**Figure 7.** Optimisation results for continuous hot-rolled sections (HEA, HD, CHS and SHS profile series) under pure compression and medium cost level.



**Figure 8.** Optimisation results for compression members considering the discrete HEA, HD, CHS and SHS profile series.

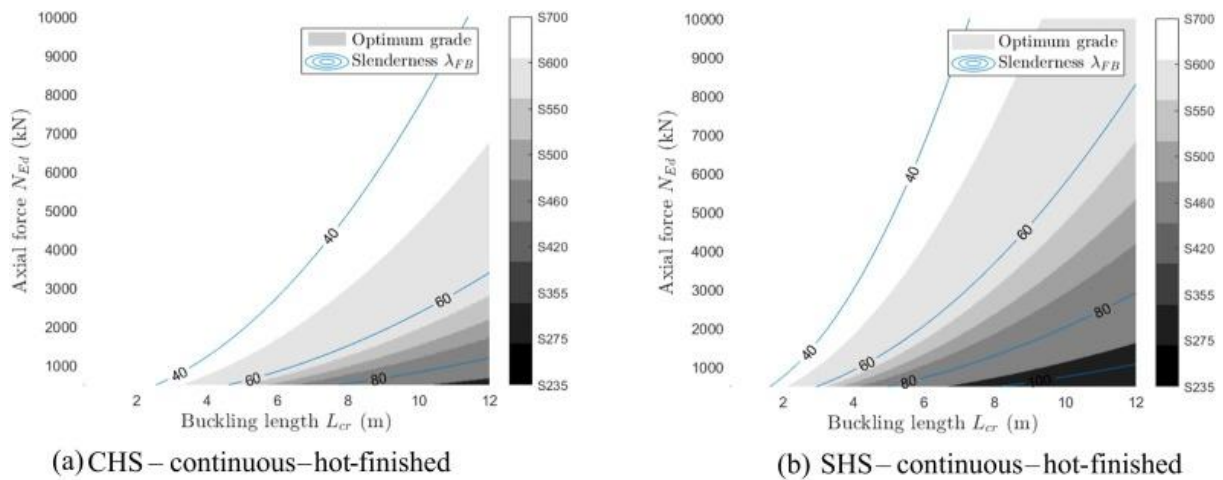


**Table 1.** Design details for a column with a buckling length of 3.0 m subjected to a compression load of 5500 kN.

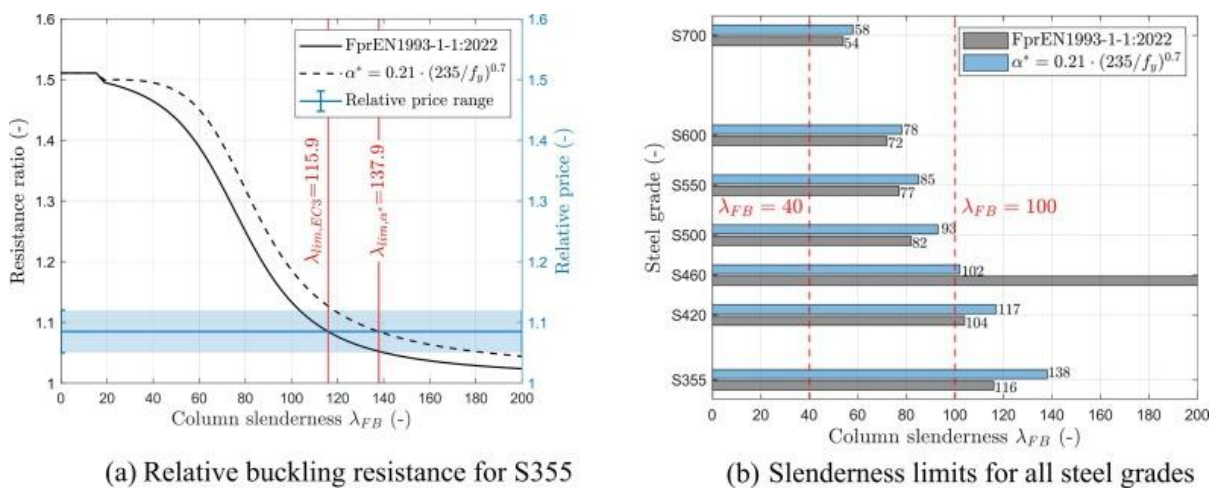


| Specimen               | HEA300 | HEA*** | HEA320 |
|------------------------|--------|--------|--------|
| $A$ [mm <sup>2</sup> ] | 11250  | 11565  | 12440  |
| $i_z$ [mm]             | 74.9   | 75.1   | 74.9   |
| $N_{b,Rd,S550}$ [kN]   | 5010.8 | 5158.4 | 5542.0 |
| Unity check S550       | 1.098  | 1.066  | 0.992  |
| $N_{b,Rd,S600}$ [kN]   | 5352.2 | 5509.6 | 5911.3 |
| Unity check S600       | 1.028  | 0.999  | 0.930  |

**Figure 9.** Optimisation results by neglecting the reduction factor associated with local buckling.



**Figure 10.** Influence of a modified imperfection factor on relative buckling resistances and slenderness limits.



## 6. Case studies

As observed with many reference structures, high-strength steels are particularly advantageous for compression members in high-rise buildings and long-span truss structures. Consequently, two case studies have been selected to illustrate this, namely the Mapfre Tower in Barcelona for high-rise buildings and the NRG stadium in Houston for long-span structures. The first application is very detailed as this case study is well-documented while the second is intentionally concise.

