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Economic benefit of high strength steel sections for steel structures

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Abstract

The present work aims at studying the field of interest of high strength steel rolled sections (f_y>460 MPa) for steel structures from an economic point of view. Whilst these high strength steel profiles do not exist yet, steelmakers are able to produce more resistant steels through more efficient production processes and a future emerging of these particular steel profiles is likely to occur. The use of this kind of steels can lead to a significant material saving. So, the use of high strength steel leads to lighter structures requiring smaller foundations, lower transportation and construction costs but also emitting less CO_2. However, buckling, fatigue or deflection requirements often reduce the advantage of high strength steels. It is for this reason that the designer is sometimes reluctant to use them. A study establishing the areas of economic benefit of high strength steel tubes in steel and composite structures had already been carried out at the University of Liège [8]. The goal of the present is to extend this study to rolled sections (H-shape and I-shape). It therefore consists in providing methods in order to help the designer determining the economic benefit of high strength steel for structural elements subjected to different loadings. These ones are then used to determinate the areas of economic benefit of the high strength steels in comparison to regular steel, depending on their relative costs.

Keywords

High strength steel, economic study, steel members, tools for practitioners

1 Introduction

During the past years, high strength steels have progressively appeared in the steel market. The ongoing development of new production technologies is constantly increasing the steel yield strength.

These steels present various advantages. In fact, the use of this kind of steels reduces the amount of required material. As a result, the foundations are smaller thanks to the fact that structures are lighter. The costs of transport and construction also decrease for the same reasons.

Unfortunately, some potential drawbacks exist. Indeed, phenomena such as buckling, fatigue or deflection requirements often reduce the advantage of high strength steels.

The present work aims at identifying the field of interest for the use of high strength steel H-shape and I-shape sections (f_y>460 MPa) for steel structures from an economic point of view and at providing tools for practitioners for the selection of the appropriate steel strength for different structural element typologies.

High strength steels (HSS) refer to steels with yield strengths between S500 and S690. These particular grades are today available for steel plates while, for steel rolled sections only S460 can be found on the European steel market. The idea of this paper is to determine whether or not zones of economic benefit exist in using them. In order to reach this objective, numerical comparisons between high strength steels and the regular steel grade (RS) S355 will be performed using current [1] and new [2] versions of the Eurocode 3 part 1-1 and adopting the methodology presented in Section 2.

In Section 3, different structural elements subjected to various loading conditions which are regularly met in steel constructions will be studied to compare the different steel grades. Then, practical guidelines for the selection of a steel grade will be proposed in Section 4. Finally, an economic study will be performed in Section 5 in order to determine the ranges of steel grades costs where there is an economic benefit in using HSS steel grades.

2 Methodology

In this section, the work methodology adopted to reach the research objectives previously presented is detailed.

2.1 Work structure

This article focuses on independent structural members. The aim is to determine the fields in which high strength steel grades ($f_y \in$ [500;

690] MPa) present an economic benefit compared to regular steel grade S355. For each structural members, different selected loadings and support conditions will be considered. The different case studies are shown in Figure 1.

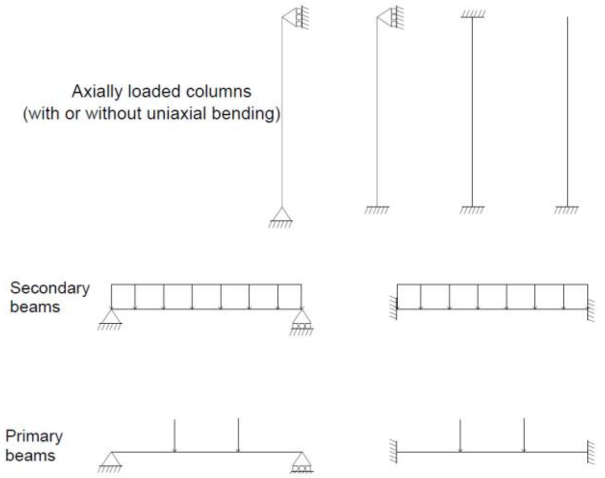


Figure 1: Different case studies considered in this work.

It is worth pointing out that only European hot rolled steel profiles are considered in the scope of this study. In order to compare different steel grades, analytical and numerical studies are performed using the well-known MATLAB software [3]. The general structure of the developed MATLAB codes is presented in Figure 2 below.

