University of Liege
Faculty of Applied Sciences - Civil engineering

MASTER THESIS SUBMITTED IN ORDER TO OBTAIN THE MASTER DEGREE IN CIVIL ENGINEERING

Quantification of the impact of fire design on the interest of using "high yield strength" steels

Florence Dechamps

Jury members:
Jean-François Demonceau (ULiège, Promoter)
Jean-Marc Franssen (ULiège, Co-promoter)
Jean-Pierre Jaspart (ULiège)
Loris Saufnay (ULiège)
Louis-Guy Cajot(SECO)

Academic year: 2021-2022

Contents

List of Tables

List of Figures

Acknowledgments

First of all, I would like to sincerely thank my promoter Mr. Jean-François Demonceau, my co-promoter Mr. Jean-Marc Franssen as well as Mr. Jean-Pierre Jaspart for their support, their wise advice but especially their great supervision throughout this work.

I would also like to thank Loris Saufnay, a doctoral student at the University of Liège, for his availability, his reactivity and particularly his great help in the progress of this work.

Then, I would like to thank Mrs. Elke Mergny from the Delta GC Design Office for her contribution and her answers to my questions. I would also like to thank Mr. Louis-Guy Cajot, member of the jury, for taking time to evaluate this work.

Finally, I would like to thank my relatives, especially my parents and my boyfriend, for the support they have given me throughout this work and my university studies. Not forgetting my friend Audrey Brüls for her support and help.

Abstract

This work is a complement to the work on the interest of high yield strength steels in steel structures [24], which was carried out at ambient temperature. The main objective of this work is to study the economic interest of high yield strength steels ($f_y > 460MPa$) compared to the standard grade S355 under fire conditions.

Using high yield strength steels allows the element to have a reduction in cross-section for the same load, which is obviously of great interest. However, when fire conditions are introduced, the mechanical properties of the steel are degraded. The consideration of instabilities will be more unfavourable than at ambient temperature. This is due to the use of a specific buckling curve, an increased slenderness to account for the higher temperature and a stricter classification of the sections. This work therefore provides an indication of the extent to which these unfavourable conditions will influence the interest in using high yield strength steels in fire conditions.

In addition to this study of the economic interest of high yield strength steel grades, a study of the dimensioning design will be carried out and will determine which design, between the design at ambient or elevated temperature, will govern the choice of the optimal profile. Indeed, fire design is indissociable from ambient temperature design, as both are complementary.

This work will be based on the development of appropriate calculation methods incorporating fire resistance at 30 minutes exposure in the process of selecting the optimal profile. These codes will take into account different situations such as whether the element is protected by intumescent paint or not, and whether it is subjected to tension or compression.

Résumé

Ce travail est un complément au travail sur l'intérêt des aciers à haute limite élastique dans le domaine de la construction métallique [24], qui a été réalisé à température ambiante. L'objectif principal de ce travail est d'étudier l'intérêt économique des aciers à haute limite d'élasticité ($f_y > 460MPa$) par rapport à la nuance standard S355 en condition d'incendie.

La prise en compte des aciers à haute limite d'élasticité permet à l'élément d'avoir une réduction de section pour une même charge ce qui est évidemment d'un grand intérêt. Cependant, lorsque des conditions de feu sont introduites, les propriétés mécaniques de l'acier sont dégradées. La prise en compte des instabilités va être plus défavorable qu'à température ambiante. Ceci est du à l'utilisation d'une courbe de flambement spécifique, d'un élancement augmenté pour tenir compte de la température plus élevée et d'une classification des sections plus stricte. Ce travail permet donc de savoir dans quelle mesure ces conditions défavorables influenceront l'intérêt d'utiliser des aciers à haute limite d'élasticité en présence de condition d'incendie.

En complément de cette étude d'intérêt économique des nuances d'acier à haute limite d'élasticité, une étude sur le design dimensionnant sera réalisée et permettra de déterminer quel design, entre le design à température ambiante ou élevée, gouvernera le choix du profil optimal. En effet, la conception au feu est indissociable de la conception à température ambiante, les deux étant complémentaires.

Ce travail sera basé sur le développement de méthodes de calcul appropriées intégrant la résistance au feu à 30 minutes d'exposition dans le processus de sélection du profil optimal. Ces codes tiendront compte de différentes situations telles que le fait que l'élément soit protégé par une peinture intumescente ou non, et qu'il soit soumis à de la traction ou de la compression.

1 Introduction

Nowadays, steel manufacturers are able to produce high performance steels thanks to even more efficient production processes. In recent years, new yield strengths have gradually become established on the market. Twenty years ago, S235 was the standard, whereas today it is S355, and it is likely that in a few years' time, other grades will also be introduced to the market. However, this transition is still relatively slow because the engineer/designer is sometimes reluctant to use them as he has very little information about the technical and/or economic interest of their use in the field of civil engineering in general, and in the field of buildings in particular.

At ambient temperature, these high strength steels have various advantages such as the dimensional reduction of the elements, the aesthetics, the environmental interest (less material used), lower transport and construction costs, smaller foundations as the structures are less heavy,... Unfortunately, there are phenomena that run against the economic interest of using these steels, such as the serviceability limit states as well as the greater susceptibility to element instability due to the dimensional reduction making the element more slender.

It is in this context that two end-of-study works have already been carried out on the economic interest of these steels (Saufnay, 2019 [24] and Franck, 2020 [14]) and that a thesis is also in progress at the ULiège on the subject. This work is intended to be a complement to the work carried out on the interest of high yield strength steels in the context of the ambient temperature design of a structural element [24] which did not take into account the influence of high temperatures on the results.

The introduction of fire conditions in the determination of the economic interest of high strength steels will be detrimental. Indeed, when a member is subjected to fire conditions, its mechanical properties are degraded by the elevated temperatures. In addition, the dimensional reduction caused by the use of these steels leads to a change in the surface area of the element exposed to fire and thus make the element more susceptible to fire. Consequently, the fire design could limit the reduction of material associated with the superior resistance of these steels and thus reduce their interest. It is therefore interesting to study the impact of this deterioration on the field of interest of HSS (high strength steels) by studying the design under fire.

This end-of-study work consists of studying the interest of using these so-called "high yield strength" steels in a fire situation and implementing adequate computation methods that allow the fire resistance to be integrated into the process of selecting optimal sections and grades.The results developed in this work are based on these codes.

In addition to this study of the economic interest of the HSS grades, a study of the dimensioning design will be carried out and will allow to determine which design , between ambient or elevated temperature design, will govern the choice of the optimal profile. Indeed, the fire design is indissociable from the ambient temperature design, as they are complementary.

This work will be structured in the following way:

1. **Methodology**
   This section will explain the assumptions and parameters used in this work as well as the structure

of the implemented codes. The main objective is to help the comprehension of the work.

2. **Economical interest: tension members**
   This section will study the interest of high yield strength steels on tensioned elements. First, the results at ambient temperature will be reviewed and then the results at elevated temperature for an unprotected or protected element will be studied. Finally, to try to obtain the most suitable solution for a given situation, a comparison will be carried out on the basis of different combinations: RS or HSS grade, protected or unprotected (intumescent paint), the optimal range of profiles and grade.

3. **Economical interest: compression members**
   This section will be conducted in the same way as in tension but for a compressed member.

4. **Ambient and elevated temperatures: governing design**
   This section is intended to determine which design between ambient and elevated temperatures will govern the choice of the optimal profile. This will be done for a tensioned as well as a compressed member, protected or not.

5. **Validity assessment of the Eurocodes recommendations**
   The purpose of this section is to verify that the assumptions made by the Eurocode on the reduction factors of the steel mechanical properties are consistent with the existing literature.

6. **Conclusions and perspectives**

7. **Appendixes**

2 Methodology

In this chapter, the methodology of the work, i.e. all the elements necessary to understand the work, will be presented. This will include the study's limitations, the assumptions made and the details of the computation method used to obtain the results.

2.1 General structure

The main objective of this work is to complement the thesis on the interest of high yield strength steels in the cold design of a structural element [24]. This study will introduce fire conditions into the determination of the economic interest of high yield strength steels compared to the regular grade S355 taken as reference in this work. When a member is subjected to fire conditions, its mechanical properties are deteriorated by the elevated temperatures. It is therefore interesting to study the impact of this degradation on the field of interest of HSS.

This study of interest will be a local study of an element considered as independent of its structure. The profiles studied will be laminated and belong to the ArcelorMittal Catalogue. In addition, two types of loading will be studied: tension, the simplest case without instability, and compression, which will induce buckling instability in these results. It is important to note that the fire design will not take into account the serviceability limit states. This work will focus on the 30 minutes fire resistance of the element which can be written as R30. Furthermore, the work will consider the economic interest of using a passive protection on the studied element: intumescent paint.

This work will be structured as follows:

1. **Methodology:**
   This chapter will define all the elements necessary for a proper understanding of this work. Firstly, the scope of the work will be defined by detailing the influencing parameters of the work as well as the length and load intervals studied. Next, the fire design method used will be introduced, highlighting its main differences from ambient design and detailing the procedure to establish the steel's temperature at 30 minutes. Then, the procedure establishing the economic interest and its assumptions will be detailed in the unprotected and protected case. Finishing this chapter on the methodology, a description of the developed routines will be given, explaining the codes in tension and compression, unprotected and protected.

2. **Economical analysis: tension and compression members**
   Following the methodology, the economic analysis of the benefits of the HSS steels will be done for a member in tension or compression and unprotected or protected. These results are based on the analysis of numerical simulations performed with MATLAB. The general structure of the implemented codes is shown in Figure 2.1. As the flowchart shows, the optimal design for the S355 (RS) grade as well as its cost will be determined for all considered couples of length L and fire load $N_{Ed,fire}$. The same approach will be used for the high strength steel grade (HSS). It will thus be possible to compare all the costs obtained to determine the interest of using grades with high yield strength. The analysis of the results obtained will first be carried out for a defined case study and then a parametric study of the results will be performed in order to understand the influence of the various parameters taken into account.

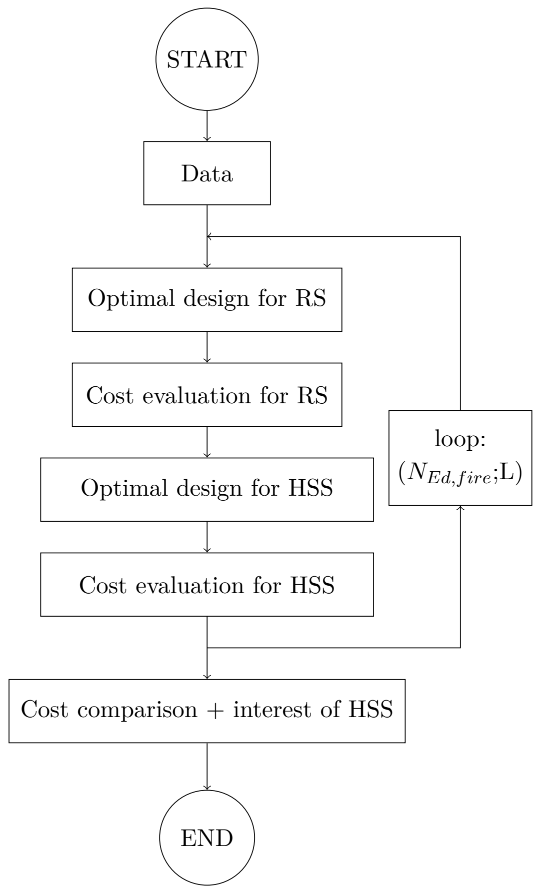


Figure 2.1: Flowchart of the general structure of the codes

In addition to the independent analysis of these four situations, the study of optimal solutions will be carried out. Indeed, the interest of the protection or not and of the RS and HSS grades will be studied simulatenously for the case study. In addition, the interest of all grades and product ranges will be investigated separately for the unprotected and protected members. These two additional studies will allow to have a first global overview on the solutions to be considered in a fire situation such as the choice of the protected element, of the product range,...

3. **Ambient and elevated temperatures: tension and compression members**
In this section, the ambient and elevated temperature designs will be compared to determine which design will govern the selection of the optimum profile for the grades under consideration. This will help to determine which condition will be the most unfavourable when selecting the profile. This section will consider the tension and compression for an unprotected or protected element.

   In order to do this, the optimal hot and cold design is computed for the grades under consideration (RS and HSS). Then the design that governs the profile selection will be the design that requires the largest profile in the range under consideration.

4. **Validity assessment of Eurocodes recommendations**
These numerical simulations will take into account the design rules defined in the former [13] and the new version [21] of the Eurocode 3 part 1-2. The use of these rules for high yield strength steels

up to S700 is justified by Eurocode 3 part 1-12 [12] which provides additional rules for the extension of the former Eurocode 3 part 1-2 up to steel grades S700. This document states that The standard is applicable to steels with grades greater than S460 up to S700 without further additional rules. However, the validity of this statement will be investigated at the end of the report.

2.2 Field of study

This section will define the field of application of this work; some hypotheses and choices had to be made in order to carry out this work.

2.2.1 Influencing parameters

The selected parameters influencing the design under fire conditions will be listed to define the research domain used in this work. Their influence on the design will be discussed briefly but will be explained in more detail in the rest of the work.

- **Grades:**
  In order to determine the interest of high yield strength steels, it is necessary to establish the reference grade, which is considered as the actual standard grade: S355. This grade will be called "RS" for regular steel. In addition, high strength steels refer to steels with a yield strength greater than 460 MPa up to 700 MPa and will be called "HSS". It is therefore logical to study the following grades: S500, S550, S620 and S690. However, two additional grades will be studied even if they do not correspond to high yield strength steels. Indeed, grade S420 and grade S460 are a regular steel (RS) but will still be included in the high yield strength steels to include existing steel grades higher than S355. This choice is made in order to have the S355 grade as a reference (considered "RS") and higher grades (considered "HSS") for comparative purposes.

- **Product ranges:**
  This work will use standard dimensions profiles from ArcelorMittal Catalogue [1] and all H-type ranges will be studied: HEAA, HEA, HEB, HEC, HEM and HD. The choice to focus on this type of profiles comes from the type of loading considered: tension and compression. The elements most likely to be subjected to an axial compression load are columns, which generally use type H sections. For the sake of simplicity of comparison, the same type of sections will be used for tension members. It is important to note that tension members usually have a different function such as a brace or a diagonal of a truss and that other profiles could have been considered such as angle bars.

  These profiles taken from the ArcelorMittal Catalogue [1] will be classified according to their mass per unit length. This classification method was taken from the thesis on cold design [24], which proved a direct relationship between the price and the mass per unit length of the profiles. This classification has therefore been adopted in this work.

  For protected element, solely the HEA and HEB ranges will be covered, and this will be justified in the section 2.4.2.

- **Reduction factor for the design load level for the fire situation: $\eta_{\mathbf{fire}}$**
  According to the former version of the Eurocode 3 part 1-2 [13], the reduction factor for the design

load level for the fire situation will be used to determine the design effect of actions for the fire situation $N_{Ed,fi}$:

$$N_{Ed,fi} = \eta_{fire} N_{Ed} \tag{2.1}$$

Based on this relation, the fire load $N_{Ed,fi}$ can be expressed based the design value of the corresponding force for normal temperature design N_{Ed}.

This value will be useful at a given stage of the study. However, at first, the results will be developed by considering directly the values of $N_{Ed,fi}$ as a reference and thus avoid reproducing the results for each value of η_{fire} considered. When required, the recommended value from the Eurocode of $\eta_{fire} = 0.65$ [13] will be used as a reference and the interval of studied values is between 0.1 and 0.75 (maximum value).

- **Exposed faces:**
  This work will focus on two different fire exposure situations: 3-sided and 4-sided fire exposure. The 4-sided fire exposure will be consider as the reference because a column is rarely exposed to fire solely on 3 faces. With a 4-sided fire exposure, the fire resistance of an unprotected element will be lower than with a 3-sided fire exposure.

- **Support conditions:**
  The support conditions are only relevant for compression where buckling length is used. The following conditions will be studied:

  - Fixed and anchored ends: with a buckling length coefficient of 0.5
  - Pinned and fixed ends: with a buckling length coefficient of 0.7
  - Pinned ends: with a buckling length coefficient of 1
  - Fixed and free ends: with a buckling length coefficient of 2

- **Buckling axis:**
  When investigating the elements in compression, both the strong and weak axis will be considered. However, the case study will consider the strong axis as a reference.

2.2.2 Length Interval

The length interval that will be studied is 1m to 8m as in the ambient temperature design study [24]. This choice can be justified by the fact that the standard height of a floor is between 2.5m and 4m if there is a suspended ceiling. The upper limit is 8m to consider columns located in large structures such as storage halls. When analysing the compression results, a height of 3.5m will be used to further analyse the economic benefits of HSS. This height is representative of a typical floor height of a multi-storey building with a suspended ceiling.

2.2.3 Load interval

The results will be obtained for fire load intervals $N_{Ed,fire}$ and not for ambient temperature loads N_{Ed}. Indeed, if the load interval was given at ambient temperature, it would be necessary to use the reduction factor for the design load level for the fire situation η_{fire} as shown in Equation 2.1. This reduction factor can vary depending on the considered situation, which would add complexity to the results analysis. By using $N_{Ed,fire}$, it will only take to divide by any chosen η_{fire} to obtain the corresponding ambient temperature load N_{Ed}.

The load interval $N_{Ed,fire}$ studied in this work will not be fixed and will vary according to the profile range considered. Indeed, the different ranges have very different loading domains. Taking the example of HD profiles, these will have a much higher strength than the other ranges studied as the profiles are more massive. Therefore, it would not be appropriate to choose a single interval for profile ranges with very different resistance ranges. The load interval will thus be defined for the maximum fire resistance of the complete range considered as well as the grade considered.

In tension, the length does not influence the fire resistance of a member, so the maximum fire resistance is equivalent for the whole considered length interval. In compression, the length will have a negative impact on the fire resistance of the element. The upper limit of the load interval will be taken as the maximum fire resistance for the minimum considered length (1m). The lower limit will be zero for tension. For compression, the lower bound will be 1kN in order to ensure the code works properly.

More information on these maximum resistances is given by the resistance tables defined in the Appendix A. These minimum and maximum fire resistance tables for each profile range and grade considered will be developed for all the considered situations: for a protected or unprotected element subjected to tension or compression with 3 or 4 faces exposed. These tables have two distinct functions:

- **Definition of the upper bound of the load interval:**
  In order to define the load interval, the product range and grade must be selected. Taking the example of an unprotected element subjected to tension in the HEA range with a grade of S355, the maximum bound will be 2385 kN as shown in Table A.2. For the case of a member subjected to tension, the strength tables can be generalised for the whole length range considered, which is obviously not the case with compression. Thus, to choose the load interval for compression, the maximum values of the resistance will be considered for the smallest length of the interval, 1m. In the case of compression, the resistance tables for a length of 1m were not realised since they would not have contributed to the understanding of the work.