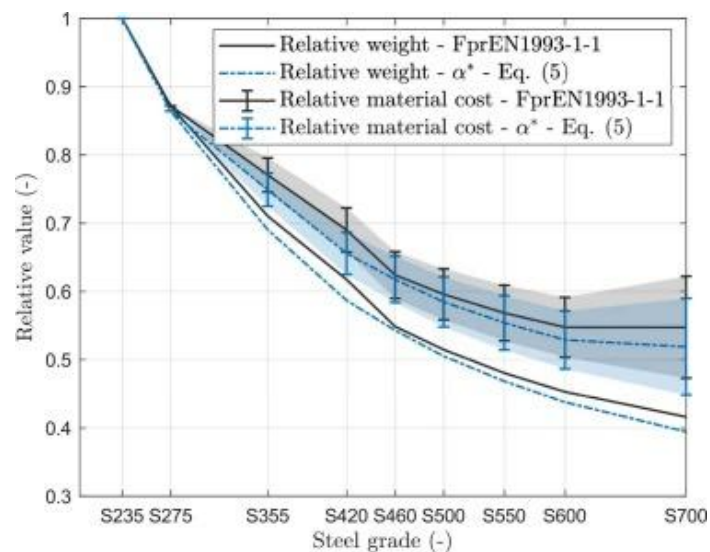
## 6.1. MAPFRE TOWER IN BARCELONA

The highest grades produced today (e.g. S460-S500 for hot-rolled sections) are often used for high-rise buildings as these structures have highly stressed columns on the lower floors as expressed in Section 1. In a promotional paper [27], 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 %, which is in close alignment with the value cited in the paper. It should be noted that the column's slenderness  $\lambda_{FB,Z}$  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 6. 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 11, 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.

As can be seen in Figure 11, passing from an S235 grade to an S460 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 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 6, the benefit for future emerging steel grades is highly sensitive to both the material cost level and the column slenderness. The advantage of utilising the maximum grade, specifically S700, is restricted to column slendernesses below 54 (Figure 6), corresponding to columns of the bottom half of the structure. As the column slendernesses 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 expressed in Eq. (8)- see Figure 11. Therefore, this case study corroborates the suitability of the slenderness limits, established in Figure 4b, in providing an initial indication of the potential benefits of considering and developing higher steel grades.