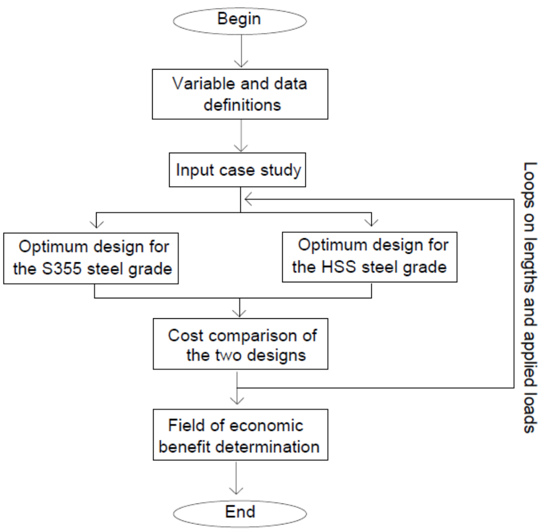


Figure 2: MATLAB code structure.

The objective of the MATLAB codes is to define the cheapest structure elements respecting current Eurocode 3 part 1-1 [1] and new version of part 1-1 [2] . Indeed, the new version of Eurocode 3 part 1-1 extends the design rules for steel grades up to S700.

2.2 Load and length range definition

The determination of the ranges of load and length for the different case studies has to be done before starting the numerical investigation on the potential benefit of HSS.

This step is based on the "SECHALO" project of ArcelorMittal [4] which was focusing on classical building configurations for which common column lengths, beam spans and loads have been determined. These ones are reported here below.

- Common length ranges
  - Column lengths: L ϵ [1 ; 8] m
  - Secondary beam lengths: Lϵ [2 ; 12] m
  - Primary beam lengths: Lϵ [2 ; 18] m
- Common load ranges
  - Uniform load applied on secondary beams: q_{Ed} ϵ [1 ; 100] kN/m
  - Point load applied on primary beams: P_{Ed} ϵ [50 ; 300] kN
  - Compressive load applied on columns: N_{Ed}ϵ [300 ; 3000] kN

As regards the tensile loads not considered in the "SECHALO" project, the same range of loads as the one for compressive loads is adopted.

These loads are factored and can be directly used for the verification of the ultimate limit states (ULS). Besides that, un-factored characteristic loads have to be defined for serviceability limit states (SLS). In this study, the characteristic loads are assumed to be equal to the factored loads divided by a mean safety coefficient taken as equal to 1.4.

It is important to note that, during the work, an important observation has been done: the larger the profile, the less the economic benefit in using HSS steel sections. But for sure, columns made of HD or HEM steel profiles, for instance, are mainly produced to support heavier loads than the HEA or HEB ones, and consequently they have no economic benefit in the load ranges N_{Ed} of usual standard buildings which are under consideration herein. On the contrary, these profiles present large fields of economic benefit for higher N_{Ed} loads. So, it is advisable to put in perspective the results of the present study accordingly.

2.3 Steel grade definitions

Steel grades considered in the study may be classified in three categories.

- **RS**: Regular Steel: steel grades between S235 and S460. S355 steel is nowadays the more commonly employed option and this one is used as reference in the comparisons.
- **HSS**: High Strength Steel: steel grades between S500 and S690. The economic benefit of all these steel grades will be discussed in the parametric study, for each structural member type.
- **UHSS**: Ultra High Strength Steel: higher steel grades than S690. This category is not considered here.

2.4 Criterion of economic benefit

For each case study, the HSS interest assessment is based on the optimum designs for two steel grades: the S355 one and the studied HSS one. This is in line with the decision, expressed earlier, to consider S355 as the reference grade. An optimum design is defined as a design which provides the lighter profile as possible, in a specific series of profiles (HEA, HEB, …). So the best material use is achieved. Then, a cost comparison between the two optimised profiles is performed. When the applied load is so that the two optimised profiles are the same for the two compared steel grades, there is no economic benefit to use the HSS steel grade instead of the RS one (here S355) because the latter is cheaper. Consequently, to present an interest, the material saving which results from the use of HSS should compensate the increase of material cost. In other words, the weight ratio between the two optimum profiles has to be bigger than the

HSS relative cost. The fundamental relation that leads the HSS economic benefit is obtained below.

$$\frac{c_{HSS}}{c_{RS}} < 1$$

where C is the cost of the considered profile.

If the length of the member is fixed, the following relationship may be expressed:

$$\frac{G_{RS}}{G_{HSS}} = \frac{A_{RS}}{A_{HSS}} > \frac{c_{HSS}}{c_{RS}} \quad (1)$$

where G is the optimum profile weight [kg/m], A is the optimum profile area [mm^2] and $\frac{c_{HSS}}{c_{RS}}$ is the HSS relative cost [-].

Section 3 entitled "Member study" focuses on the definition of interest areas for different loading types, in the specific field considered for load intensities and member dimensions (see Section 2.2).