- **Decision aid for the profile range and grade to be used:**
  These tables can help the user to select a profile range and a grade for a given fire load $N_{Ed,fire}$ or a normal temperature load N_{Ed} with its corresponding η_{fire}. Based on the fire load $N_{Ed,fire} = N_{Ed} \times \eta_{fire}$, e.g. for $N_{Ed,fire}$ of 6000 kN for an unprotected tension member, Table A.2 shows that the HD range can be used as well as the HEM range from grade S500 upwards. For tension, the tables can be applied for all lengths considered, this is not the case with compression. The tables were therefore made for compressed elements with a length of 3.5m. This choice of length was made because this element length corresponds to a column height that can be considered as standard.

The computation of these resistances is based on the explanations in the section 2.3.2.

2.3 Structural fire design

The objective of this section is to explain the computation method used to verify that the element in tension or compression resists the fire load for 30 minutes fire. The major differences resulting from the introduction of fire conditions will be highlighted for tension and compression elements. The procedure to determine the steel temperature at 30 minutes will be also explained. The procedure for fire design computations is taken from the former and future Eurocode 3 part 1-2 [13][21].

2.3.1 Design methods

According to the former and future versions of Eurocode 3 part 1-2 [13] [21], two design methods exist to determine the fire resistance of an element and can be explained as follows:

- **Advanced computation models:**
  It provides a realistic analysis of structures exposed to any fire (nominal or natural fire) and for any materials. It requires to determinate the thermal response but also the mechanical response which take into account the changes of mechanical properties with temperature, geometrical non-linear effects and non-linear material properties. Therefore, this method has a large field of application but is complex and applied in specific projects [15].

- **Simplified computation models:**
  Simple computation models are simplified methods for individual members based on conservative assumptions.

In the context of this study, it is obvious that the advanced method of computation adds too much complexity for a local study of an element in order to determine a field of economic interest. Furthermore, the Eurocodes cover the simplified method and not the advanced method. In order to have simple computations, this work will also assume that the temperature distribution is uniform in the cross-section.

2.3.2 30-minute fire resistance

Based on the the simplified method, the following condition can be used to determine if the considered element resist for 30 minutes:

$$N_{Ed,fi} \leq R_{fi,30min,Rd} \tag{2.2}$$

Where $R_{fi,30min,Rd}$ is the design resistance of the steel member for the fire design situation after 30 minutes which is represented by $N_{fi,30min,Rd}$ for a tension member and $N_{b,fi,30min,Rd}$ for a compression member, $N_{Ed,fi}$ is the design effect of actions for the fire design situation. As a reminder, $N_{Ed,fi}$ may be obtained from a structural analysis for normal temperature design as [13]:

$$N_{Ed,fi} = \eta_{fire} N_{Ed}$$

Where N_{Ed} is the design value of the corresponding force for normal temperature design and η_{fire} is the reduction factor for the design load level for the fire situation.

Reduction factors of the steel mechanical properties

In order to determine the 30-minute fire resistance in tension and compression, the reduction factors for the mechanical properties of the steel must first be defined. The first reduction factor is the reduction factor for the effective yield strength and is expressed as: $k_{y,\theta} = f_{y,\theta}/f_y$. The second is the reduction factor for the slope of the linear elastic range and is written as: $k_{E,\theta} = f_{E,\theta}/f_E$. The values of the reduction factors were taken from the Table 5.3 of the future version of the Eurocode 3 part 1-2 [21] by interpolating linearly the values from the table with the temperature of the steel at 30 minutes. These degradation factors will logically decrease with increasing temperature. The procedure for establishing the temperature of the steel will be explained in Section 2.3.3. The validity of these factors given by the Eurocode will be discussed at the end of the work in Section 6.

Tension member

According to the future version of the Eurocode 3 part 1-2 [21], the design fire resistance $N_{fi,30min,Rd}$ of a tension member is computed by modifying the design resistance of the cross-section for a normal temperature design N_{Rd} taking into account the degradation of the mechanical properties of the steel at high temperatures. This will be done with the use of the yield strength reduction factor $k_{y,\theta}$ that will depend on the steel temperature θ at 30 minutes. This can be written as follows:

$$N_{fi,30min,Rd} = k_{y,\theta} \times N_{Rd} \times [\gamma_{M,0}/\gamma_{M,fi}] \tag{2.3}$$

Where $\gamma_{M,0} = 1$ and $\gamma_{M,fi} = 1$.

Compression member

The procedure to determine the design fire resistance $N_{b,fi,30min,Rd}$ of a compression member at 30 minutes is taken from the future version of the Eurocode 3 part 1-2 [21]. This strength will be impacted by different elements. Firstly, as in the tension case, high temperatures will degrade the steel's mechanical properties by using the yield strength reduction factor $k_{y,\theta}$ that will depend on the steel temperature θ at 30 minutes.

As in the cold design in compression, the resistance will be computed with the gross cross-sectional area A for Classes 1, 2 and 3 and with the effective cross-sectional area A_{eff} in the case of Class 4. However, the computation of this effective cross-sectional area will differ between the cold and hot design as the reduction factor for plate buckling differs (Section 7.3 [21]). The computation procedure for determining the effective cross-section for a class 4 is based on the new version of the Eurocode 3 part 1-5 [22]. In addition to this, the classes of sections are not the same as a reduction factor of 0.85 will be considered in the classification criteria due to the high temperatures(section 7.2 [21]).

Furthermore, the instability due to buckling must be taken into account, and therefore, the buckling length of the element will be consider. Since a local study is performed, the buckling length will be determined as in the cold design. The introduction of the instability is done by using the reduction factor for flexural buckling in the fire design situation χ_{fi}. This strength penalty factor is not equivalent to the one at ambient temperature as it will consider the degradation of the mechanical properties of the steel thanks to $k_{y,\theta}$ but also thanks to $k_{E,\theta}$ the reduction factor for the slope of the linear elastic range by increasing the relative slenderness. Additionally, when designing for fire, a specific buckling curve is to be considered.

Therefore, the design buckling resistance $N_{b,fi,30min,Rd}$ at 30 minutes of a compression member is determined based on the following equations:

- For Class 1,2 or 3 cross-sections

$$N_{b,fi,30min,Rd} = \chi_{fi} \times A \times k_{y,\theta} \times f_y/\gamma_{M,fi} \tag{2.4}$$

- For class 4 cross-sections

$$N_{b,fi,30min,Rd} = \chi_{fi} \times A_{eff} \times k_{y,\theta} \times f_y/\gamma_{M,fi} \tag{2.5}$$

Where $\gamma_{M,0} = 1$ and $\gamma_{M,fi} = 1$.

2.3.3 Steel temperature at 30 min establishment

This section focuses on the establishment of the steel temperature development for an unprotected internal steelwork. The procedure is taken from the future version of the Eurocode 3 part 1-2 [21] and the future version of the Eurocode 1 part 1-2 [19]; the major assumptions are the uniform temperature distribution of the cross-section and the use of the Standard fire curve. To determine the temperature of the steel at 30 minutes $\theta_{a,30min}$, the increase in its temperature $\Delta\theta_{a,t}$ will be computed every second using the methodology of the flowchart shown in Figure 2.2. The steel temperature development will depend on the section factor A_m/V which depend from the number of exposed faces and the considered profile.

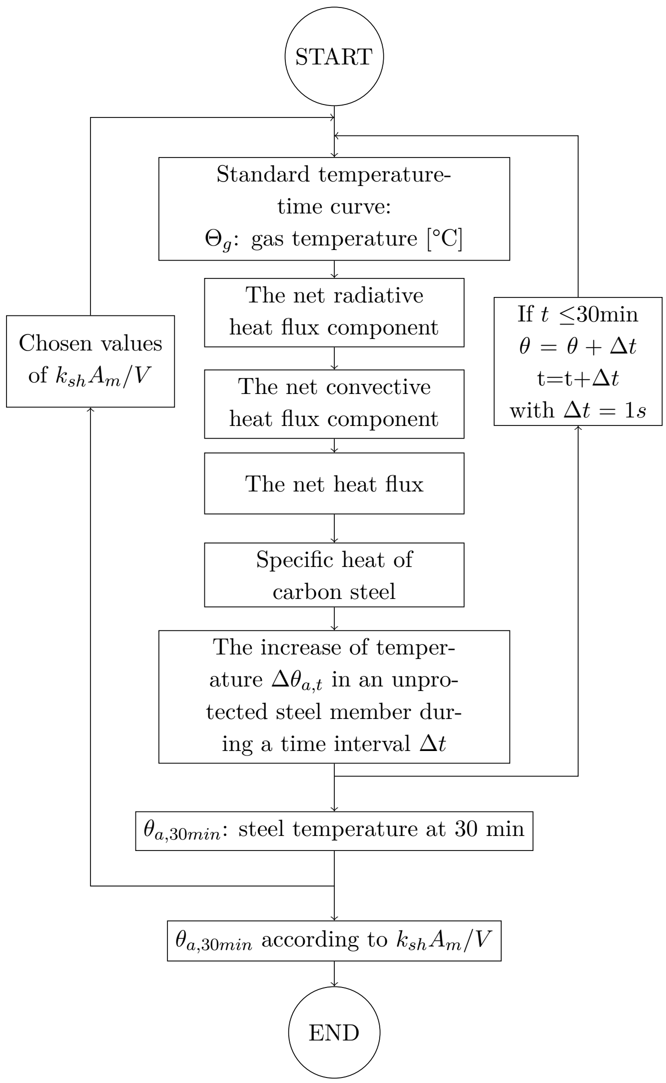


Figure 2.2: Flowchart of the steel temperature development

The computation of the temperature of the steel at 30 minutes for each considered profiles is time consuming due to the high number of iterations required. Indeed, for each considered profile it will be necessary to compute the section factor and then enter the loop and iterate for each second until 30 minutes. Therefore, it was necessary to find a solution that would avoid computing the steel temperature evolution for each profile considered. As shown in this flowchart, the 30-minute temperature $\theta_{a,30min}$ will be determined by the steel temperature development procedure for selected values of section factor A_m/V.

However since the temperature increase $\Delta\theta_{a,t}$ is a function of $k_{sh}A_m/V$ where k_{sh} is the correction factor taking into account the shadow effect, the input values will be values of $k_{sh}A_m/V$. In the case of the studied sections, the shadow effect correction factor takes the following form:

$$k_{sh} = 0.9\frac{[A_m/V]_b}{[A_m/V]} \tag{2.6}$$

Where $[A_m/V]_b$ is the box value of the section factor and is the ratio of the exposed surface area of the box that can be defined around the profile by the steel volume. By using $k_{sh}A_m/V$ instead of A_m/V for the chosen values, the following simplification occurs [15]:

$$k_{sh}A_m/V = 0.9\frac{[A_m/V]_b}{\cancel{[A_m/V]}}\cancel{[A_m/V]} = 0.9[A_m/V]_b \tag{2.7}$$

The input values are function of the section factor but the reduction factor for the shadow effect is considered in order to simplify computations. Each value of $k_{sh}A_m/V$ will thus be associated with a value of $\theta_{a,30min}$ as represented in Table 2.1. These pairs of values will be stored in the implemented function *interp_Amv_temp* which will allow to linearly interpolate the temperature $\theta_{a,30min}$ according to the section factor of the considered profile. In addition, the minimum and maximum boundaries of the chosen values of $k_{sh}A_m/V$ were selected to include all product ranges studied.

$k_{sh}A_m/V$ $[m^{-1}]$	5	10	20	30	40	50	60	70	80	90	100	120	140	160	180	200	240
θ_{30min} [°C]	148	257	431	554	636	690	721	734	741	753	767	792	809	819	825	828	832

Table 2.1: θ_{30min} for the chosen values of $k_{sh}A_m/V$

Figure 2.3 has allowed to verify the chosen values as well as the choice of a linear interpolation. As it is shown, the linear interpolation of the selected points allows to approximate the real evolution of the temperature at 30 minutes according to the section factor while using a reduced number of points.

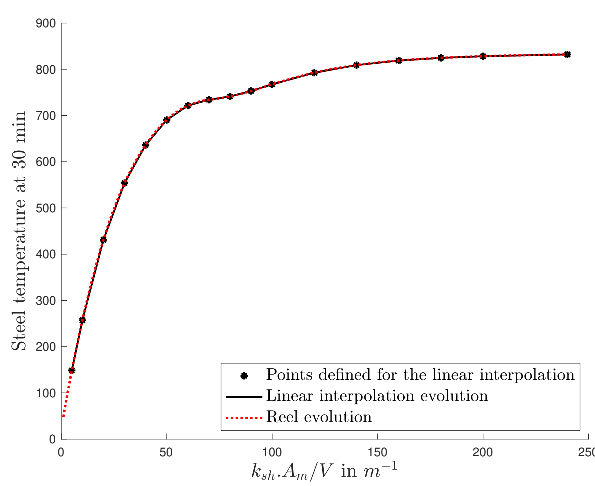


Figure 2.3: θ_{30min} for the chosen values of $k_{sh}A_m/V$

In addition, Figure 2.3 shows the extent to which the section factor is a determining factor in the fire resistance computation. As already mentioned, the temperature of the steel at 30 minutes is proportional to this factor. The higher the section factor, the higher the temperature of the steel at 30 minutes as the graph proves it. This is due to the definition of the section factor itself; as a recall, A_m/V is defined as the ratio of the surface area exposed to fire to the volume of the section $[m^{-1}]$. Indeed, It is logical that if this ratio is higher, the profile is less massive (less material) and therefore heats up faster. This also explains why the number of exposed faces influences the temperature of the steel as the section factor decreases as the number of faces decreases.

2.4 Economic assessment procedure

In order to assess the economic interest of the considered HSS grade, it will be necessary to compare the cost of the optimum profile of the RS grade and the one for the HSS grade. The computation of these costs will vary depending on whether the considered element is protected or not. The economic interest condition for the HSS grade will therefore be :

$$\frac{Cost_{HSS}}{Cost_{RS}} < 1 \tag{2.8}$$

If this condition is not met, the use of the HSS grade will not be relevant.

2.4.1 Unprotected members

In the case of an unprotected element, the procedure for determining the economic interest of the HSS grade compared to the RS grade is similar to the one developed in the study of HSS for steel structures [24]. The cost of the considered grade will therefore be computated as follows:

$$Cost_{grade} = G \times L \times c_{grade} \tag{2.9}$$

Where G is the mass per unit length of the considered profile (kg/m), L is the length of the member (m) and c_{grade} is the price per kilogram of the considered grade (€/kg) which is composed of the relative cost of the HSS grade under consideration $\frac{c_{HSS}}{c_{RS}}$ and the price of steel per kilogram for the RS grade (S355).

The condition of interest 2.8 can be rewritten in the same way as in the ambient temperature study [24]:

$$\frac{G_{RS}}{G_{HSS}} = \frac{A_{RS}}{A_{HSS}} > \frac{c_{HSS}}{c_{RS}} \tag{2.10}$$

Where $\frac{c_{HSS}}{c_{RS}}$ is the relative cost of the HSS grade compared to the RS grade.

To remain consistent with the work done under ambient conditions [24], the same relative costs between grades will be used. These will be computed using Equation 2.11 and are listed in Table 2.2.

$$\frac{c_{HSS}}{c_{RS}} = \sqrt{\frac{f_{y,HSS}}{355}} \tag{2.11}$$

Relative cost	**Value**
$\frac{c_{S420}}{c_{S355}}$	1.0877
$\frac{c_{S460}}{c_{S355}}$	1.1383
$\frac{c_{S500}}{c_{S355}}$	1.187
$\frac{c_{S550}}{c_{S355}}$	1.245
$\frac{c_{S620}}{c_{S355}}$	1.321
$\frac{c_{S690}}{c_{S355}}$	1.394

Table 2.2: Relative costs for the considered HSS grades

As a reminder, these relative costs are related to material costs for hot rolled plates as HSS profiles do not yet exist. Although these relative costs vary with time, we will take the values from the Table 2.2 as references in this study.

S355 steel price

In this work, it was necessary to define the S355 steel price per kilogram in order to be able to carry out the cost evolution curves but also to be able to study the case of protected elements. In the context of this work, the steel cost will take into account the grade. However, the real price of a steel section will take into account a multitude of parameters such as the dimensions, the length of the element, the range studied,... These parameters will lead to cost increases but these will not be included in this work. Furthermore, the price does not take into account the cost of installation and transport. Only the material cost of the steel is therefore studied.

In the current crisis situation, the price of steel has risen significantly as shown by the statistical data provided by the MEPS website [5]. By comparing the values of the last few months of the world steel prices for sections and beams, a price of 1.2 $/kg can be obtained. According to the Boursorama website [2], the exchange rate between the dollar and the euro is 1. The price is therefore 1.2 €/kg.

The price of the steel supplied by MEPS for the sections and beams (H beam) has been defined for specific conditions. Indeed, this price is based on a grade of S235JR and S275JR which does not generate any additional cost. To reach a grade of S355JR, an additional cost of 35 €/ton must be applied to the basic price as mentioned in the ArcelorMittal price-list [8]. This additional cost is relatively low and the price of 1.2 € /kg can be maintained for S355 grade. Furthermore, the profile category is a category 3 and therefore it is an intermediate category containing the HEB 240 profile.

It is important to note that the steel cost fluctuates significantly over time. It will therefore be necessary to carry out a sensitivity study of this cost in order to fully understand its impact. The value used in this work will therefore be 1.2 €/kg to be as consistent as possible with the current economic situation. Taking price values provided by Bouwenmetstaal [3], a price of 0.8 €/kg can be taken for a hot rolled S355 grade outside the actual crisis period. Therefore, the sensitivity study of the cost of steel will take place for a pre-crisis value of 0.8 €/kg and for an even higher value of 1.6 €/kg to see the effect on the results.

2.4.2 Protected members

In the case of an element protected with intumescent coating, the procedure needs to be adapted: the price will be composed of two components. The first component is the cost of the optimal profile required, which is equivalent to the cost of an unprotected element, and the second component is the cost of the intumescent painting.

$$Cost_{\text{grade,protected}} = \underbrace{G \times L \times c_{grade}}_{\text{Cost of the steel profile}} + \underbrace{C_{coating}}_{\text{Coating cost}} \tag{2.12}$$

In order to determine the relative cost of the passive protection, some major assumptions had to be made. Indeed, the determination of this cost is complex due to the limited price information available. In this study, two types of coating costs have been used to get as close as possible to the real cost of this paint. The first cost computation will be based on the data provided by the company Promat [23], while the second cost computation will be based on the data provided by the company Bauforumstahl [7].

Cost computed based on Promat data

In order to be able to estimate the coating cost, it was necessary to determine the thickness required to meet the fire resistance for a type of profile. The coating considered can be applied to metal structures and is called PROMATPAINT-SC4 from Promat. Promat provides design tables giving a Dry Film Thickness (DFT) to be applied on the member for a given strength (R30, R60, R90), a profile type (HEA 100 to HEA 600 and HEB 100 to HEB 600) and a number of exposed faces (3 or 4 faces).

In addition, Promat provides a critical temperature depending on the number of exposed faces: T_{cr} = 500°C for 4 exposed faces and T_{cr} = 570°C for 3 exposed faces. This work will take into account the thickness of intumescent paint to be applied on HEA and HEB product ranges to achieve a 30 minutes fire resistance (R30).