**Figure 11.** Benefit in increasing the material yield strength for columns in the Mapfre tower.



## 6.2. NRG STADIUM IN HOUSTON

As stated in the paper of Griffis et al. [38], the specific design of the retractable roof was constructed using high-strength steels to achieve optimal efficiency. The advantage of opting for a Grade 65 (450 MPa) instead of a Grade 50 (345 MPa) was analysed and discussed in the paper [38]. For the highly loaded super trusses used for the retractable roof, compression members were made from double W4-sections laced together with single angles. This approach was pursued to maintain the length of compression members at a minimum level and maximise the benefit of using a higher grade. In the case of trusses with lower loads, single W4 chord members were employed, and the efficient bracing configuration ensures that the buckling lengths remain low. The authors presented a histogram of the member slenderness for the compression members employed in the stadium.

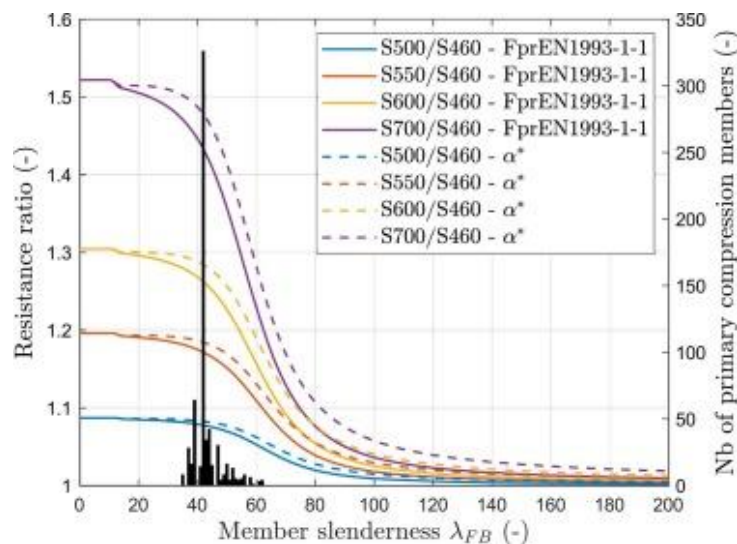
For the sake of conservatism, the worst-case scenario has been considered to evaluate whether the maximum practical grade, i.e. S500, as well as future emerging grades (up to S690), would be of interest for this particular application. The results are reported in Figure 12 on which the histogram of compression members used in the retractable roof is superposed.

This second case study demonstrates that, for the predominantly represented slenderness ratio ( $\lambda_{FB} = 42$ ), there is a significant advantage in considering the maximum grade under concern. Indeed, Figure 12 demonstrates that the relative resistance is frequently close to, or even occasionally higher than, the yield strength ratio. This phenomenon can be attributed to the gain of one buckling curve between grades S355 and S460, as recommended by current design guidelines [13]. Furthermore, as illustrated in Figure 12, most of the column slenderness values are close to the lower boundary of  $\lambda_{FB} = 40$ , meaning that there is an economic and environmental advantage in considering yield strength above the practical range in this specific application. It is nevertheless noteworthy that the designer employed a range of strategies intending to minimise the risk of

structural instability by implementing an adequate structural system (with bracings to reduce the buckling lengths), thereby optimising the benefit of using high-strength steels. This highlights the importance of adequate designs for an optimum valorisation of the material performance.

In conclusion, these comparative investigations on case studies provide valuable insights into the advantages of high-strength steels in multi-storey buildings and long-span truss structures. The results of this study demonstrate that, for a non-sway building or a well-designed super truss, the typical buckling length is such that the column slenderness remains within a range where there is a clear advantage in developing grades above the practical range. In such applications, the development of higher grades beyond the practical range could therefore result in significant weight, cost and carbon savings.

**Figure 12.** Benefit of high-strength steels for the retractable roof of the NRG stadium at Houston.



## 7. Conclusions

This publication aims to support the development and the use of appropriate steel grades in order to help designers achieving optimised structural solutions, leading to significant reductions in weight, cost and carbon emissions. Indeed, in cases for which the design cannot be achieved using a conventional steel grade, designers then consider switching to a high-strength steel grade. This approach reflects a reactive rather than proactive use of high-strength steels.