The HSS relative costs will be, at the beginning at least, considered as equal to values proposed by B. Johansson [5]. It is important to mention that these cost ratio values refer to steel plates. However, due to the lack of data concerning the relative costs for steel profiles which are not yet produced in HSS, they will be adopted as reference values. These values are reported in Figure 3.

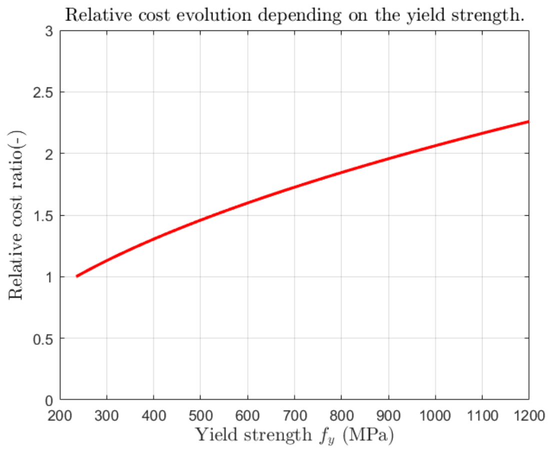


Figure 3: Relative costs of HSS steel grades in comparison with S235.

However, this graph considers S235 as a reference and not S355 as in the present study. An adaptation of these relative costs is therefore required:

$$\frac{c_{HSS}}{c_{RS}} = \sqrt{\frac{f_{y_{HSS}}}{235}} \cdot \frac{1}{\sqrt{\frac{355}{235}}} = \sqrt{\frac{f_{y_{HSS}}}{355}}$$

Finally, the cost ratios (relative costs) for HSS steel grades, which will be the reference costs through this work, are reported in Table 1.

Table 1: The numerical values of HSS relative cost ratios.

Cost ratios	Numerical values
$\frac{c_{S500}}{c_{S355}}$	1.187
$\frac{c_{S550}}{c_{S355}}$	1.245
$\frac{c_{S620}}{c_{S355}}$	1.321
$\frac{c_{S690}}{c_{S355}}$	1.394

It should be noted that Section 3 does not give the percentage of economic benefit but indicates the range of lengths and loads for which an economic benefit in using HSS grades exists. In addition, the variation of the values of the HSS relative cost provided in Table 1 will be studied in Section 5 in order to illustrate the effect of such a variation on the results showed in Section 3.

3 Member study

This section constitutes the main part of the paper. It consists in identifying the fields of economic benefit of HSS for different types of members namely tension members and compression members. The Master's thesis of the author [6] extends this work by considering members in bending and members subjected to combined compression and bending.

3.1 Tension members

The first structural member studied is the member in tension. It is the simplest and the most efficient structural element. Its response is not at all guided by instabilities or SLS (serviceability limit states) conditions that are susceptible to reduce the economic benefit in using HSS. The resistance of a tension element only depends on its cross-section resistance. And this one is proportional to the yield strength of the steel, so large fields of HSS economic benefit are expected.

Let consider the HEA profile series and the S500 HSS steel grade. The optimum designs provide the lightest HEA profiles required for S500 and S355 steel grades respectively. The number of gap profiles between the two optimum designs is represented in Figure 4. These ones correspond to the number of profiles that separates the two optimum profiles. For example, if the optimum profile in S355 steel grade is HEA140 and the optimum profile in S500 steel grade is HEA120, it is considered that there is one gap profile.

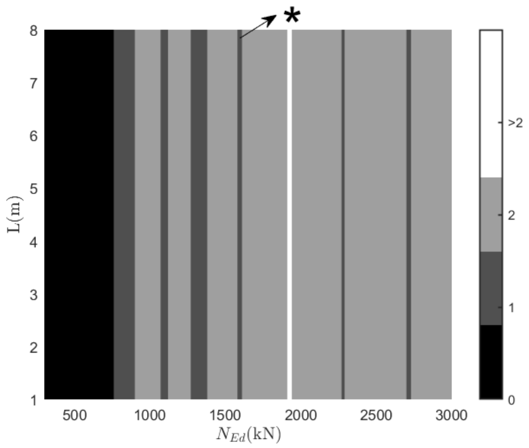


Figure 4: Gap profiles between both optimum designs for tension members.

The material costs for both optimum profiles are evaluated and compared in order to see whether it exists an economic benefit to use the S500 HSS grade. As explained in Section 2.4, there is no economic benefit to use the HSS steel grade when the HEA100 (the smaller cross-section in the HEA series) is sufficient in both steel grades (in this case, there is no gap profile see Figure 4). For the rest of the field, there is an economic benefit if, for some gap profiles, the weight ratio between the two optimum profiles is higher than the cost ratio according to condition (1). However, the weight ratio between two successive profiles in the HEA range is not a constant as it can be seen in Figure 5.