	HEA	HEB
100	188	188
120	191	188
140	188	188
160	188	188
180	188	188
200	188	188
220	188	188
240	188	188
260	188	188
280	188	188
300	188	188
320	188	188
340	188	188
360	188	188
400	188	188
450	188	188
500	188	188
550	188	188
600	188	188
650	188	188
700	188	188
800	188	188
900	188	188
1000	188	188

Table 2.3: DFT [μm]: R30 and 3 faces exposed

	HEA	HEB
100	381	332
120	381	312
140	369	289
160	349	252
180	343	230
200	326	205
220	305	176
240	272	160
260	262	143
280	242	124
300	218	104
320	191	104
340	160	104
360	143	104
400	124	104
450	104	104
500	104	104
550	104	104
600	104	104
650	104	104
700	104	104
800	104	104
900	104	104
1000	104	104

Table 2.4: DFT [μm]: R30 and 4 faces exposed

Promat's design tables are represented by Tables 2.3 and 2.4 and give the Dry Film Thickness for the profiles HEA 100 to HEA 600 and HEB 100 to HEB 600 which do not correspond to the entire product ranges. However, Tables show a plateau area of DFT. In Table 2.3, the thickness is similar for all profiles in the range while in Table 2.4, this plateau appears from HEA 400 and HEB 300 onward. Based on this observation, it is possible to go through the whole range considered by making the assumption that the thickness is similar for these added profiles above HEA 600 and HEB 600 (colored in these tables). This assumption can be considered as conservative. Indeed, as the section factor decreases with increasing profile in the two ranges considered, the real temperature of the steel at 30 minutes will be lower than the temperature values imposed by Promat for the same protection thickness. This assumption will allow us to more easily compare the results of protected and unprotected elements for the HEA and HEB whole product ranges.The origin of this plateau is not given by Promat but might be the result of a minimum thickness of protection to be applied on the element due to technical constraints.

Before being able to establish the price, it is necessary to distinguish the Dry Film Thickness (DFT), which relates to the required dry layer of paint, from the Wet Film Thickness (WFT), which relates to the layer of paint in liquid state to be applied to obtain the dry layer (DFT) required by the design tables. The following ratio is given by Promat to allow the relation between these two thicknesses:

$$\frac{DFT}{WFT} = 0.65 \tag{2.13}$$

Thanks to this ratio, the price can be determined. The price inclusive of all taxes of the paint solution is 507 € for 25 litres of solution and is taken from the building materials website "Gobert Matériaux" [4]. As this price is related to liquid state of the paint and the thickness of the design tables is given for the DFT, it will be necessary to take into account the ratio of Equation 2.13 in the cost computation. The cost of the material according to the required thickness and the surface to protect is the following:

$$Cost_{coating} = \frac{\text{DFT}}{0.65} \times A_L \times L \times c_{\text{WTF}} = \text{WFT} \times A_L \times L \times c_{\text{WTF}} \tag{2.14}$$

Where DFT is the Dry Film Thickness (mm) given by the design tables, WFT is the Wet Film Thickness (mm), A_L is the painted surface per unit length (mm^2/mm), L is the length of the considered member (mm), c_{WFT} is the price per mm^3 of coating in liquid state (€$/mm^3$).

In this study, only the HEA range and the HEB range will be studied due to the limited data provided for other ranges. However, by converting the profile type by the section factor, it is possible to extrapolate the thickness values (DFT) for other section factors and thus study other product ranges.

Cost computed based on Bauforumstahl data

In the document "Kosten im Stahlbau" of Bauforumstahl [7], an order of magnitude for the intumescent paint price for a 30 minutes fire resistance is provided depending on whether the paint is applied on site or in the factory. The price indication for factory application is 15 to 25 €$/m^2$ of surface to be covered, whereas for on-site application the price varies from 18 to 28 €$/m^2$ of surface to be covered. Therefore, the overall price range for intumescent paint considering a 30 minutes fire resistance is 15 to 28 €$/m^2$ of surface to be covered. This indicative price is given with a restrictive hypothesis; it concerns only the complete range of HEB profiles, IPE 300 to IPE 450. This price is thus limited to a specific domain. However, as this work is limited to the HEA and HEB range for the study of protected elements, it is reasonable to extend these indicative prices to the HEA range. On the basis of this price range, it is possible to compute the coating costs for the profile in question:

$$Cost_{coating} = A_L \times L \times c_{\text{coating}} \tag{2.15}$$

Where A_L is the painted surface per unit length (m^2/m), L is the length of the considered member (m), c_{coating} is the price per m^2 of surface to cover with coating and falls within the range of 15 to 28 €$/m^2$.

Coupling of these two coating costs

The costs computed based on Bauforumstahl data are only an order of magnitude. Indeed, it does not take into account the required thickness of the protection according to the considered profile. Moreover, there is a considerable difference between the prices obtained on the basis of Equation 2.14 and those obtained on the basis of Equation 2.15 as shown in Table 2.5. This is due to the fact that the price based on the Promat data only takes into account the material cost. Based on the cost estimates in the Bauforumstahl document, it would appear that the material price is not reflective of the actual cost of the coating, which must have a high application cost. This is why these two computation methods will be coupled and will allow to estimate a credible cost value.

Table 2.5 represents the cost analysis carried out in order to couple the two prices. The Bauforumstahl price has two values as the lower and upper bounds of the cost interval will be considered for each profile, 15 and 28 €$/m^2$ respectively.

Product range	HEA				HEB			
Profiles	**HEA 100**		**HEA 1000**		**HEB 100**		**HEB 1000**	
Promat coating cost [€]	6.67		10		5.87		10	
Bauforumstahl coating cost [€]	8.41	15.7	46.4	86.6	8.5	15.87	46.65	87.08
Cost ratio: Bauforumstahl/Promat	1.26	2.35	4.62	8.62	1.44	2.7	4.62	8.62

Table 2.5: Cost analysis: coating costs and cost ratios

This price analysis aims to determine how the Promat price of Equation 2.14 can be adjusted in order to reflect the values of the Bauforumstahl price. Based on the ratio of the two types of prices, it is possible to obtain an amplification factor. Since the ratio varies between 1.26 and 8.62, this study will conservatively assume that the amplification factor is 10. Given the uncertainty of the real price of the intumescent coating, it is preferable to have a cost that may appear to be overestimated to avoid drawing false conclusions about the economical interest of the intumescent coating. A sensitivity analysis of this amplification factor will be carried out.

The coupled price taking into account the thickness of the protection as well as the application can be determined as follows:

$$Cost_{coating} = \text{WFT} \times A_L \times L \times c_{\text{WTF}} \times \text{Amplification factor} \tag{2.16}$$

The total cost for a protected element can therefore be written as follows:

$$Cost_{\text{grade,protected}} = \underbrace{G \times L \times c_{grade}}_{\text{Cost of the steel profile}} + \underbrace{\text{WFT} \times A_L \times L \times c_{\text{WTF}} \times \text{Amplification factor}}_{\text{Coating cost}} \tag{2.17}$$

2.4.3 Summary of costs and interest conditions

This section summarizes the conditions of interest that will be used in this work as well as the cost computation that will be used. The condition of interest of HSS over RS can be written in a general way as follows:

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

When the element is unprotected, it is possible to use the following condition:

$$\frac{G_{RS}}{G_{HSS}} = \frac{A_{RS}}{A_{HSS}} > \frac{c_{HSS}}{c_{RS}}$$

Then, the cost computation will depend on whether the element is protected or not. In the unprotected case, only the price of the steel will be considered and the cost equation is written as such:

$$Cost_{grade} = G \times L \times c_{grade}$$

When the element is protected, the cost of the paint as well as the steel will be taken into account which gives the following cost equation:

$$Cost_{\text{grade,protected}} = G \times L \times c_{grade} + \text{WFT} \times A_L \times L \times c_{\text{WTF}} \times \text{Amplification factor}$$

2.5 Code structure for unprotected and protected members

The objective of this section is to explain in more detail the structure of the implemented codes used to determine the economic interest of high yield strength steels under fire conditions. As introduced in the general section, the codes will have a common structure represented by the flowchart in Figure 2.1. As a reminder, for each pair of considered load and length ($N_{Ed,fire}, L$), the optimal design and its cost will be computed for each grade (RS or HSS). For the studied load and length intervals, the costs of the optimal RS and HSS design will be stored. Then, the economic interest of the HSS grade over the RS grade will be determined based on the condition of the equation 2.8 which compares the costs of the two designs. If the cost of the HSS grade is lower than the one of the RS grade, then the HSS grade is economically attractive.

The flowcharts presented in this section are therefore intended to detail the structure of the code used to determine the optimal design and the related cost computation. The codes, and therefore the flowcharts, are based on procedure from the Eurocode 3 part 1-1, part 1-2 and part 1-5. Depending on the considered situation, it is simply necessary to select the code, and thus the corresponding flowchart and place it in the general structure of Figure 2.1. The possible cases are: protected or unprotected members subjected to tension and protected or unprotected members subjected to compression.

All of these codes have been verified with a complete design example in tension in the Appendix B - 1 and in compression in the Appendix B - 2.

2.5.1 Under tension

Unprotected member

When the element is not protected, the flowchart in Figure 2.4 must be used. A first loop on all the profiles of the considered range will compute the fire resistance at 30 minutes $N_{fi,Rd,30min}$ of each profile for the considered grade and is based on the Section 2.3.2.

To determine the fire resistance of a profile, the section factor of the element considering the number of exposed faces is used in order to compute the temperature of the steel at 30 minutes θ_{30min} as explained in the section 2.3.3. If the section factor is high, the temperature θ_{30min} will be high. Then, the effective yield strength reduction factor $k_{y,30min}$ which will degrade the element's resistance can be computed according to the steel temperature. The 30 minutes fire resistance of the considered profile will be given by the plastic resistance of the section at ambient temperature N_{Rd} reduced by the reduction factor $k_{y,30min}$ accounting for the degradation of the mechanical properties due to high temperatures.

When the fire resistances $N_{fi,Rd,30min}$ of all the profiles in the range have been determined, the first loop is completed and the second loop is entered, which runs through all the couples of fire load and length ($N_{Ed,fire}, L$) within the studied intervals. In this loop, the optimal profile, and therefore the cheapest profile resisting the imposed fire load $N_{Ed,fire}$, will be determined. The associated cost of this optimal profile will be computed from Equation 2.9 and will therefore depend on the mass of the profile, the grade cost and the element length.

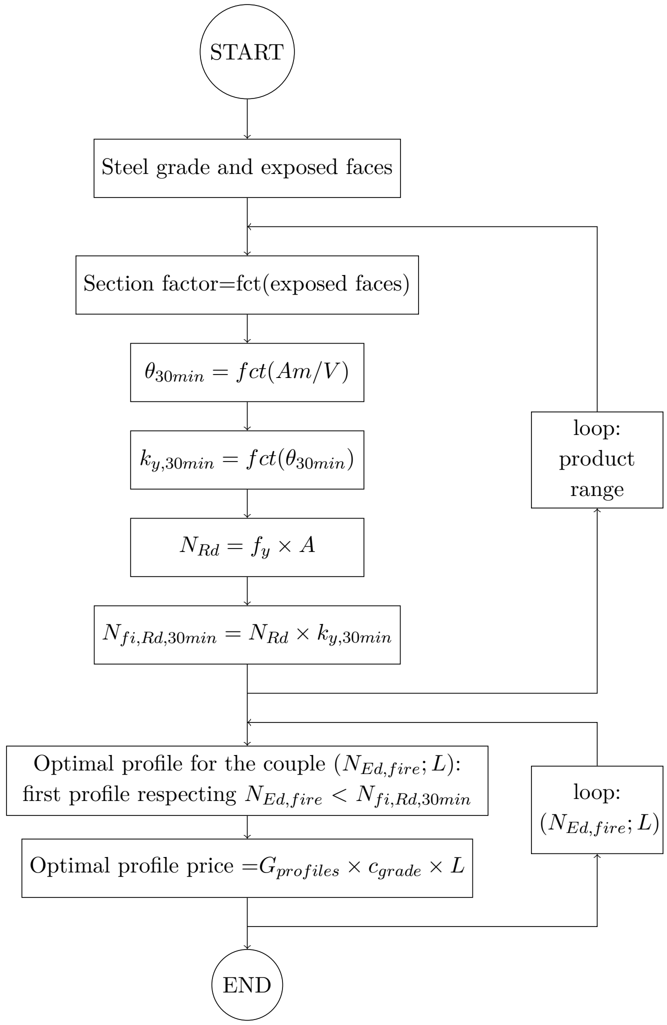


Figure 2.4: Flowchart for the unprotected member in tension

Protected member

For a protected element subject to tension, some adaptations to the flowchart for an unprotected element must be made to take into account the protection. However, the structure of the code remains similar.

In the section 2.4.2, the price has been expressed on the basis of data from Promat design tables which are limited to the HEA and HEB ranges. These tables give the dry film thickness required to resist fire for 30 minutes depending on the profile considered. Therefore, the function *Coating_thickness_promat* will give a vector $thickness_{Promat}$ containing the necessary dry film thicknesses associated to another vector A_p/V_{Promat} containing the section factors associated to these thicknesses. Moreover, the temperature of the steel at 30 minutes is imposed according to the number of exposed faces; the reduction factor k_y will be unique for all the profiles considered, which was not the case for a non-protected element.

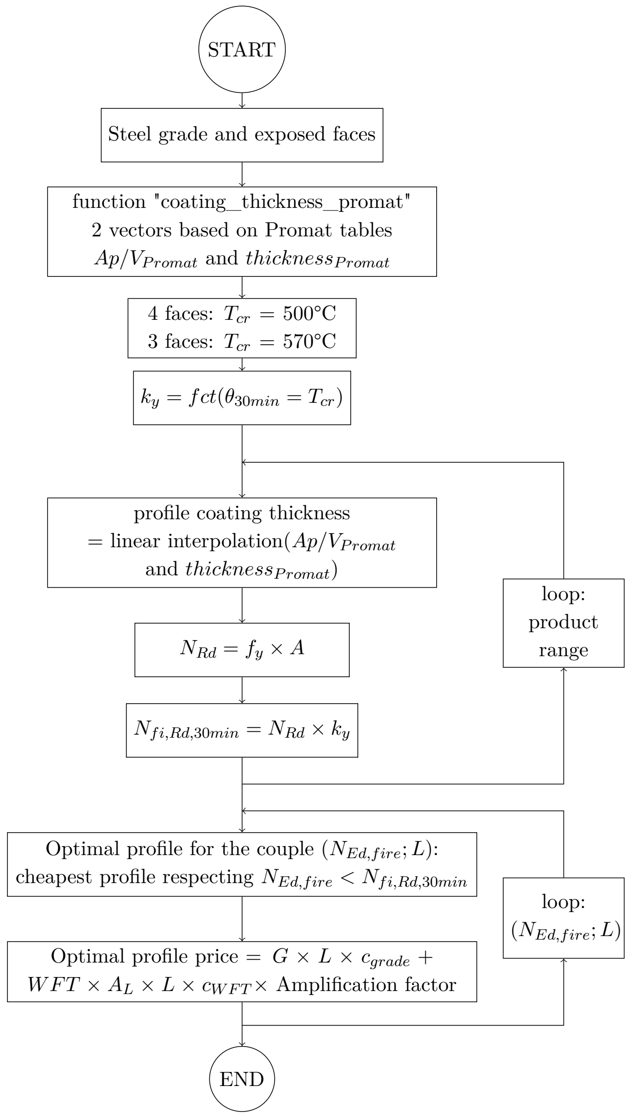


Figure 2.5: Flowchart for the protected member in tension

Then, the first loop on profiles of the considered range must be entered. This loop will compute the necessary Dry Thickness Film for each profile according to its section factor by performing a linear interpolation of the vectors obtained by the function *coating_thickness_promat*. This loop will also compute the fire resistance $N_{fi,Rd,30min}$ of each profile as in the unprotected case.

Once all the profiles have been covered, the second loop starts and will run through all the couples $(N_{Ed,fire}, L)$. As with the unprotected version, the optimal profile is determined and its associated cost can be computed. The optimal profile will correspond to the cheapest profile resisting $N_{Ed,fire}$. In the case of the protected element, the price will be computed using Equation 2.17 and will therefore depend on the price of the element without protection (as with the unprotected element) and the price of the intumescent coating, which depends on the Wet Film Thickness required, the surface area to be coated, the element length, the coating cost and the amplification factor accounting for the coating application cost. As a reminder, the relationship between the wet film thickness and the dry film thickness is given by Equation 2.13.

2.5.2 Under compression

In these two flocharts shown in Figures 2.6 and 2.7, the element is subjected to compression, and therefore to instability. This work takes into account section classes 1, 2, 3 and 4. Unlike tension, the self weight of the profile will be taken into account in the load $N_{Ed,fire}$ to be resisted by the element. This implies that the value of $N_{Ed,fire}$ must be adapted for each profile. This adjustment will be made in the identification of the optimal profile.

Unprotected member

The first step is to classify the cross-sections for each profile in the studied range using a reduced value of ϵ to take into account the high temperatures. If the cross-section is of class 4, an effective cross-section will be used in the further development. Next, the section factor of each profile can be determined according to the number of exposed faces. This section factor will be used to determine the temperature of the steel at 30 minutes for each profile and thus obtain the two corresponding reduction factors of the mechanical properties; $k_{y,30min}$ corresponds to the reduction factor of the effective yield strength while $k_{E,30min}$ corresponds to the reduction factor for the slope of the linear elastic range.

Then, a loop on the fire load and length couples $(N_{Ed,fire}, L)$ starts to determine the optimal profile and its cost for a given couple. If the code has to consider the strong axis and the weak axis, the identification of the optimal profile will be done separately for each axis considered and the highest profile needed will be selected as the optimal profile. The cost could thus be computed with Equation 2.9. The optimum profile for the given axis will be taken as the first profile with a resistance $N_{b,fi,Rd,30min}$ that is greater than the modified fire load $N_{Ed,fire}$ considering the profile's own weight.

To obtain the optimal profile in the considered buckling axis, it is required to evaluate the design buckling resistance at 30 minutes $N_{b,fi,Rd,30min}$ along the considered axis. First, based on the support conditions and other parameters such as the inertia of the considered axis and the non-dimensional slenderness at ambient temperature $\overline{\lambda}$ can be computed. Then, the non-dimensional slenderness for the temperature at 30 minutes $\overline{\lambda}_\theta$ will give a higher slenderness value to consider the degradation at elevated temperature. Then, the imperfection factor α can be computed from a unique buckling curve that is specific to the fire conditions. The design buckling resistance at 30 minutes $N_{b,fi,Rd,30min}$ will be obtained using the reduction coefficient for flexural buckling in the fire design situation, taking into account the instability at elevated temperature as well as the ambient temperature section resistance degraded by the reduction factor of the effective yield strength $k_{y,30min}$ and by β_A considering the effective cross-section for Class 4 sections.