To improve the design strategy of designers, i.e. to consider higher steel grades since the first design stages, and to answer to the research questions expressed in Section 1, the developed routines have been used to update the conclusions previously expressed by Johansson [33], [34] for an older practical context, the established limits are gathered in Table 2.

Table 2 confirms the conclusions expressed throughout this paper that there is a benefit in considering high-strength steel grades when slenderness ratios fall below 80. Table 2 also illustrates the significant influence of the cost level on the slenderness limits. It is important to note that these slenderness limits were determined without accounting for strength reductions due to local buckling, and under the assumption of continuous catalogues of profiles. By introducing slenderness ratio limits and reference charts that correlate appropriate steel grades with axial loads and buckling lengths, designers gain valuable insights to select more suitable grades. Nonetheless, the selection of the appropriate steel grade is constrained by the availability of specific grades. These optimizations are only feasible if appropriate steel grades are available for each product. Therefore, the paper pursues a second main objective which is to guide steel producers in developing suitable grades tailored to their products.

Indeed, this study highlights that, if in the future, new steels with higher yield strengths than the practical range will be developed, the existing catalogue of sections should be reviewed to limit the wall slenderness of the profiles available in high-strength steels and increase this profile availability in order to ensure material efficiency. Indeed, current catalogues were originally developed for conventional steels and must inevitably be revised to optimize the use of high-strength steels, enabling designers to achieve optimized designs. The results of this research can assist producers in producing their profiles in appropriate steel grades and the promotion of the most suitable steel grade for a given application. Figure 4b provides manufacturers with slenderness limits from which there is an economic benefit in developing a new grade for a specific profile and buckling length, enabling informed decisions about which grades are relevant to be produced for each configuration. For instance, the study highlights that HD sections, due to their substantial cross-sectional area, are particularly well-suited for high-strength steels. Producing these profiles in mild steel is rarely justified, as their use is typically reserved for highly loaded structural applications. As illustrated by the second case study in Figure 12, manufacturers can statistically evaluate the ordered slenderness ratios to conduct targeted market analyses and tailor their production accordingly.

By aligning product development with material performance and fostering transparent communication between producers and designers, structural engineers will be better equipped to optimize their structural designs and thus realize significant weight, cost and carbon savings on their structural projects. In the context of the "build efficiency" of the hierarchy to net zero [57-59], it becomes crucial to adapt product catalogues to offer the widest range of available profiles in the relevant steel grade, to realise optimised designs (utilisation ratio close to 1) and to maintain a benefit in considering hot-rolled sections.

Beyond these considerations, the research also highlights the necessity of having appropriate design rules to take benefit from the material strength and the importance of adapting the design concept by limiting the slenderness of the constitutive members ("build clever").

Looking ahead, 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 relevant design tools, appropriate industrial profile catalogues, appropriate design standards and effective collaboration between the

designer and the supply chain to ensure the efficiency of the performed designs. Such advancements and collaborations would definitely contribute to more sustainable structural designs.

As a perspective, it would be prudent to incorporate fire design into the existing routines to address this aspect as well as the impact of considering high-strength steels with regard to the dynamic performance of structures. Indeed, this could be particularly relevant for wind- or seismic-induced loads in high-rise buildings, as well as crowd-induced loads in stadiums. Finally, 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.

**Table 2.** Relevant slenderness ratios established based on the developed routines in the present paper.

| Grades      | $\lambda_{lim,L}$ | $\lambda_{lim,M}$ | $\lambda_{lim,H}$ |
|-------------|-------------------|-------------------|-------------------|
| S460        | 100               | 90                | <b>80</b>         |
| $\geq$ S500 | <b>80</b>         | 70                | 65                |
| $\geq$ S600 | 70                | 60                | 55                |

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