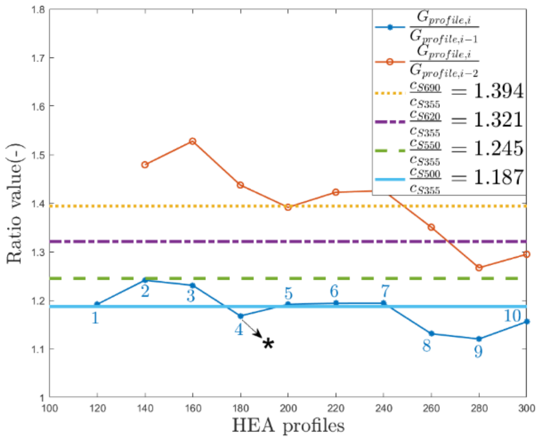


Figure 5: Comparison between the HSS relative cost and the evolution of weight ratios for gap profiles equal to 1 and 2.

Finally, the chart reported in Figure 6 represents the areas of economic benefit in using S500 instead of S355 steel grade.

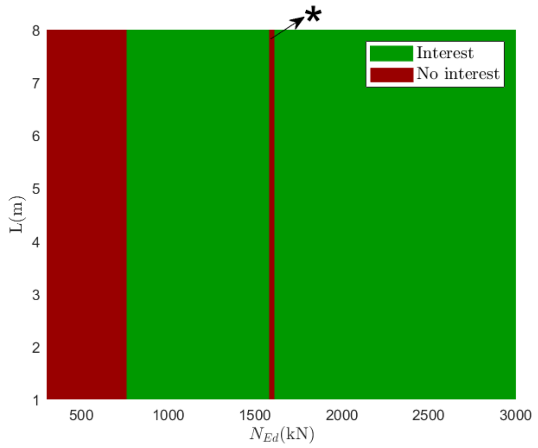


Figure 6: Field of economic benefit of S500 steel HEA profiles ($\frac{c_{S500}}{c_{S355}} = 1.187$).

As expected, the results are not dependent of the length for tension members and there is a large economic benefit area.

As shown in Figure 6, the first area where S500 steel grade has no economic benefit is the area where there are not any gap profiles between the two designs. It means that both optimum profiles are the HEA100. Therefore, a general conclusion is the fact that as long as the optimum design in S355 steel provides the first profile of the range, there is no economic benefit in using HSS steel grades.

However, another area (*) of no interest appears. This particular area presents one gap profile between the two optimum designs as shown in Figure 4. The optimum designs lead to the following profiles: HEA180 (S355) and HEA160 (S500). The weight ratio (*) between these two successive profiles is the first one below the S500 relative cost in Figure 5. Therefore, the condition (1) is not verified and there is no economic benefit in using S500 grade in this range of loads.

Obviously, the results depend on the S500 relative cost value. The variations of this value and their influence on the economic benefit of HSS will be addressed in Chapter 5.

The here-above described study has been extended (parametric study) so as to investigate other series of profiles and HSS steel grades. The following conclusions may be drawn:

- Other HSS steel grades: large fields of economic benefit are similarly identified, what seems logical as, the structural resistance of a tension member is directly proportional to its yield strength as already stated.
- Series of rolled profiles: the larger the profile, the less the economic benefit in using HSS. Table 2 lists the plastic resistances of each first profile in S355 steel for various ranges of profiles.

Table 2: Plastic resistance of the first profiles.

Profile Type	Plastic resistance (kN)
HEA100	752,6
HEB100	923,0
HEC100	1395,15

HEM100	1888,6
HD260x54.1	2449.5

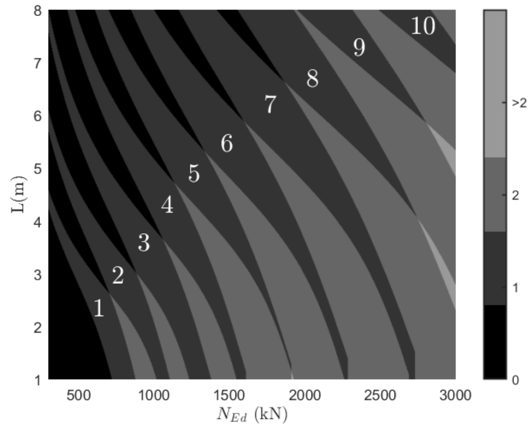
This conclusion must, however, again, be relativized, given that the present study concentrates on loads in classical buildings. Profiles such HEM or HD target higher loads and would obviously present high economic benefit in these higher load ranges.