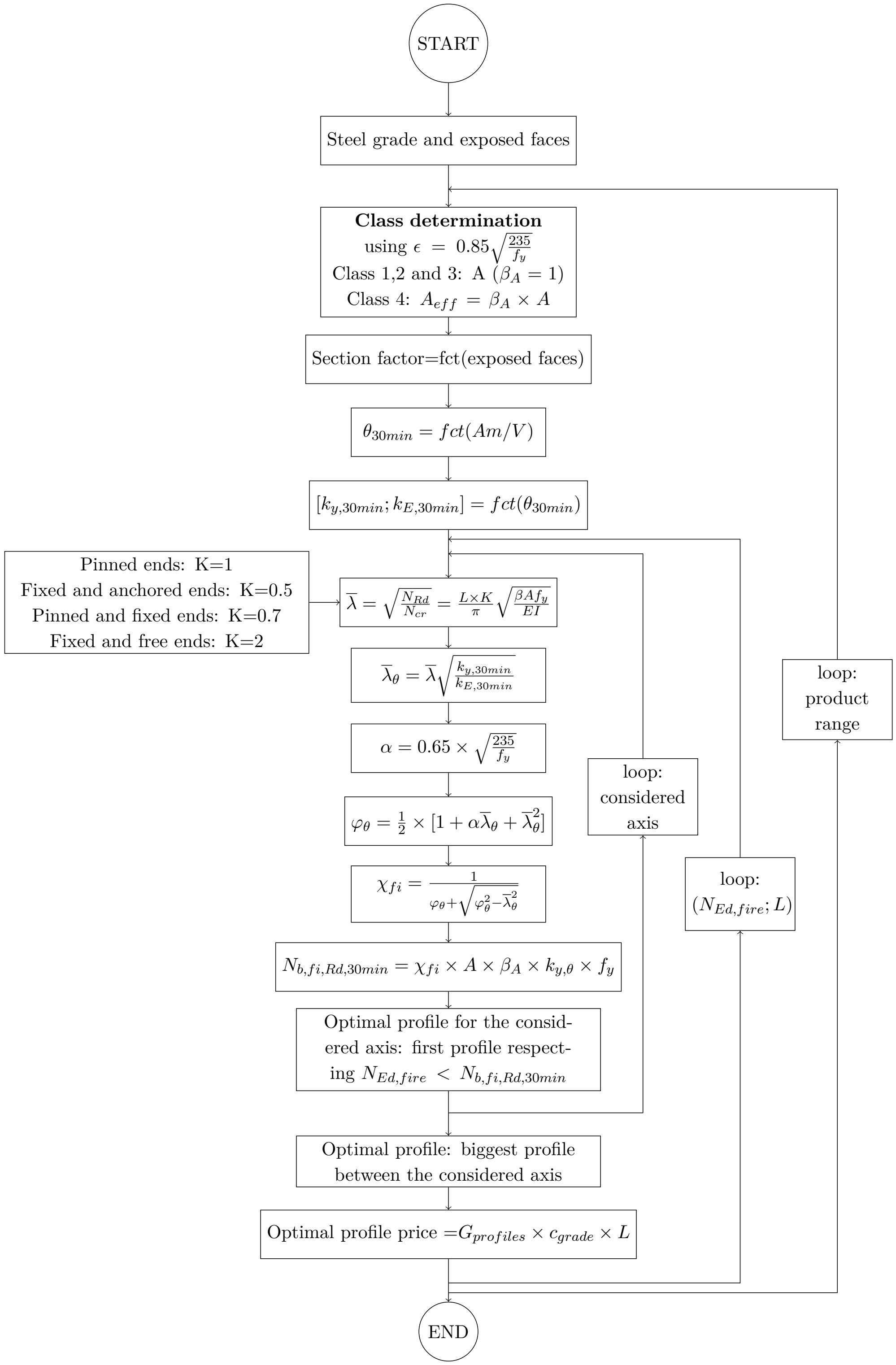


Figure 2.6: Flowchart for the unprotected member in compression

Protected member

When the element in compression is protected, the structure of the flowchart in Figure 2.7 is quite similar to the one in Figure 2.6 and its explanations given previously. Indeed, the only differences are found in the computation of the required coating thickness, in the computation of the price following the equation

2.17 and in the steel temperature at 30 minutes which is imposed and will therefore allow the computation of two unique factors of reduction of the mechanical properties for all the profiles: k_y and k_E.

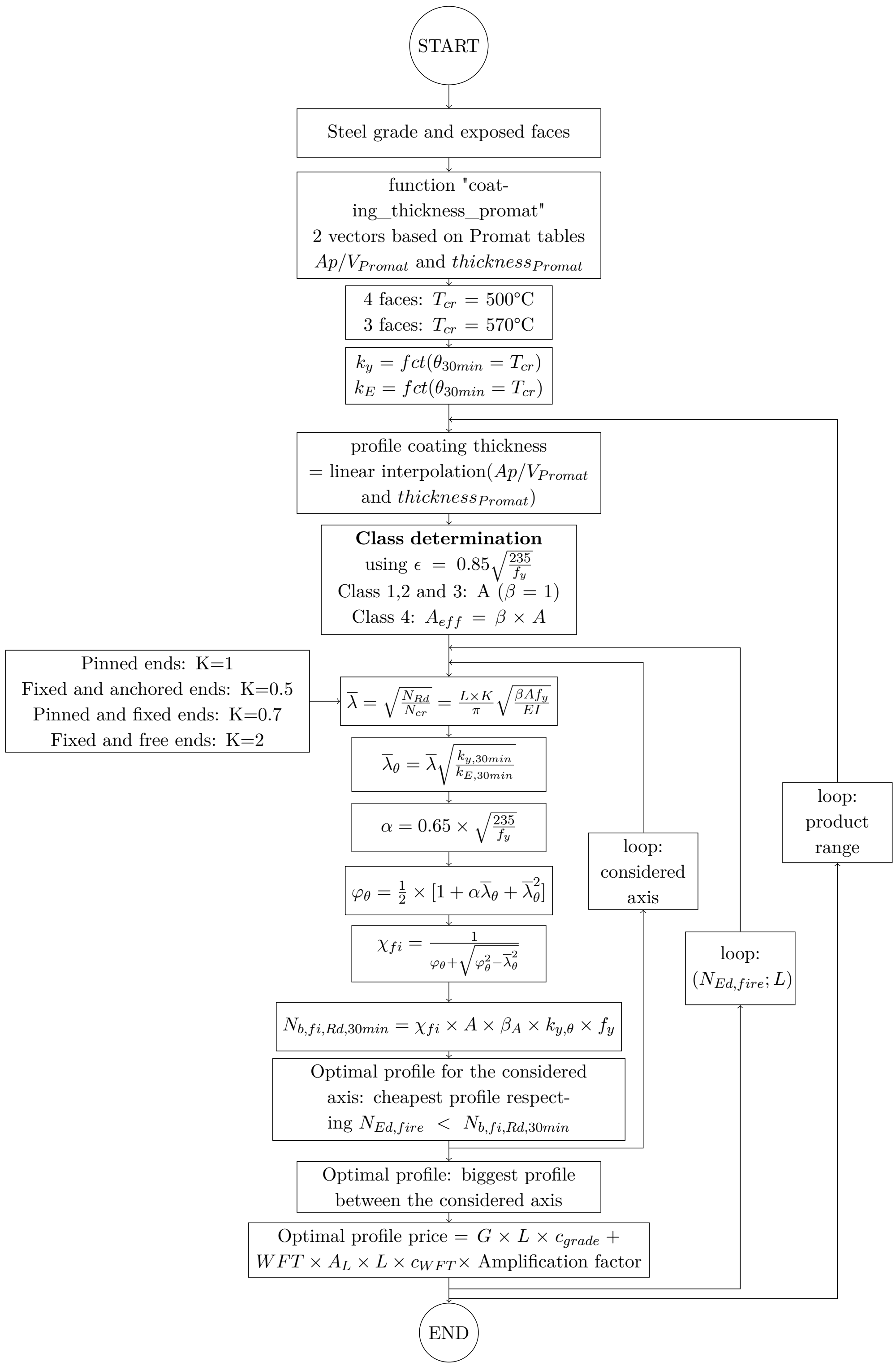


Figure 2.7: Flowchart for the protected member in compression

3 Economical analysis: tension member

In this section, the economic interest of high yield strength steels in protected and unprotected tension members will be investigated. Modifications will be gradually introduced to understand the results better. As explained in Figure 2.1, all of these results will be given for a comparison between RS and HSS grades for a defined profile range. A member in tension will be the simplest loading case as it will not introduce instability. Logically, the range of interest of HSS should be higher for tension than for compression since there is no instability to decrease the interest of HSS.

First, the results at ambient temperature [24] for a specific case study as well as the conclusions drawn from the sensitivity analysis will be summarized in this work. Next, the fire conditions will be introduced with an unprotected element. The case study and the sensitivity study of the parameters will be developed and explained in detail. The same will be done for a protected element.

Then, the protected and unprotected case will be combined in a section that will study a specific case and will also provide an economic evaluation method to obtain the optimal solution. This method will allow the user to choose which solution (RS or HSS, unprotected or protected) is the cheapest and which profile to use for a given load.

Finally, an additional optimal solution study will be carried out. This will be done independently for the protected and unprotected elements, but all the ranges and grades considered will be combined. The objective will be to have a first overview of the optimal ranges and grades.

3.1 Ambient temperatures

The results in this section are based on the thesis studying the economic interest of HSS for steel structures [24]. The resistance of tensioned members will be governed by their cross-sectional resistance depending on the grade considered. Neither the serviceability limit states nor the instabilities must be considered.

In this work at ambient temperature, the results provided are displayed in green when the HSS grade is of economic interest and in red if it is not, this is based on the condition 2.8. This graphical representation will be kept in this work but will be supported by cost curves as well as interest curves to better assess the economic interest of the HSS grade. Indeed, by using the red and green graph, there is no information on the difference of costs and so when the difference of costs is insignificant, the zone will be green whereas the interest is not substantial. In tension, the length will not influence the resistance computation but the cost computation. Therefore, the graphs will be represented for a length of 1m to have the cost per linear meter and thus have a general representation.

3.1.1 Case study definition

In this section, the case study considered is the following:

- Grades: comparison between a RS S355 grade and a HSS S500 grade
- Profile range: HEA profile range
- Steel price for S355 grade: 1.2 €/kg

In tension, the length and support conditions will not influence the results.

3.1.2 Case study results

The results of the ambient temperature study were determined for a specific load range: $N_{Ed} \in [300; 3000]kN$. In order to be able to compare the results at ambient and elevated temperatures, the considered load range will be adapted by using the maximum value of the sectional plastic resistance for the HSS grade as the upper bound of the load range. The results for the case study defined in this work are shown in Figure 3.1 where two non interest zones (in red) were identified.

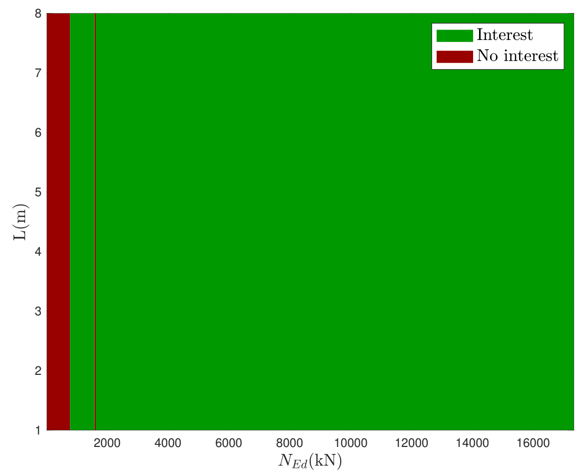
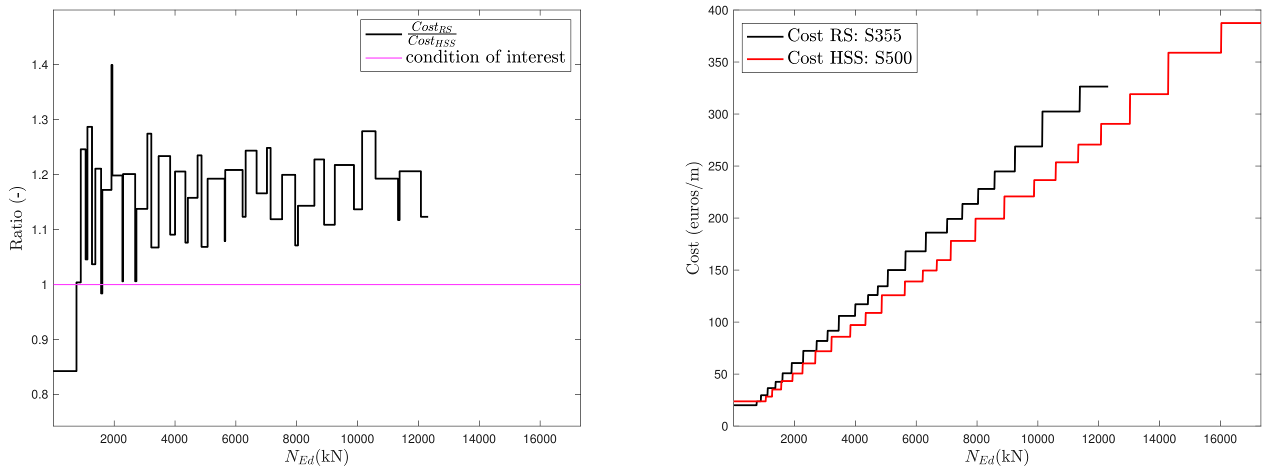


Figure 3.1: Case study for tensioned members at ambient temperature: interest of HSS

The first non interest zone (left) corresponds to the zone where the design axial load N_{Ed} is smaller than the plastic axial resistance of the first profile in the catalogue for RS steel (S355). This zone would never be of interest as the design for the RS grade and the design for the HSS grade require the first profile in the product range. It is therefore logical that there is no economic interest as the cost of the HSS grade is always higher than the one of the RS grade. Elsewhere in the domain, and therefore for the second non interest zone in the case study, any non-interest zone will depend solely on the condition 2.8 which can also be expressed as used in the ambient temperature study with the condition 2.10 indicating that there is no interest if the mass ratio of the RS grade to the HSS grade is greater than the relative cost of the HSS grade to the RS grade.

As already mentioned, two additional representations will be introduced in order to have a better understanding of the interest of the HSS grade. To generate the figure on the interest condition, the condition 2.8 comparing the costs of the two shades will be used. In this work, the use of the 2.8 condition will be preferred to the condition 2.10 in order to allow an easier comparison of the costs according to the solution considered (protected or unprotected). The costs are computed on the basis of the equation 2.9 which is equivalent for ambient or high temperature designs.



(a) Condition of interest

(b) Cost evolution

Figure 3.2: Case study for tensioned members at ambient temperature

In Figure 3.2(a) representing the condition of interest 2.8, the two zones of non-interest correspond to the zones where the condition 2.8 is not respected since the cost ratio falls below unity. Additional observations can be drawn from this figure, some areas that have been defined as interesting in Figure 3.1 have a limited interest since the cost difference is less than 5%. This figure also illustrates that elsewhere in the interest domain the cost of using the RS grade is between 10% and 40% higher than the cost of the HSS grade. It is also important to note that this interest curve stops when the maximum strength of the S355 grade is reached, as only the HSS grade is able to provide sufficient strength to take the axial load N_{Ed}.

This observation can be supported by Figure 3.2(b), which represents the cost evolution of the considered grade according to the imposed axial load N_{Ed}. The zones of non-interest can be identified where the HSS cost curve is above the RS cost curve. These two types of graphs can therefore be used to justify the zones of interest with different approaches: respect of a criterion or a comparison of cost evolutions.

3.1.3 Key conclusions

Finally, the key conclusions drawn in this work at ambient temperature [24] for the tension members are as follows:

- When a member is in tension, the range of interest for HSS is considerable once the design resistance of the first profile in the catalogue for the RS grade is reached.
- By increasing the grade of the HSS considered, the interest range narrows as the additional cost is not compensated by the increase in strength. However, this conclusion should be balanced, as it is based on a fixed load range. By extending this range to the maximum sectional resistance for the considered HSS grade, the conclusion can be adapted to this new range. By increasing the grade of the considered HSS, the range of interest at the beginning of the load interval becomes narrower, but since the strength is proportional to the grade, the range of interest will expand for higher axial loads N_{Ed}.
- The larger the first profile area, i.e. the more massive the profile range, the smaller the economic

interest of the HSS grade in the area that has been considered. It is therefore the profiles with the smallest cross-sections that are likely to have the greatest areas of interest. These results should be put into perspective as the HEM or HD range of sections are able to resist loads beyond those considered in the study area. When considering a load range covering the entire profile range, the HSS grade will be of great interest.

3.2 Unprotected member at elevated temperature

In this section, an unprotected tension member will be subjected to fire conditions. The code structure for this situation has been explained in Section 2.5.1 based on the flowchart in Figure 2.4. The profile resistance will be degraded by the yield strength reduction factor to take into account the high temperature impact on the mechanical properties of the steel. This reduction factor will modify the results obtained in Section 3.1. It is important to mention that in the unprotected case, a justification based on the 2.10 condition will be used to have an easier understanding of the results.

3.2.1 Case study definition

In this section, the case study considered is the following:

- Grades: comparison between a RS S355 grade and a HSS S500 grade
- Profile range: HEA profile range
- Number of exposed faces: 4 faces
- Steel price for S355 grade: 1.2 €/kg

In tension, the length and support conditions will not influence the results.

3.2.2 Case study results

In the case study for unprotected elements under tension at elevated temperatures, the results are represented in Figure 3.3.

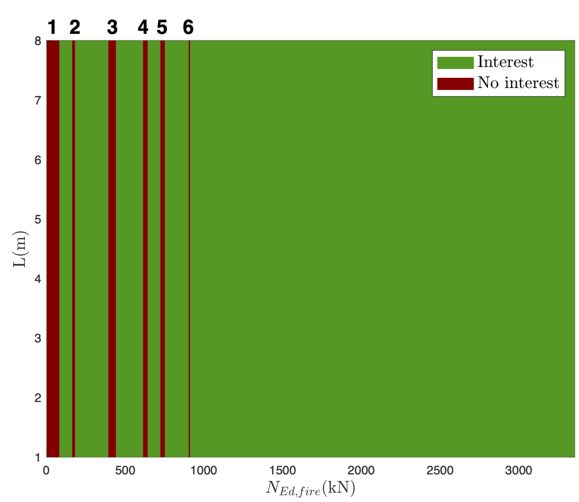


Figure 3.3: Case study for unprotected tensioned members: Interest of HSS

The 6 non-interest zones (in red) in Figure 3.3 will be fully explained in this section. In the rest of the work, this explanation will not be further detailed and will be considered as understood since the explanations are similar to those provided in this section. The explanation of these non-interest zones is comparable to the one carried out at ambient temperature [24].

These zones will be identified by their number in Figure 3.4. This figure illustrates the optimal design profile for the RS grade and the HSS grade according to the axial fire load $N_{Ed,fire}$ and the length even if it has no influence on the design. Based on the optimal profile of each design, it is possible to identify the number of profiles of difference between the two designs which is done in Figure 3.5.

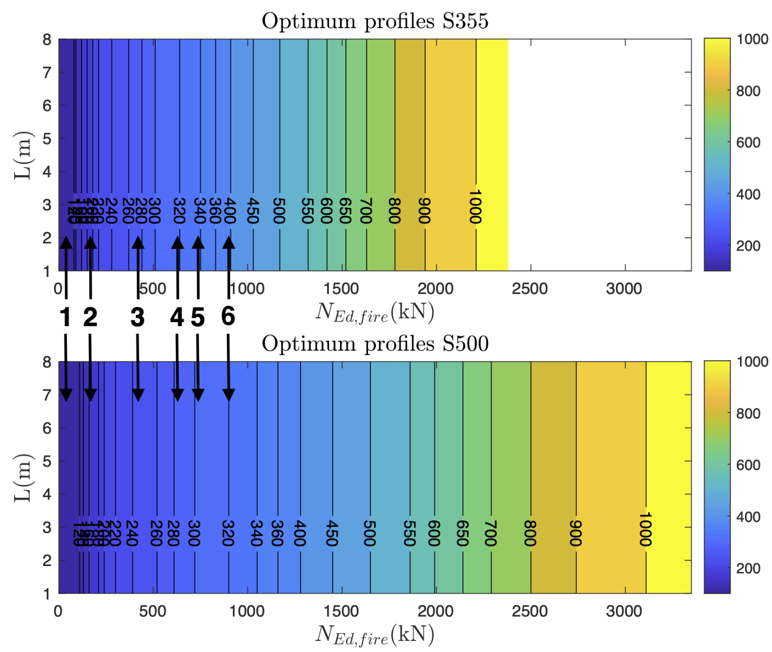


Figure 3.4: Case study for unprotected tensioned members: optimum profiles for RS and HSS designs

Based on Figures 3.4 and 3.5, it is possible to explain the zone 1. This zone corresponds to a similar optimal profile for both designs. When there is no profile gap between the two grades, it is obvious that the zone is not relevant as the cost of the HSS grade is higher than the RS grade. This zone is caused by a lower axial fire load $N_{Ed,fire}$ than the axial resistance at high temperature of the first profile in the catalogue (HEA100) with a S355 grade:

$$N_{Ed,fire} < N_{fi,30min,Rd,HEA100} = 75kN \tag{3.1}$$

As a further remark, the resistance of the HEA profile at ambient temperature $N_{pl,Rd,HEA100}$ is 752 kN which is 10 times higher. This is explained by the introduction of the reduction factor of the yield strength which has a value close to 0.1 for the HEA 100 profile for a resistance computed at 30 minutes. This demonstrates the degree to which the introduction of the fire conditions has an impact on the strength of the considered profile. However, these two resistances will not be compared to the same load. In fact, $N_{fi,30min,Rd,HEA100}$ will be compared to the fire load $N_{Ed,fire}$ where $N_{Ed,fire} = N_{Ed} \times \eta_{fire}$, whereas $N_{pl,Rd,HEA100}$ will be compared to N_{Ed}.

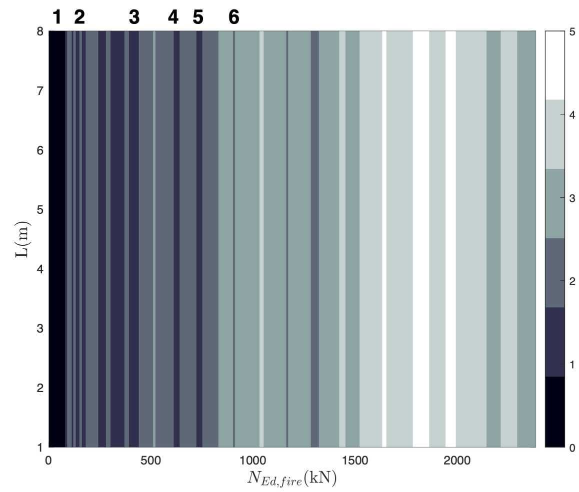


Figure 3.5: Case study for unprotected tensioned members: number of profile gaps between RS and HSS designs

For the other zones of non-interest (2, 3, 4, 5, 6), the explanation is different. The required data to support these zones, from Figures 3.5 and 3.4, have been summarised in Table 3.1.

Zone	**Optimal profiles**		**Number of profile gaps**
	S355	**S500**	
1	HEA 100	HEA 100	0
2	HEA 180	HEA 160	1
3	HEA 260	HEA 240	1
4	HEA 300	HEA 280	1
5	HEA 320	HEA 300	1
6	HEA 360	HEA 320	2

Table 3.1: Case study for unprotected tensioned members: non-interest zones

The number of gap profiles and the condition 2.10 will enable to justify the zones of no interest. Based on this condition, there is no interest if $\frac{G_{RS}}{G_{HSS}} < \frac{c_{HSS}}{c_{RS}}$ with $\frac{G_{RS}}{G_{HSS}}$ the weight ratio between the optimal design of the RS grade and the HSS grade. To illustrate this condition, Figure 3.6 will be used. It illustrates the condition 2.10 through the evolution of the weight ratio of the considered HEA range for a 1 profile gap $\frac{G_{profiles,i}}{G_{profiles,i-1}}$ and for 2 profiles of difference $\frac{G_{profiles,i}}{G_{profiles,i-2}}$ as well as the relative cost of the S500 grade $\frac{c_{HSS}}{c_{RS}}$. As the graph shows, the different zones of non-interest correspond to places where the weight ratio is lower than the relative cost of the S500 grade.

As an example, for zone 2, as shown in Table 3.1, both designs have one gap profile in the catalogue, which corresponds to the $\frac{G_{profiles,i}}{G_{profiles,i-1}}$ curve (in black). In addition, the point for zone 2 is located for HEA 180 for the RS grade. As shown in Figure 3.6, this point in zone 2 is below the cost ratio of grade S500: the interest condition is not satisfied.

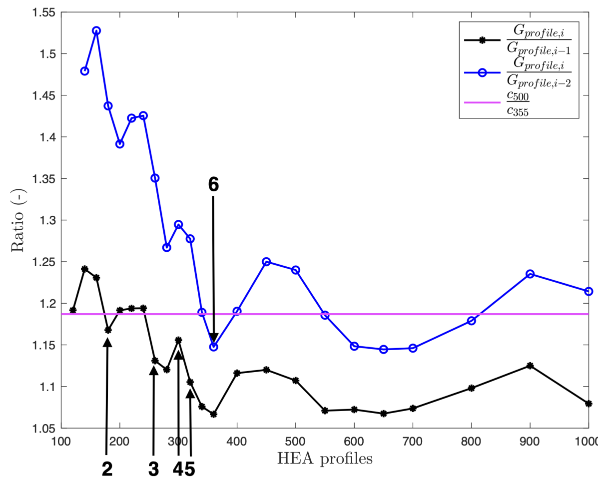
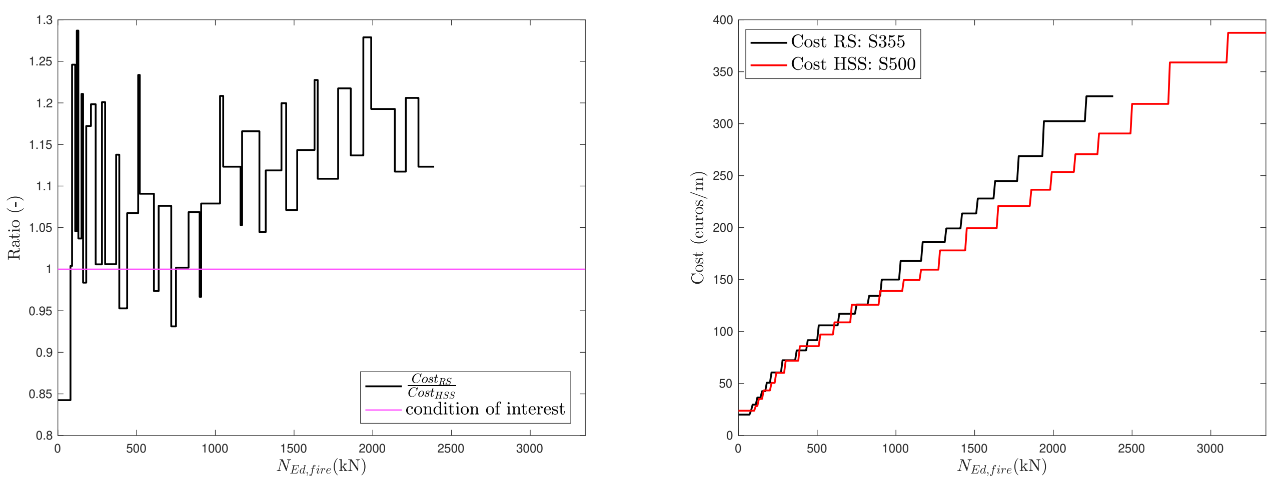


Figure 3.6: Case study for unprotected tensioned members: weight ratios and relative costs of HSS grade

As in the ambient temperature work, one can conclude that the first zone of non-interest corresponds to where the axial fire load $N_{Ed,fire}$ is lower than the fire resistance of the first profile in the catalogue for the RS grade. This occurs because the same optimal profile is defined for both designs. Since the cost of the HSS grade is higher than the RS grade, there will be no economic interest in using the HSS grades in this region. The rest of the non-interest areas depend on the interest condition 2.10 or 2.8.

This explanation of non-interest zones is only valid for unprotected elements. As already explained in Section 3.1, two other graphical representations will be used to justify the zones of non-interests in order to have a common criterion between the protected and unprotected elements. Therefore, the condition 2.8 will be used.



(a) Condition of interest

(b) Cost evolution

Figure 3.7: Case study for unprotected tensioned members

In Figure 3.7(a), the 2.8 condition is represented and 6 zones are below unity which matches the non-interest zones previously defined. Furthermore, the cost of the RS grade is 5 to 30 % higher than the cost of the HSS grade. In Figure 3.7(b), the evolution of the costs of the two grades as a function of the load $N_{Ed,fire}$ shows that up to a fire load $N_{Ed,fire}$ of 1000 kN, the two grades' costs tend to be relatively close. This can be confirmed by Figure 3.7(a) where the percentage difference between costs varies but a general trend of small difference can be identified (around 5%).

3.2.3 Sensitivity analysis of parameters

In this parameter sensitivity analysis section, tables of fire and ambient temperature tensile strengths defined in Appendix A will be used. The ambient temperature resistances are represented in Table A.1 and will be used to compare it with the resistances at high temperatures. As a recall, these minimum and maximum fire resistance tables for each profile range and grade considered have two distinct functions: to define the load interval studied and to help the user to select a profile range for a given fire load $N_{Ed,fire}$ or a normal temperature load N_{Ed} with its corresponding η_{fire}.

This section will focus on the influence of key parameters of this work: the reduction factor for the design load level for the fire situation η_{fire}, the grades, the profiles ranges, the exposed faces and the steel price. In this parametric study, the case study will be kept and each parameter will be varied individually, i. e. only one parameter will be varied at a time.

Reduction factor η_{fire}

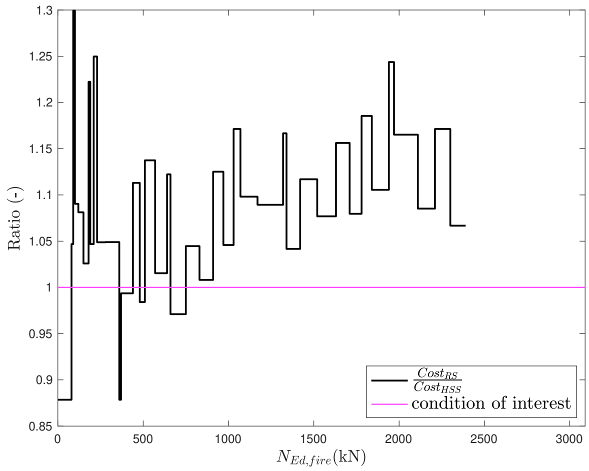
As a reminder, η_{fire} will multiply the applied load at ambient temperature N_{Ed} to give the equivalent fire load $N_{Ed,fire}$ as shown by the relationship 2.1. This means that the lower the η_{fire} value is, the lower the fire load applied for the same applied load N_{Ed}. It will thus be more advantageous to have a low η_{fire} in order to obtain a lower fire load for the considered N_{Ed}.

The results of this work are given in terms of fire load to avoid adding an extra variable to the results. The impact of this reduction factor will be discussed in Section 5 which will aim to determine which design, at ambient or elevated temperature, will govern the optimal profile choice.

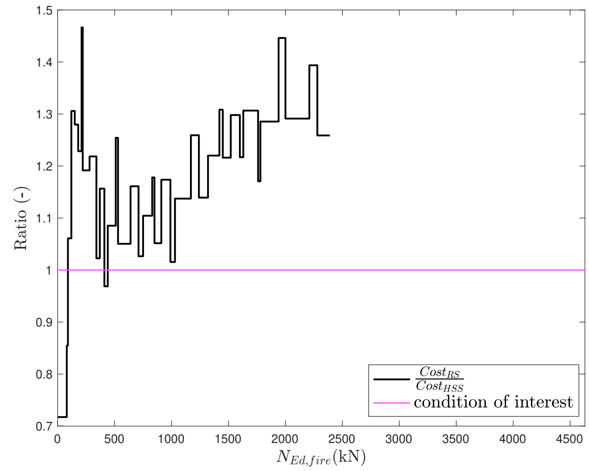
Grades

The influence of the HSS grade considered will be studied on the results obtained from the S460 and S690 grades.

First of all, a higher grade of HSS steel will achieve a higher fire resistance and therefore a larger field of interest. This is well supported by Figure 3.8 and Table A.2 which show that the maximum fire load for a grade S460 is 3090 kN whereas it is 4635 kN for a grade S690. In addition to this, as the grade increases, the number of non-interest zones decreases. This occurs as the grade increases, the difference between the costs of the S355 and HSS grades increases and therefore the ratio between them rises. This is well supported by Figure 3.8 as the ratio between the two costs increases with the grade considered. Indeed, in the case of the S460 grade, the cost difference is up to 25%, whereas for the S690 grade, the difference is up to over 40%.



(a) Condition of interest of S460



(b) Condition of interest of S690

Figure 3.8: Unprotected tensioned members: grades

The comparison of the results for the different HSS grades indicates that the first zone of non-interest of HSS profiles goes beyond the tensile fire resistance of the first profile in the catalogue (HEA 100 in RS steel) for grades S550, S620 and S690. Indeed, this first zone ends at 75 kN for grade S460 as well as grade S500, this value corresponds to the fire resistance in tension of the first profile in the catalogue (HEA 100). For grades S550, S620 and S690, the zone ends at 90 kN, which will be justified based on the number of gap profiles for the different HSS grades. Figure 3.9 represents the number of gap profiles between grades S355 and S690 and is intended to explain the increase in the first non-interest zone for an HSS grade of S690. This figure is a zoom on the concerned zone.

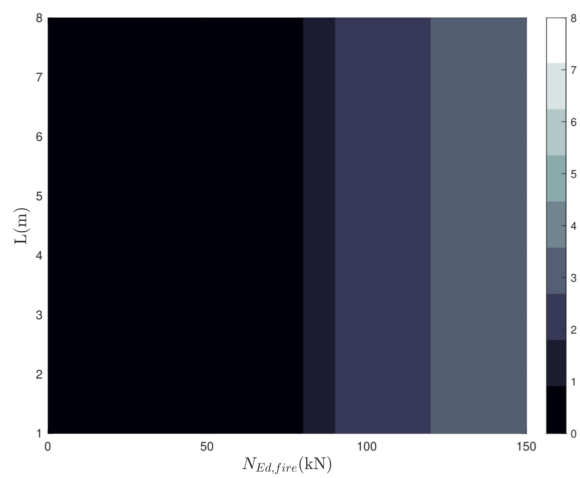


Figure 3.9: Unprotected tensioned members: gap profiles between S355 and S690 designs

Based on Figure 3.9, the increase in the first non-interest area can be identified as the only area with a unique gap profile. The fact that there is no economic interest can be explained by Figure 3.10 which will represent the 2.10 condition and is composed of the cost ratios between the RS grade (S355) and the HSS grade (S460 or S690) as well as the weight ratio between the consecutive profiles of the HEA range.

In this area with a single profile gap, the required profiles are HEA120 for the RS grade and HEA100 for the HSS grade. Based on the condition 2.10, there is no interest when the weight ratio between these two profiles is less than the relative cost of the HSS grade considered. The weight ratio is higher than the relative cost of the S460 grade (blue curve under the black curve) but lower than the relative costs of the S690 grade (red curve above black curve). Thus, there is no economic interest for the S690 grade, which can be generalised for all the S550, S620 and S690 grades (Table 2.2).

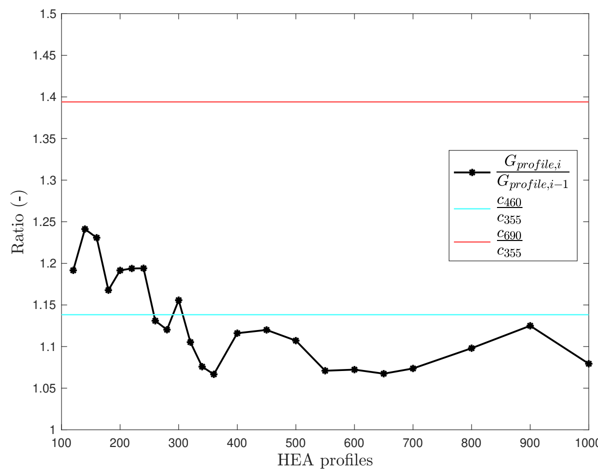


Figure 3.10: Unprotected tensioned members: weight ratio and relative cost ratios for S460 and S690 grades

Profile ranges

The profile range's influence on the economic interest of HSS grades will be studied based on the considered product ranges. For this purpose, Table A.2 in addition to the various graphical results will be used as it contains the minimum and maximum fire resistance values of the profile ranges. Thus, this table allows to give the boundaries of the field of interest.

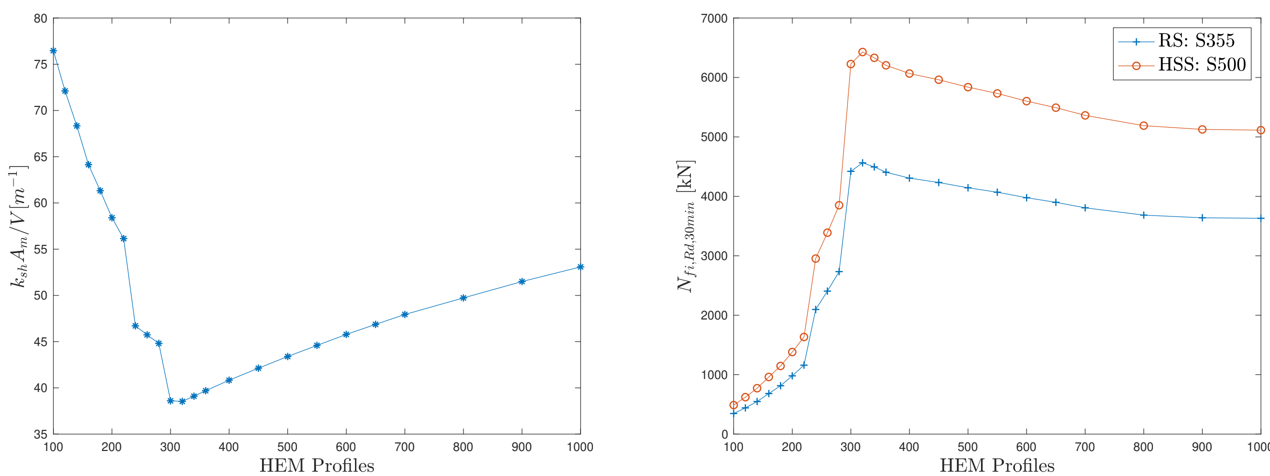
First, Table A.2 and Figure 3.12 show that the load range covered by the ranges varies greatly. The profile ranges will reach increasing maximum strengths in the following order: HEAA with 2529 kN, HEA with 3359 kN, HEC with 3152 kN, HEB with 4199 kN, HEM with 6428 kN and HD with 82735kN. The HD range is a range suitable for much higher loads than the other ranges. A more detailed discussion of this range will be conducted in this section.