3.2 Compression members

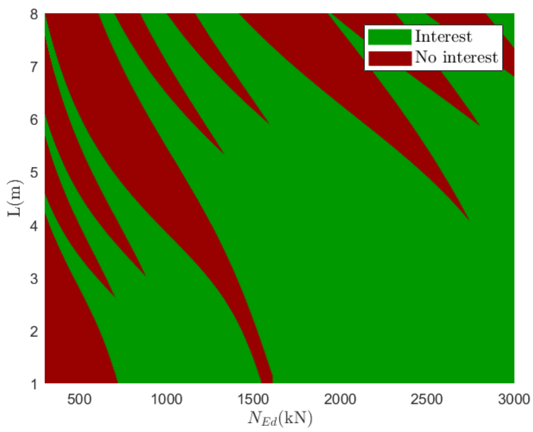
This section addresses elements subjected to pure compression. Two different types of members are considered:

- Short columns, with a reduced slenderness $\bar{\lambda} \leq 0.2$; no instability is met and so the failure corresponds to the yielding of the cross-section.
- Long columns with a reduced slenderness $\bar{\lambda} > 0.2$; buckling governs the failure in this case.

This section focuses only on the second type as the first type gives exactly the same results than those obtained for tension members. Let present so the results for long pinned HEA columns in S355 and S500 steels. It has to be noted that it is assumed that weak axis (z-z) instability is prevented and only column buckling around strong axis (y-y) is here considered. The number of gap profiles between the two optimum designs and areas of economic benefit in using S500 are represented in Figure 7.



(a) Gap profiles between both designs.



(b) Areas of S500 interest.

Figure 7: Number of gap profiles and areas of S500 interest for HEA pinned columns along y-y.

In the same way as for tension members (Figures 4 and 6), the results may be explained according to condition (1). There is no economic benefit in the "no gap profiles" zones (HEA100 sufficient).

Moreover, the areas 4, 8, 9 and 10, which present one gap profile between both optimum designs in Figure 7 (a), are "No interest" areas in Figure 7 (b) as the corresponding weight ratio is lower than the S500 relative cost, as shown in Figure 5.

As it can be seen in Figure 7, the economic benefit of HSS depends on the lengths of the elements by contrast with tension members. This may be explained by referring to Figure 8 based on the European buckling curves and illustrating the evolution of the buckling resistance of a column made of RS and HSS steel grades.

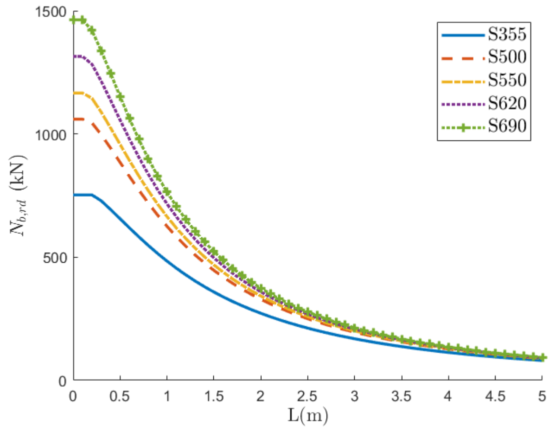


Figure 8: European buckling curves according to current and new versions of Eurocode 3 part 1-1.

In this figure, the buckling resistance tends to become the same, regardless the steel yield strength, with the increase of the member length. So, the economic benefit of HSS decreases with the length of the column. Therefore, the flexural buckling considerably limits the economic benefit of the HSS in comparison with "cross-section resistance guided" members.

Here again a parametric study of compression members has been achieved (different HSS grades and profiles series, but also variation of some significant buckling parameters reported below) and the following observations have been drawn.

- <u>Other HSS steel grades:</u>

The economic benefit in using HSS decreases with the increase of the HSS yield strength. It can be explained by the fact that the buckling instability considerably limits the economic benefit of HSS as explained previously (Figure 8). Moreover, as can be seen in Figure 5, all weight ratios of one gap profile and some of two gap profiles are lower than the cost ratios of S550, S620 and S690 steel grades. Therefore, there is less economic benefit in using high HSS steel grades instead of the S500 one.

- <u>Support conditions:</u>

A pinned column is a disadvantageous support condition for buckling as the buckling coefficient is equal to 1.0 (in braced or some non-sway structural systems), rotations at support nodes being free. However, if the support condition is changed for fixed ends or fixed-pinned ends, the buckling coefficient becomes respectively 0.5 and

0.7, so limiting the risk of buckling. Therefore, the lower the buckling coefficient, the higher the economic benefit in using HSS for compression members.

- Buckling axis:

If buckling around the weak axis is considered, the field of economic benefit reduces due to the fact that buckling phenomena appear earlier.