It is necessary to highlight an important detail regarding the maximum fire resistance of the HEM range, which is given in Table A.2. As shown in Table 3.2, most profile ranges will achieve the maximum range fire resistance for the same profile as the maximum cold resistance corresponding to the last profile in the profile range. This is not the case for the HEM range. The profile with the highest fire resistance $N_{fi,30min,Rd}$ is the HEM 320 profile and will not correspond to the profile with the highest cold resistance N_{Rd}, the HEM 1000 profile.

Profile range	Profile of the higher resistance	
	Normal temperature design	Elevated temperature design
HEAA	HEAA 1000	HEAA 1000
HEA	HEA 1000	HEA 1000
HEB	HEB 1000	HEB 1000
HEC	HEC 320	HEC 320
HEM	HEM 1000	HEM 320
HD	HD 400 x 1299	HD 400 x 1299

Table 3.2: Unprotected tensioned members: profiles with the higher resistance for ambient and elevated temperature

This can be explained on the basis of Figure 3.11 representing the evolution of the section factor multiplied by the correction factor for the shadow effect as a function of the profile of the HEM range. This shows that the section factor decreases up to the HEM 320 profile and then increases. Since the fire resistance increases with a decreasing section factor, this growth after the HEM 320 profile will be an issue because the fire resistance of the profiles will decrease as represented in Figure 3.11. Therefore, the maximum fire resistance is given by the HEM 320 profile. This also leads to the conclusion that for fire conditions, the HEM range will not be of interest above the HEM 320 profile.

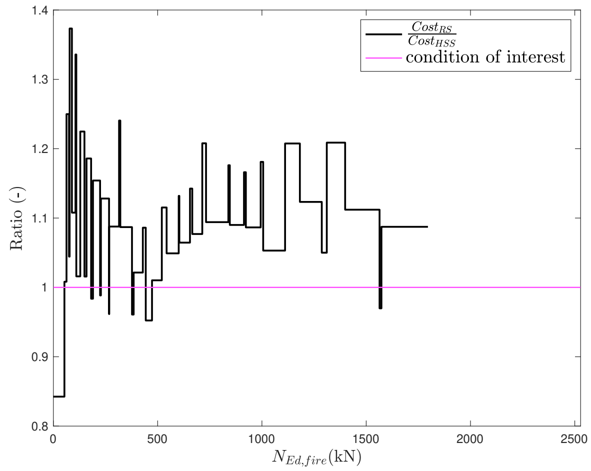


(a) Evolution of $k_{sh}A_m/V$

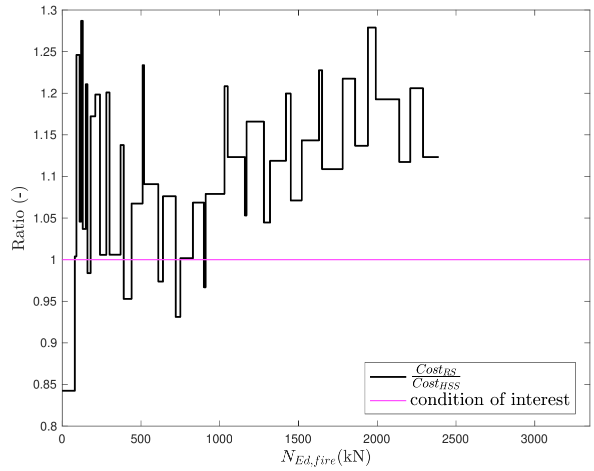
(b) Evolution of the fire resistance

Figure 3.11: Unprotected tensioned members: HEM product range

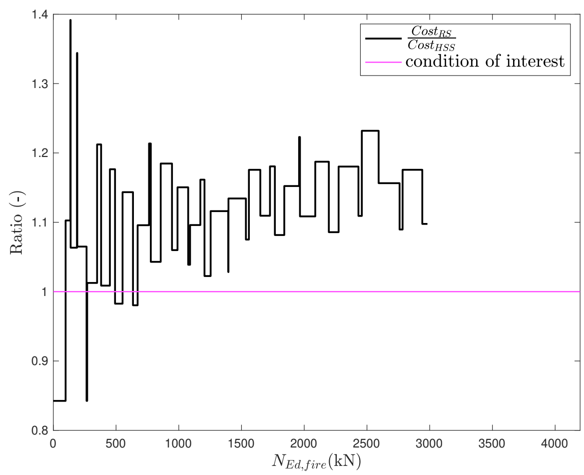
Then, the change in profile range will reduce the interest of the HSS grade in the first area of non-interest. As long as the fire resistance of the first RS profile is not achieved, there will be no point in using HSS grades costing more tha RS, as the design of both RS and HSS grades requires the same profile. As shown in the minimum fire resistance column of Table A.2, the first zone of no interest, the fire resistance of the first profile in the range, will increase in the following order: HEAA, HEA, HEB, HEC, HEM and HD. The larger the area of the first profile, the more the economic interest of the HSS grade is limited in this first non interest zone.



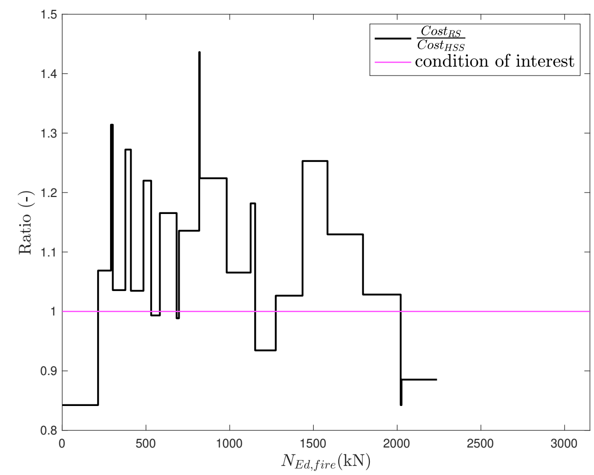
(a) HEAA



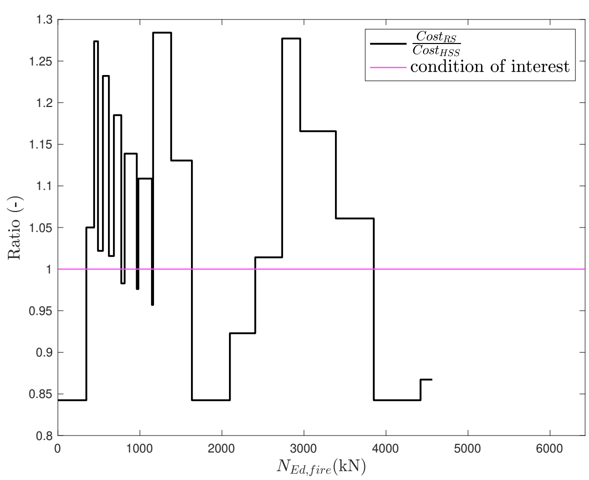
(b) HEA



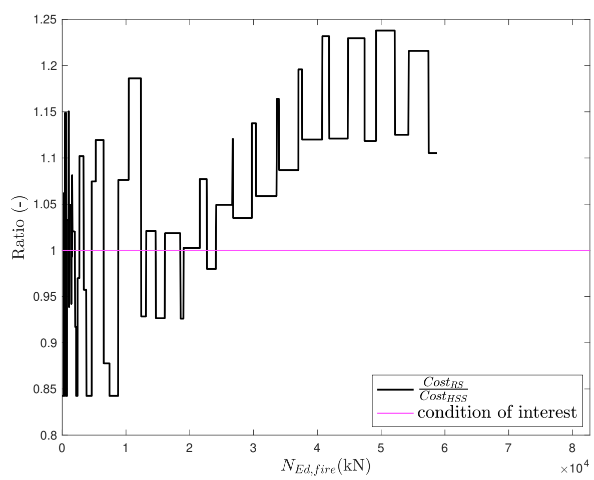
(c) HEB



(d) HEC



(e) HEM



(f) HD

Figure 3.12: Unprotected tensioned members: product ranges

The HEAA, HEA and HEB product ranges have a significant range of interest in HSS steels as shown in Figure 3.12 (a) (b) (c). For the HEC, HEM and beginning of the HD range, the range of interest of HSS steels is limited as shown in Figure 3.12 (d) (e) (f). When there are few profiles in a range, there may be large differences in fire resistance between two consecutive profiles in the catalogue, which will lead to areas of non-interest.

Taking the example of the HEM range, it is possible to explain these consequent zones of non-interest visible on Figure 3.12 by using Figure 3.11(b). Indeed, a jump in resistance occurs between the HEM 220 and HEM 240 profiles as well as between the HEM 280 and HEM 300 profiles. These two jumps in fire resistance will be the source of the two large non-interest zones in the middle of the load interval. Because of the resistance jump, the optimal profile of the two large central non-interested zones for the RS grade is similar to that of the HSS grade. Since the cost of the RS grade is lower, there will be no point in using the same profile but with an HSS grade.

The HD range of profiles is different from the other ranges. Indeed, as shown in Table A.2, the maximum fire resistances of this range are much higher than the other ranges studied. This difference in resistance is due to the high mass of these profiles. Given this difference, it was not very interesting to compare the different ranges for a fixed load interval.

Furthermore, for HD range, the comparison between the maximum resistance value of Tables A.2 and A.1 shows that the maximum value of the fire resistance is equivalent to the ambient temperature resistance. The explanation for this is that all the profiles in the range have a low section factor. Therefore, they will heat up significantly slower than the other ranges and the mechanical properties of the steel will degrade much less than with the other ranges. As shown in Table 3.3, the HD range will have a yield strength reduction factor between 0.1 and 1, the upper limit of this range will reach the unit for the HD 400 x 1299 profile (the profile in the range with the highest fire resistance) reflecting that fire will not degrade the mechanical properties of the profile and therefore the fire resistance is similar to the ambient one.

Product range	k_y	
	min	**max**
HEAA	0.09	0.18
HEA	0.1	0.19
HEB	0.1	0.21
HEC	0.15	0.27
HEM	0.18	0.41
HD	0.1	1

Table 3.3: Unprotected members: yield strength reduction factor k_y according to the product range

Figure 3.13 represents the evolution of the strength at ambient and elevated temperatures in the HD range of profiles. This figure shows that the strength of the profile is only slightly degraded by fire and that the profiles with the most massive sections will not have any fire related degradation.

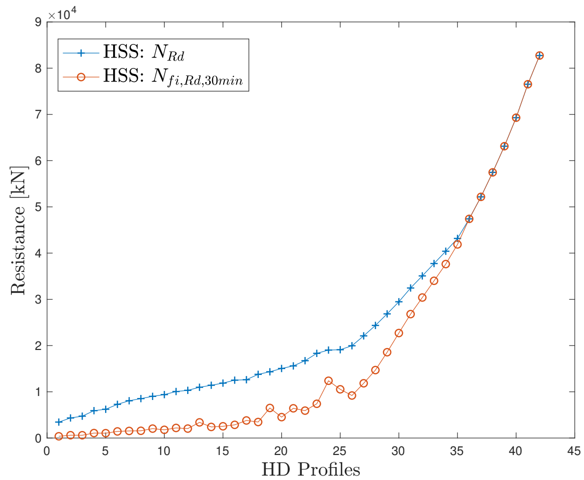


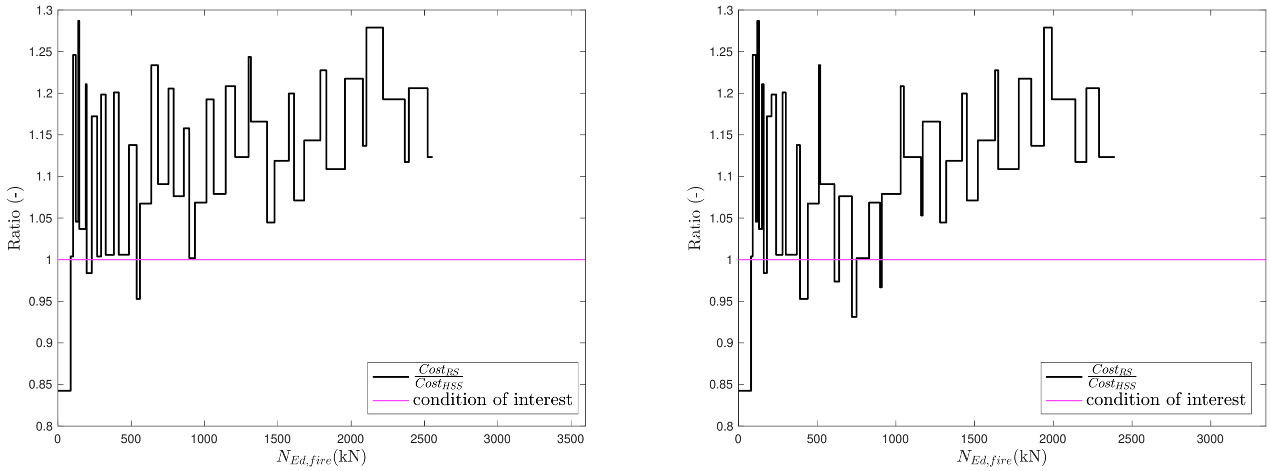
Figure 3.13: Unprotected tensioned members: resistance at ambient and elevated temperature for grade S500 with HD product range

The following conclusion on the interest of HSS steels can be drawn from the results of this section. Indeed, for loads below 4199 kN, the HEAA, HEA and HEB ranges will have a wide range of economic interest for the HSS grade, whereas this range would be restricted for the other profile ranges. When the applied loads are high, the HEM and HD ranges will be more suitable. However, the HEM range will not achieve as high loads as the HD range partly due to the truncation of the range due to the degradation of mechanical properties by fire. The HEC range has a narrower range of interest than the HEAA, HEA and HEB ranges for a comparable load range.

Exposed faces

The number of exposed faces will have an impact on the computation of the section factor and so on the temperature of the steel at 30 minutes of the considered profile. If only 3 faces are exposed to the fire and not 4, the surface area exposed to fire is reduced. Therefore, the section factor A_m/V will be lower which will result in a lower temperature at 30 minutes as represented in Figure 2.3. This will result in higher reduction factors in the mechanical properties of the steel (k_y and k_E). The element's resistance will be less degraded by the high temperatures and so, the fire resistance will be higher than with a 4-sided fire exposure.

In Figure 3.14, the condition of interest of HSS defined by the condition 2.8 is shown for 3 and 4 exposed faces with the same conditions as the study case.A first observation is the decrease in the HSS non-interested zones with three exposed faces, which is due to the increased strength of the profiles. This increase in fire resistance for three exposed faces will result in a smaller increase in the optimal profile required. This will also result in an increase in the accessible fire load range $N_{Ed,fire}$ which will be greater for a 3-sided exposed element. Indeed, the maximum load with 3 exposed faces is 3598 kN (Table A.3) and is 3359 kN (Table A.2) for 4 faces exposed to fire. In addition, the first non-interested zone will be larger with 3 exposed faces as the strength of the first profile in the catalogue will be increased to 86 kN compared to 75 kN for a 4-sided exposure.



(a) Condition of interest for 3 faces exposed

(b) Condition of interest for 4 faces exposed

Figure 3.14: Unprotected tensioned members: number of exposed faces

Steel price

In this sensitivity study, the price of S355 steel will vary to determine its impact on the results. As explained in Section 2.4.1, the price of steel for the grade of steel under consideration will depend on the cost of S355 steel as well as the relative cost of the HSS grade under consideration compared to the RS grade. Therefore, the variable is the S355 steel cost.

In the results obtained for an unprotected tensile member, only the cost curves will change as the price of S355 steel changes. Indeed, since the interest condition of an unprotected element can be written as represented by the condition 2.10, only the relative cost of the HSS grade compared to the RS grade will be needed for this condition. Thus, the interest condition of HSS steels will be similar whatever the price of the RS steel considered.

3.2.4 Conclusion

The fire resistance in tension of an unprotected member will be degraded by the yield strength reduction factor to take into account the high temperature impact on the mechanical properties of the steel. This reduction factor will modify the results obtained at ambient temperature in Section 3.1. The axial strength of the profiles will therefore be reduced when the fire conditions are introduced and the number of non-interest zones increases.

The main conclusions regarding the economic value of unprotected tension members under fire conditions are listed below:

- The lower the η_{fire} value is, the lower the fire load applied for the same applied load N_{Ed}. It will thus be more advantageous to have a low η_{fire} in order to obtain a lower fire load for the considered N_{Ed}.
- The higher the grade, the higher the maximum fire resistance of the range and therefore the higher the area of interest. In addition, the cost difference between RS and HSS grades will be greater and

so, there will be less area of non-interest. However, the beginning of the domain will be smaller for higher grades.

- The HEAA, HEA and HEB product ranges have a significant range of interest in HSS steels. For the HEC, HEM and beginning of the HD range, the range of interest of HSS steels is limited.

  For fire loads below 4000 kN, the HEAA, HEA and HEB ranges will have a wide range of economic interest for the HSS grade, whereas this range would be restricted for the other profile ranges. When the applied loads are high, the HEM and HD ranges will be more suitable. However, the HEM range will not achieve as high loads as the HD range partly because of to the truncation of the range due to the degradation of mechanical properties by fire.

  For fire conditions, the HEM range will not be of interest above the HEM 320 profile. The HD range is a range suitable for much higher loads than the other ranges and the profile's strength of the HD range is only slightly or not degraded by fire. The HEC range has a narrower range of interest than the HEAA, HEA and HEB ranges for a comparable load range.
  The larger the area of the first profile, the bigger the first zone of non interest is.

- The element's resistance will be less degraded by the high temperatures for an element with 3 faces exposed and result in an increase in the accessible fire load range $N_{Ed,fire}$ which will be greater for a 3-sided exposed element. A 3-sided exposed element will have less HSS non-interested zones.

- The interest of HSS steels will be similar whatever the price of the RS steel considered.

3.3 Protected members at elevated temperature

In this section, protected tension members will be subjected to fire conditions. As a reminder, the protected elements study is limited to the HEA and HEB profile ranges. The code structure for this situation has been explained in Section 2.5.1 based on the flowchart in Figure 2.5.