- Series of profiles:

The same conclusion as for tension members is observed. the larger the profile, the smaller the field of economic benefit in using HSS, again in the field of loads considered here.

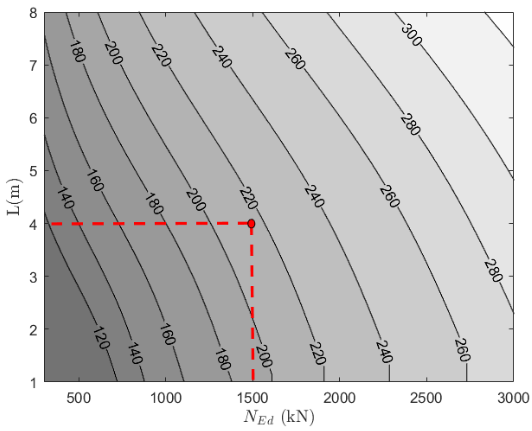
As mentioned in the beginning of this Chapter 3, other types of structural members such as members in bending or subjected to combined compression and bending are detailed in the Master's thesis of the author [6].

4 Practical guidelines for the selection of a steel grade

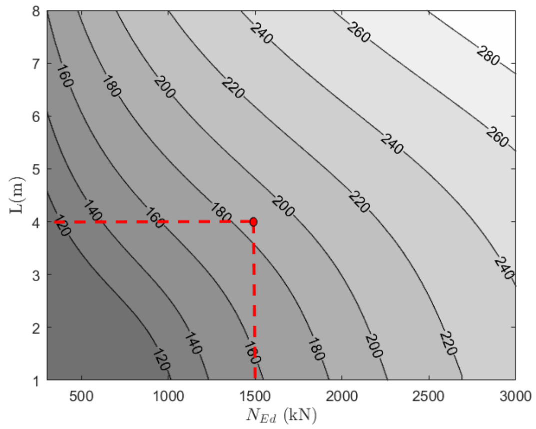
The final objective of the present work is to derive practical guidelines which could help designers in determining whether or not the use of high strength steels has an economic benefit. Two methods are presented below. But, as expressed just above, only structural members in tension and in compression will be addressed in section 4. For further results, reference is again to be made to the Master thesis of the author [6].

4.1 First method: direct determination of optimum profiles

It consists in determining graphically or numerically the two optimum profiles required respectively for the reference steel grade (S355) and the considered HSS steel grade. As soon as these two optimum profiles are known, the weight ratio may be determined and, as long as the relative cost for the HSS grade is available, one can easily see whether or not there is an economic benefit in using HSS steel. A MATLAB routine has been developed that can be directly used by the designer; but as an alternative, graphs derived through the application of the MATLAB routine may be used. An example of such a graph is presented in Figure 9 for pinned HEA elements subjected to compression with possible buckling about strong axis. For instance, for a column with a length of 4m and a load to be supported equal to 1500 kN, a HEA200 S355 profile can be contemplated while a HEA180 S500 profile can be selected if the use of HSS is considered. If the criteria of condition (1) is respected for these two profiles, then there is an economical benefit in using HSS.



(a) RS grade: S355.



(b) HSS grade: S500.

Figure 9: Graphs for the selection of optimum HEA profiles for elements in compression, with possible buckling about strong axis

Alternatively, as above said, the designer may simply introduce the properties of the member (i.e. its length, the load to be supported and the considered steel grades) into the MATLAB routine that will numerically define whether or not an economic benefit exists.

4.2 Second method: direct determination of the weight ratio

By contrast with the first method, the second one directly provides the weight ratios of both required profiles to designers in order to help them to know the most suitable steel grade. Some charts like the one represented in Figure 10 below can be provided. This type of graphs could be used by the designer in the design step when he exactly knows the member length and the applied load. For instance, Figure 10 represents the weight ratio between the optimum HEA profile made in S355 and the optimum HEA profile made in S500 (for pinned columns). Due to the fact that the designers know the current relative cost of the S500 steel grade and with the help of condition (1), they can easily evaluate the economic benefit in using S500 instead of S355 in their configuration. At this stage, however, the size of the required profiles is still unknown. So the designer, who knows the most suitable steel grade, has to define the optimum profile through an additional calculation, what can be seen as the negative aspect of this second method.

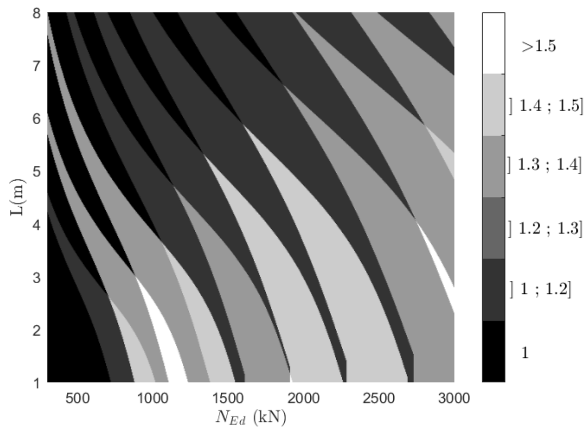


Figure 10: Weight ratios for compression pinned columns.

It is important to underline that the weight ratios are grouped into six categories in order to improve the chart readability.

Moreover, Figure 10 only represents the weight ratios for the HEA category and pinned elements subjected to buckling around y-y axis.

More similar charts are displayed using colours in the appendices of the Master's thesis of the author [6]. Finally, this type of figures is very useful to study the effect of the relative cost value on the economic benefit. Therefore, they are abundantly used in the following chapter concerning the economic study.

5 Economic study

The last section of this paper has the objective to study the impact of a variation of the HSS relative cost on the economic benefit of HSS.

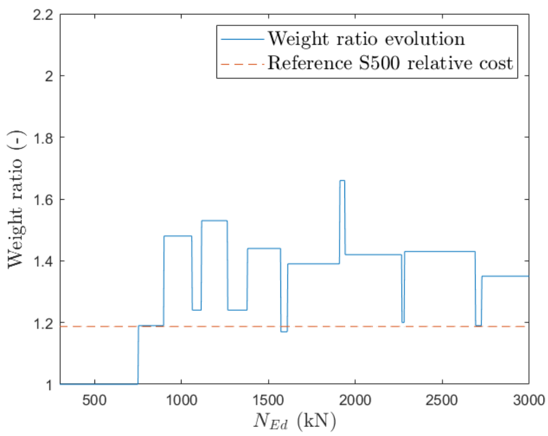
The values of the relative cost provided in Table 1 just include the costs of material (for the reference steel and for a HSS steel), and not at all the costs related to manufacturing and transportation. In fact, HSS steels can lead to a significant material saving and thus should reduce the transportation costs. Moreover, HSS steels can lead to extra costs for welding and thus increase the manufacturing costs in comparison to S355. These economical parameters are not easy to obtain and may vary according to the involved workshop. It is therefore very difficult to “guess” reasonable and reliable production and transportation costs and so to update Table 1 accordingly. The main author should investigate further these aspects in his PhD thesis.

As above explained, the member resistance increases proportionately with the yield strength as long as no instabilities or SLS conditions are governing the design. In order to by-pass this difficulty, solutions can be found to limit these detrimental effects and so to increase the economic benefit in using HSS; for instance, by reducing the member buckling length (to avoid instabilities) or considering a member pre-cambering (to mitigate SLS requirements). The effect of pre-cambering refers to members in bending and so it is detailed in the scope of the Master’s thesis of the main author [6].

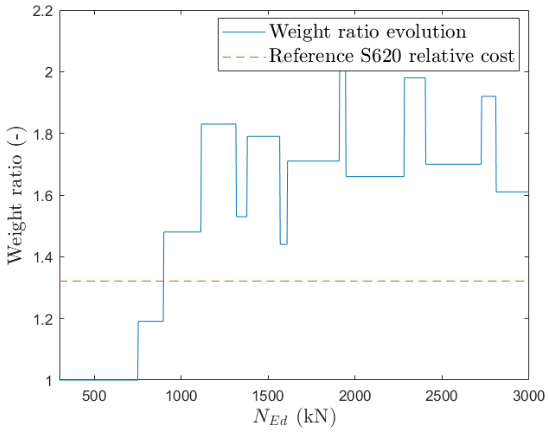
All charts provided by the second method established in Section 4.2 are useful in this chapter to compare instantaneously the weight ratios and the relative cost in order to evaluate the economic benefit in using HSS according to condition (1).

5.1 Application to tension members

The resistance of tension members does not depend on their length as these are not subjected to buckling. The weight ratio evolution, which depends of the axial load, is represented in Figure 11.



(a) S500 HSS grade



(c) S620 HSS grade

Figure 11: Weight ratio evolution depending on the applied axial load for HEA sections.

As seen in Figure 11, the higher the yield strength, the higher the economic benefit of the considered grade, according to the fundamental condition (1). The relative percentage of economic benefit, when passing from a HSS grade to another, is illustrated in Figure 12.