3.3.1 Case study definition

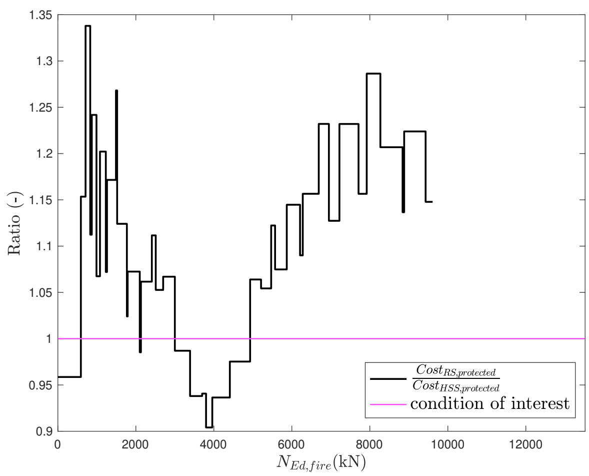
In this section, the case study considered is the following:

- Grades: comparison between a RS S355 grade and a HSS S500 grade
- Profile range: HEA profile range
- Number of exposed faces: 4 faces
- Steel price for S355 grade: 1.2 €/kg
- Amplification factor for the coating price: 10

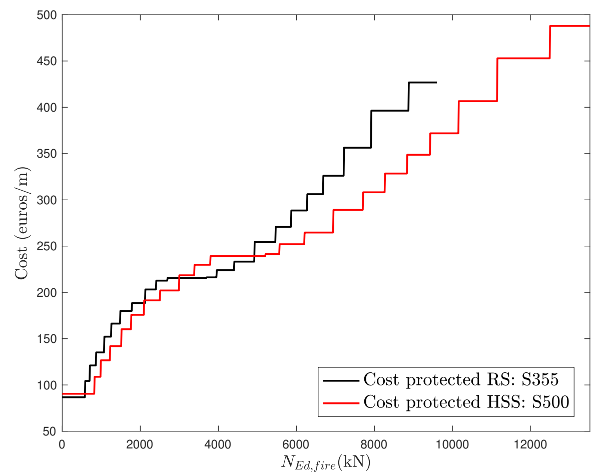
In tension, the length and support conditions will not influence the results.

3.3.2 Case study results

This section will contain the results for the case study with both grades protected (S355 and S500) and these are shown in Figure 3.15.



(a) Condition of interest



(b) Cost evolution

Figure 3.15: Case study for protected tensioned members

One benefit of applying intumescent coating is that the temperature of the steel is reduced at 30 minutes, which will result in a higher fire resistance of the protected element compared to an unprotected one. This is supported by the results of Figure 3.15 as well as by the values of Tables A.2 and A.4 in Appendix A. Indeed, the HEA range for the HSS grade has a maximum fire resistance of 13525 kN in the protected case whereas in the unprotected case this value is 3359 kN. This difference in strength is considerable and is due to the " given " temperature at 30 minutes of 500 °C for a protected element with 4 exposed faces as shown in Flowchart 2.5.

In the unprotected case, the 30-minute temperature of the steel varies around 700 °C and 800°C. As a result, the yield strength reduction factor that degrades the strength of the profile for a protected element is 0.78, whereas it varies between 0.1 and 0.2 in the unprotected case. This explains the high difference in strength between a protected and unprotected element. The introduction of the protection will therefore allow to cover a considerably higher range of fire loads than in the unprotected case.

In terms of the economical interest of HSS steels, several areas of non-interest can be identified in Figure 3.15(a). As in the unprotected case, the first area of non-interest (left) is related to the lower fire load $N_{Ed,fire}$ compared to the fire resistance of the first profile in the catalogue (HEA 100) for the RS grade. A large area of non-interest for $N_{Ed,fire}$ ranging from 3000 kN to 4930 kN can also be observed. Based on Figure 3.15(b), a plateau zone can be noticed in the costs of the RS grade and the HSS grade. The two plateau zones will be the direct cause of this zone of non-interest and will be justified through an analysis of the different costs taken into account in the total cost of a protected element.

Figure 3.16 illustrates the evolution of the total cost of a protected element as well as the evolution of the components of this cost: the cost of the optimal profile "Profile Cost" and the cost of the intumescent paint "Coating cost". These cost trends are expressed in terms of the profiles in the HEA range and the costs are expressed in euros per linear meter. To avoid redundancy, only the plateau in the cost evolution of the protected HSS grade will be analysed in this figure. The same conclusions can be drawn for the RS grade.

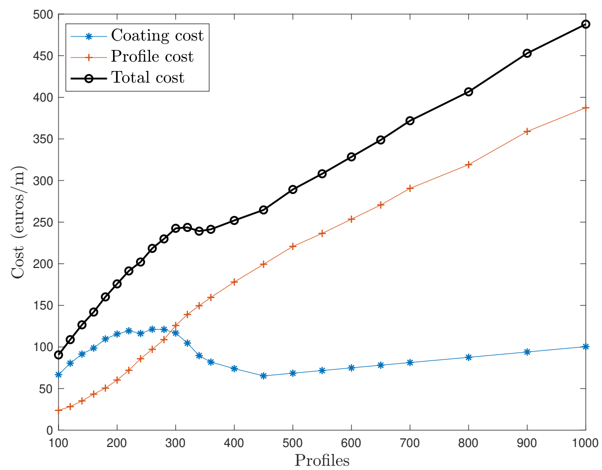


Figure 3.16: Case study for protected tensioned members: detailed costs for S500 grade (amplification factor=10)

In order to understand the plateau in Figure 3.15(b), it is necessary to study the influence of both the paint cost and the optimal profile cost on the total cost. For the cost of the profile, it grows with the increase of the needed profile. As explained in Section 2.4.2, this cost is different for HSS and RS and will be higher for HSS for the same profile. The cost of the paint will depend on the required thickness of protection as well as the surface area to be protected which will depend on the considered profile.

As a recall from Section 2.4.2, the required thickness will be defined for each profile on the basis of design tables. In this case study, the element is fire exposed on all 4 sides. Therefore the required thickness will be the highest for the first profile of the range (HEA 100) and will decrease based on the values of Table 2.4. In contrast, the surface area to be covered will increase with the type of profile considered, as its dimensions will increase with the selection of a larger profile in the product range.

Since the evolution of the thickness and of the surface to be protected are opposite, the evolution of the cost of the protection will have a particular trend as shown in Figure 3.16. A zone of high decrease in the cost of painting can be observed between the HEA 280 and HEA 360 profiles and will result in a decrease in the total cost for this interval of profiles. Indeed, the price of the paint has a significant importance in the total cost and if it decreases the total cost decreases.

The "Total cost" curve in Figure 3.16 shows that the use of the HEA 300 and HEA 320 profiles will generate a higher total cost than the HEA 340 profile and will therefore not be of any interest. The choice of the optimal profile will not be for the first resistant profile in the catalogue (HEA 300 or HEA 320) but for the cheapest resistant profile (HEA 340). This justifies the plateau zone which appears in Figure 3.15(b) and which leads to a consequent zone of non-interest.

3.3.3 Sensitivity analysis of parameters

In this parameter sensitivity analysis section, tables of fire and ambient temperature tensile strengths defined in Appendix A will be used to compare them to each others.

This section will focus on the influence of key parameters of this work: the reduction factor for the design load level for the fire situation η_{fire}, the grades, the profiles ranges, the exposed faces, the steel price and the amplification factor of the coating price. In this parametric study, the case study will be kept and each parameter will be varied individually, i. e. only one parameter will be varied at a time.

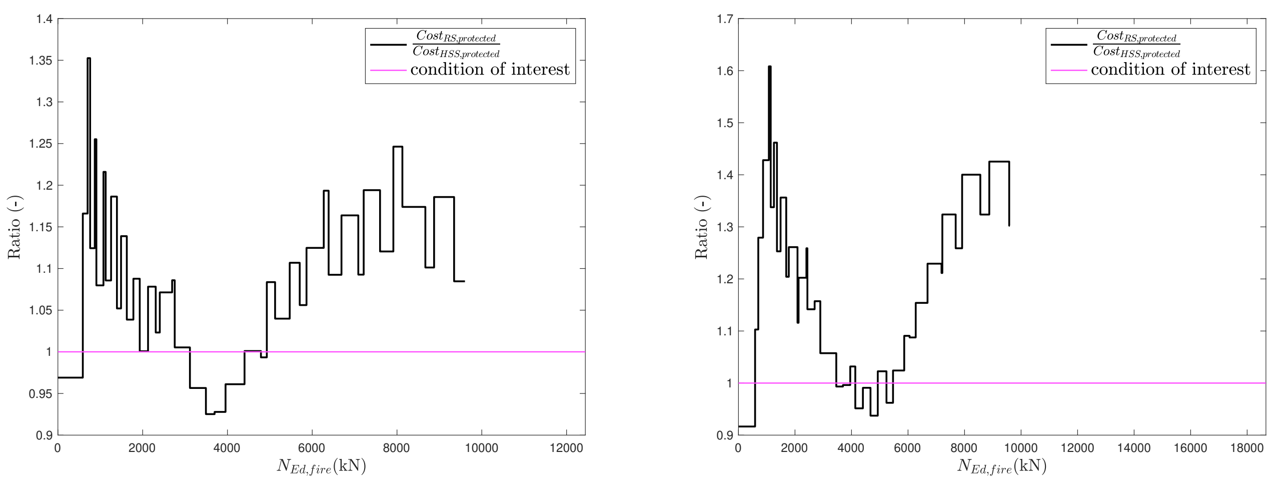
Reduction factor η_{fire}

As for unprotected members in tension (Section 3.2.3), the lower the η_{fire} value is, the lower the fire load applied for the same applied load N_{Ed}. It will thus be more advantageous to have a low η_{fire} in order to obtain a lower fire load for the considered N_{Ed}.

The results of this work are given in terms of fire load to avoid adding an extra variable to the results. The impact of this reduction factor will be discussed in Section 5 which will aim to determine which design, at ambient or elevated temperature, will govern the optimal profile choice.

Grades

In order to study the influence of the considered grade on the results for a tensioned protected member, only the two grades S460 and S690 will be used as with the unprotected members.

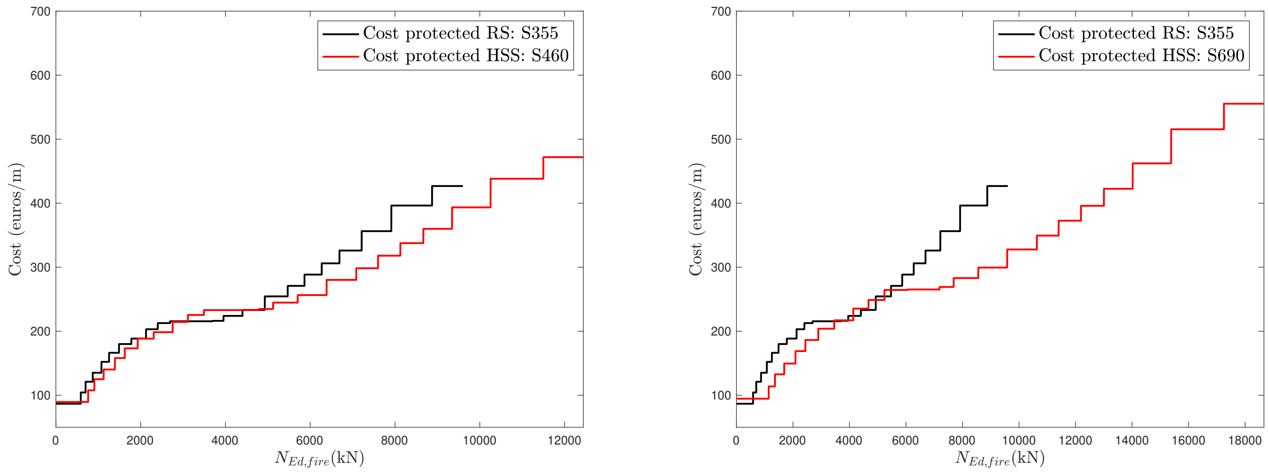


(a) Condition of interest of S460

(b) Condition of interest of S690

Figure 3.17: Protected tensioned members: grades (condition of interest)

In Figure 3.17, the condition of interest of the two grades considered, S460 and S690, is shown. Various observations can be made on the basis of this figure. Logically, increasing the grade will lead to higher fire resistance and thus increase the area of interest of the HSS grade. This can be supported by Table A.4 which gives a value of 9603 kN for S355, 12443 kN for S460 and 18665 kN for S690 with 4 faces exposed to fire. In addition, the higher the grade, the smaller the areas of non-interest. For a protected element, this can be justified on the basis of the cost evolution of the grades in Figure 3.18.



(a) Cost evolution with S460

(b) Cost evolution with S690

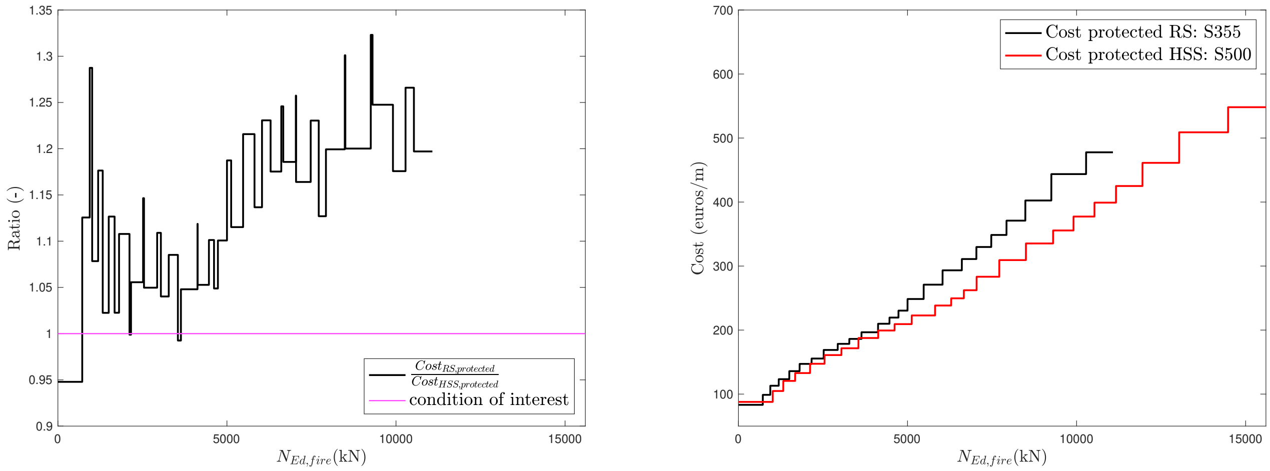
Figure 3.18: Protected tensioned members: grades (cost evolution)

As explained in Section 3.3.2, the existence of a plateau in the cost curves will be at the origin of the non-interesting zones which do not respect the condition 2.8. As the grade increases, the fire resistance of the element will increase and therefore the cost plateau will be shifted to the right. Furthermore, the higher the grade, the higher the difference between the cost curves. This is confirmed by Figure 3.17 which shows that the cost difference is up to 25% for grade S460 whereas it is up to 45% for grade S690. It is also important to point out that as the grade increases, the total cost will increase and the cost of steel will have a greater weight in the total cost.

Profiles ranges

The two ranges of profiles considered in the protected case will be compared: the HEA range and the HEB range. This work is restricted to these two ranges as only these two ranges are given in the dimensioning tables to define the required protection thickness. The graphical representations of the HEB range will only be presented in this section as the results for the HEA range can be found in Section 3.3.2.

Figure 3.19(a) shows that the HEB range will have a greater economic interest area of HSS steel compared to the HEA range which is represented in Figure 3.15(a). In addition, these two figures and Table A.4 show that the HEB range logically achieves a higher maximum strength and therefore a wider domain of interest. Indeed, the maximum strength of the HEA range for a grade of S500 is HEA 13525 kN whereas it is 15600 kN for the HEB range.



(a) Condition of interest

(b) Cost evolution

Figure 3.19: Protected tensioned members: HEB product range

The reduction in zones of no interest for the HEB range will be studied on the basis of Figure 3.19(b) representing the evolution of costs and Figure 3.20 representing the detail of the total cost of a profile. As explained in Section 3.3.2, the areas of non-interest in the protected case will be due to the price of the paint which will strongly influence the total cost. When using the HEB range, less intumescent paint will be required as the profiles are more massive and will therefore take longer to heat up. Thus, less protection will be required to achieve a similar steel temperature than for HEA range profiles as shown in Table 2.4 (thickness for 4 exposed faces). In addition, this table shows that the HEB range will have more sections with the "plateau" thickness of 104 μm (smaller value). These different observations will have a direct impact on the areas of non-interest as the plateau induced by the price of paint will not appear.

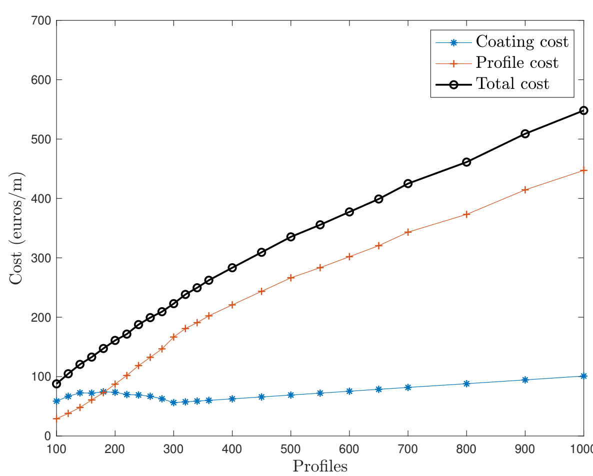


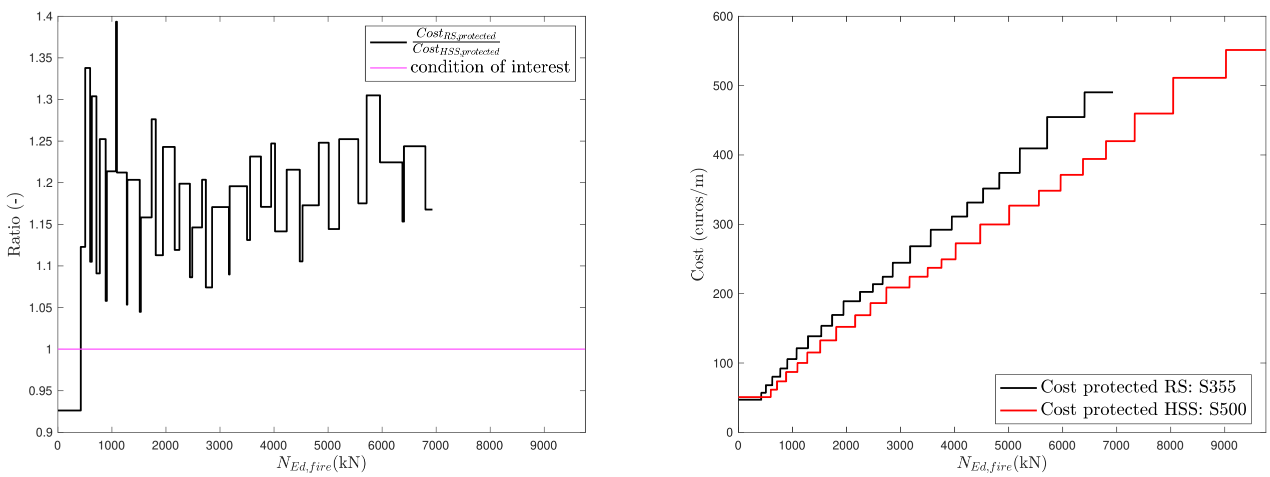
Figure 3.20: Protected tensioned members: detailed costs for S500 grade with HEB product range

As shown in Figure 3.20, the HEB range will have an increasing total cost with increasing profiles in the range whereas in the case of the HEA range in Figure 3.16, the evolution of the total cost of the profiles will have a zone where bigger profiles in the catalogue will have a lower price as explained in Section 3.3.2. Given the increasing evolution of the total cost, the cost plateau area identified in the study case will not appear and so, the areas of non-interest relating to this plateau will not appear as shown in Figure 3.19(b). Thus, the cost of the paint will have less influence on the total cost than for the HEA range and will therefore increase the areas of interest for the HSS grade.