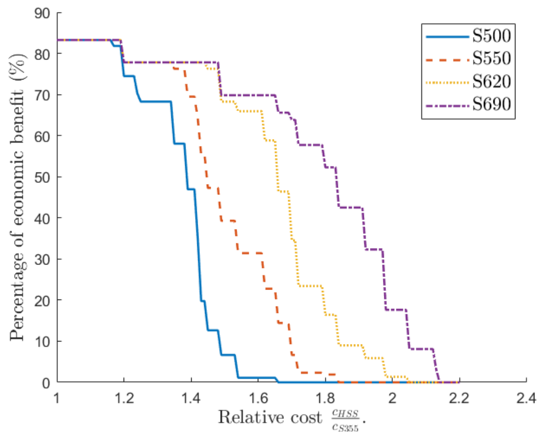


Figure 12: Relative percentage of economic benefit for different HSS yield strength for tension HEA members.

This type of chart could be very useful for a manufacturer who has to decide about the optimise relative cost to propose to its clients.

5.2 Application to compression members

By contrast with tension members, the bearing capacity of compression members is highly dependent on their length, because of the risk of flexural buckling instability. The most useful chart to represent the evolution of the weight ratio as a function of the length and the applied axial load is a chart similar to the one for HEA pinned columns shown in Figure 10.

The percentage of economic benefit, for pinned HEA column (buckling around the strong axis), can be established in the same way than for tension members (Figure 13).

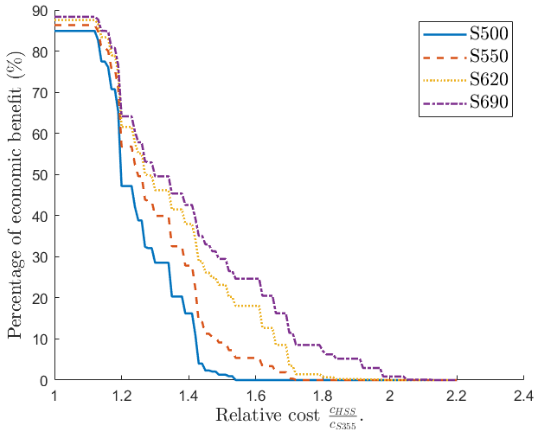


Figure 13: Percentage of economic benefit depending on the HSS yield strength for compression HEA members.

All the lines reported in Figure 13 are closer than those which applies to tension members (see Figure 12). This means that the interest to pass from a HSS grade to a higher one presents very few economic benefit. This is mainly due to the fact that, for high column slenderness, yielding is not governing the bearing capacity, as already explained before.

6 Conclusions and perspectives

The present paper addresses the economic benefit of the use of HSS rolled profiles in steel members submitted to different loadings. A cost comparison between two optimum designs (one with a regular steel grade S355 and another one with a high strength steel grade) is established for several structural members. The main conclusions of these comparisons are:

- HSS structural elements subjected to an axial load present large fields of interest in the domain of load intensity considered in the present study, as long as buckling phenomena are not of concern. In the reverse case, the potential benefit in weight resulting from an increased steel grade is partially or sometimes totally compensated by instability effects, the importance of which is associated to the element slenderness.
- Changing from one HSS steel grade to another one tends to decrease the economic benefit of the HSS grade by comparison with the RS grade. Indeed, in many cases, the benefit in terms of resistance or weight does not offset the increase of the HSS relative cost.
- The detrimental influence of instabilities around weak axis is more significant than for buckling about strong axis.
- The Master's thesis of the main author [6] has provided a general conclusion about a structural element subjected to pure bending. This type of members features very few interest areas by comparison with the other types of structural elements. It can be explained by the fact that SLS conditions must be complied for this type of elements. Moreover, despite the fact that considering lateral torsional buckling makes the ULS conditions stricter, it presents a positive effect on the economic benefit in using HSS because the stricter the ULS conditions, the less the zones governed by SLS conditions. Finally, the beam pre-cambering always increases the interest areas even if the pre-cambering procedure is associated to extra costs.
- The higher the load eccentricity, the less the field of HSS benefit.

One of the main goal was to develop some methods in order to help designer determining economic benefit of HSS steel grades. Two methods are developed as described in section 4. The second method requires charts representing the weight ratios in the entire studied field. Only charts for structural elements subjected to compression is represented in this article, charts for other structural elements and other set of parameters can be found in the Master's thesis of the main author [6].

It is worth recalling that the cost investigation is done on a predefined field of length and load. The pre-definition is based on conventional buildings according to the SECHALO project [4]. Except the choice of the most suitable steel grade, different ranges of steel profiles (HEA, HEB, ...) are more suitable for the considered loads than other ones. The idea could be to extend the research and to determine simultaneously the most suitable steel grade and the most suitable range of products.

Finally, the methodology of this work is thought to be applicable for other problems, such as partially or fully encased steel-concrete composite sections. The methodology could also be applied for a global study on trusses or steel portals. This constitutes perspectives to the present study.

7 References

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