Exposed faces

When the number of exposed faces is changed in the protected case, the results are different than in the unprotected case due to the introduction of the protection.

A first observation comes from the maximum resistance which is decreased with a number of 3 exposed faces instead of 4. This observation is opposed to the results for an unprotected element as described in Section 3.2.3. When the element is protected on these 4 faces, the imposed temperature will be 500 °C whereas it will be 570 °C for 3 exposed faces. A unique factor for all the profiles of the considered range will defined based on these two temperatures. As already mentioned, the higher the temperature, the more the strength of the profile is degraded. Indeed, the yield strength reduction factor is 0.78 for 4 exposed faces and 0.563 for 3 exposed faces. Thus, an element exposed on its 3 faces will have a lower strength as the strength degradation will be higher. This can be confirmed on the basis of the values in Table A.4 for 4 exposed faces and Table A.5 for 3 exposed faces. The domain of interest will therefore be smaller for 3 exposed faces as confirmed by Figures 3.21(a) and 3.15(a).



(a) Condition of interest

(b) Cost evolution

Figure 3.21: Protected tensioned members: 3 faces exposed

When the element is protected, the 30 minutes temperature of the steel will be similar for all profiles and the thickness of the protection will vary to reach this temperature for each profile in the range. For 3 exposed faces, the required thickness of the HEA range used for the case study is given by Table 2.3. The thickness can be considered constant for any profile in the range in the case of 3 exposed faces. This was not the case when the 4 faces were exposed, which will considerably modify the areas of interest. Indeed, the parameter that will influence the results is the thickness of the necessary coating which will directly influence the total cost as explained in Section 2.4.2.

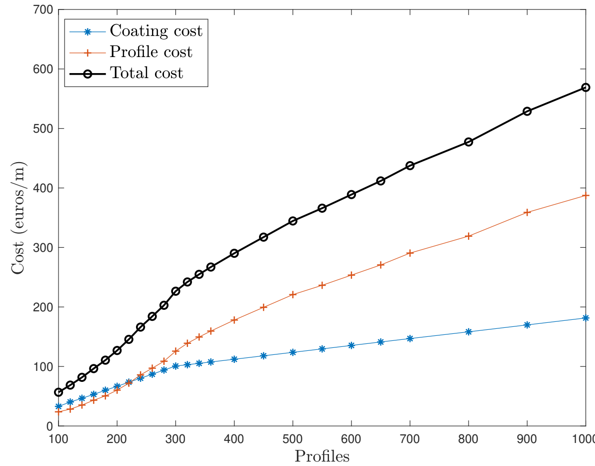


Figure 3.22: Protected tensioned members: detailed costs for S500 grade with 3 faces exposed

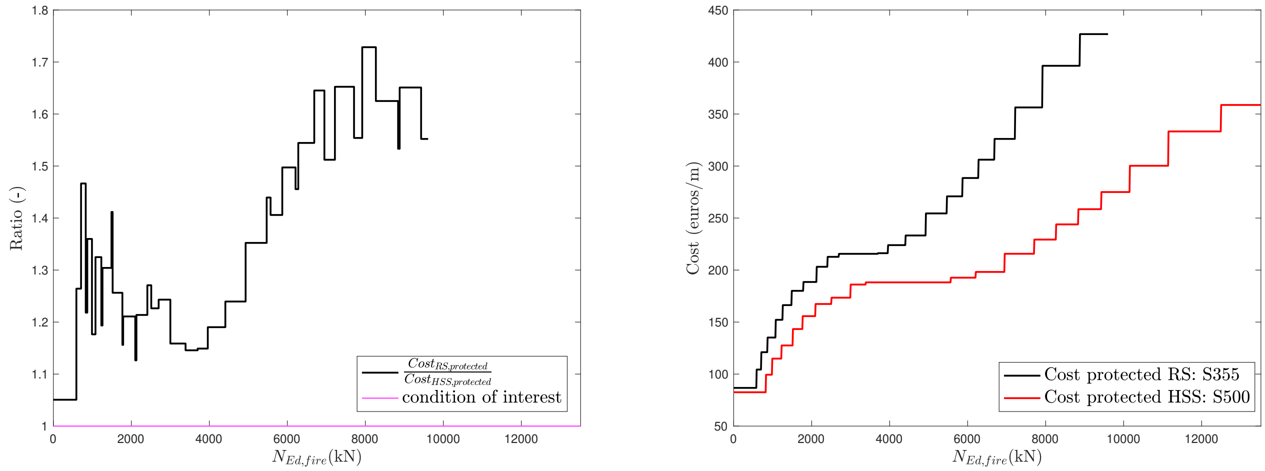
On the basis of Figure 3.22, it can be seen that the evolution of the total cost is increasing for all the profiles in the range. This is due to the two components of the total cost which are both increasing, it was not the case for an element exposed on its 4 faces. Given the increasing evolution of the total cost, no cost plateau will appear in Figure 3.21(b) which will therefore not generate the large area of non-interest linked to this plateau (plateau explained in Section 3.3.2).

Steel price

As explained in Section 2.4.1, the price of steel for the grade of steel under consideration will depend on the cost of S355 steel as well as the relative cost of the grade under consideration compared to the RS grade (S355). Therefore, the variable is the cost of S355 steel. The price of S355 steel will vary to determine the impact of this price on the results. A pre-crisis value of 0.8 €/kg and a high value of 1.6 €/kg will be studied in addition to the value of 1.2 €/kg corresponding to the current value in the middle of the economic crisis.

In the case of a protected tensile member, the steel price for a grade S355 is required in order to compute the cost ratio between the designs for the RS grade and the HSS grade which corresponds to the condition 2.8 by taking the cost computation from Equation 2.17.

As shown in Figure 3.23, when the price of steel for a RS grade is lower, there will be more interest in using the HSS grade. Indeed, this can be justified by the fact that it will be more interesting to take a more massive profile requiring a lower protection because of the high price of the intumescent paint. As a reminder, when the value was 1.2 €/kg, the cost difference was between 5 and 30% and areas of non-interest appeared. With 0.8 €/kg the difference increases and is between 5 and 70% and there is no more zone of no interest of the HSS grade.

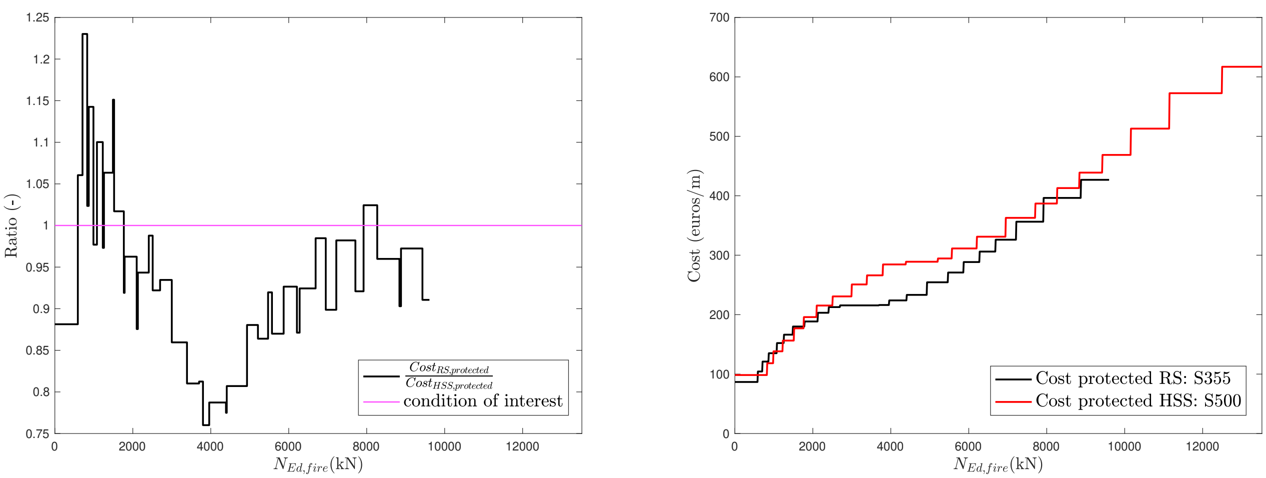


(a) Condition of interest of HSS

(b) Cost evolution

Figure 3.23: Protected tensioned members: steel price=0.8 €/kg

As shown in Figure 3.24, when the steel price for a RS grade is increased, the interest of the HSS grade will decrease. This is because the steel price will dominate the total price and therefore it will be more interesting to take a less massive profile with a higher protection. This leads to a reduction in the areas of interest of the HSS grade.

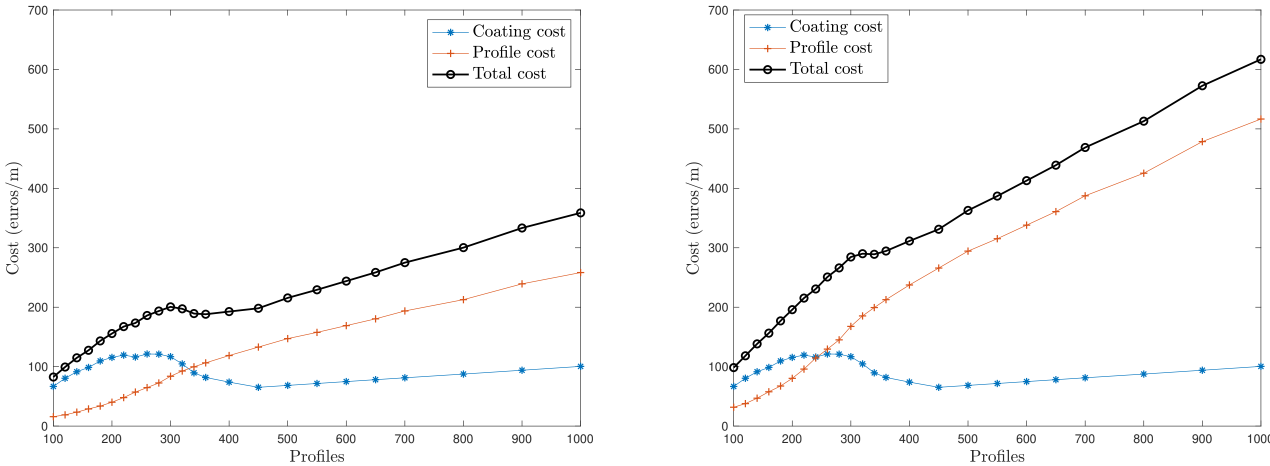


(a) Condition of interest of HSS

(b) Cost evolution

Figure 3.24: Protected tensioned members: steel price=1.6 €/kg

Figure 3.25 shows that when the price of steel is low, the total price for a chosen profile will initially be dominated by the price of paint and then by the price of steel for end of range profiles. In the case where the price is increased, the profile price will follow the general trend of the profile cost and thus dominate it.



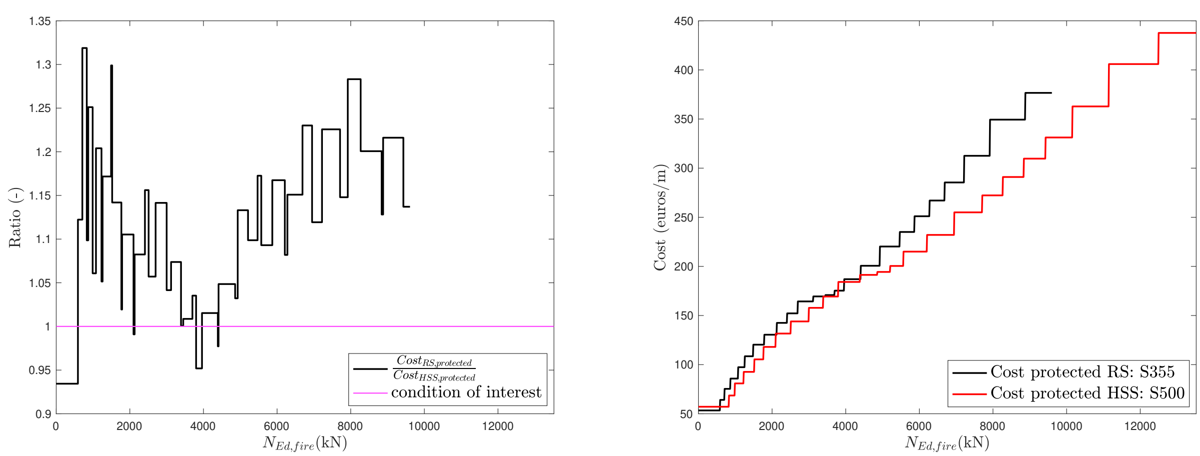
(a) steel price=0.8 €/kg

(b) steel price=1.6 €/kg

Figure 3.25: Protected tensioned members: detailed costs for S500 grade depending on the steel price

Amplification factor

As mentioned in Section 3.3, the paint cost will have a negative influence on the domain of interest of HSS steels as it will generate a considerable area of non-interest in the middle of the domain of interest. This section will focus on the amplification factor which is involved in the intumescent coating price and has been defined as equal to 10 for the case study. The case study will be used with an amplification factor of the intumescent coating price of 5, 10 and 15. The results are shown in Figures 3.26, 3.15 and 3.27 respectively. As a reminder, when the factor is 10, an extended zone of non-interest of HSS appears from 3000 kN to 4830 kN, it is precisely this zone that will be studied in this sensitivity analysis of the amplification factor.

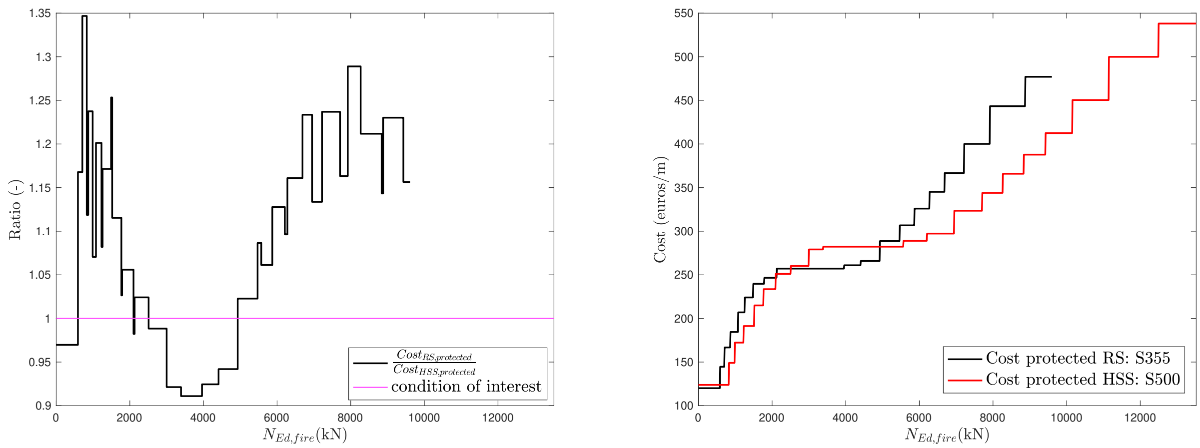


(a) Condition of interest of HSS

(b) Cost evolution

Figure 3.26: Protected tensioned members: amplification factor = 5

As Figure 3.26(a) shows, with an amplification factor of 5, the large area of non-interest for an amplification factor of 10 will be drastically reduced. This is because the plateau in the cost curves (Figure 3.26(b)) will disappear with a low factor. As shown in Figure 3.28(a), the price of the intumescent paint will decrease and the price of the required profile will dominate over the price of the paint. Thus, the total cost will increase with the increase of the considered profile of the product range.

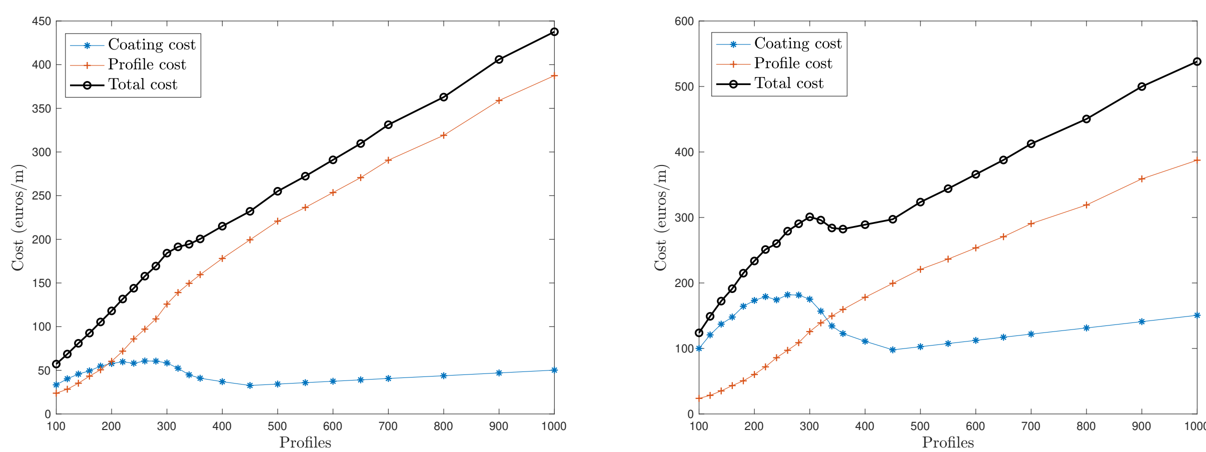


(a) Condition of interest of HSS

(b) Cost evolution

Figure 3.27: Protected tensioned members: amplification factor = 15

If the amplification factor is 15, the zone of no interest will be larger and will extend from 2540 kN to 4930 kN as shown in Figure 3.27(a). This area will increase due to the expansion of the plateau zone in the cost evolution curves. This can be explained on the basis of Figure 3.28(b). Indeed, the higher the amplification factor, the higher the cost of the paint which will dominate the overall cost. The figure shows that the total cost of the HEA 260, HEA 280, HEA 300, HEA 320 and HEA 340 protected profiles is higher than the total cost of the HEA 360 protected profile. Therefore, these profiles will not be chosen for the optimal profile selection and will generate the bigger plateau. As the amplification factor increases, the number of profiles not used in the selection of the optimal profile will increase and so will the plateau.



(a) Amplification factor=5

(b) Amplification factor=15

Figure 3.28: Protected tensioned members: detailed costs for S500 depending on the amplification factor

In conclusion, the raising cost of the intumescent coating will increase the non-interest areas of the HSS as the price of the paint will dominate the total cost. Around the area of the cost plateau, it will be more profitable to use a profile with the RS grade and use higher profiles from the catalogue than to use lower profiles that require more protection.

3.3.4 Conclusion

The introduction of the protection will induce a large zone of non-interest in the study case. This area is linked to a plateau in the evolution of costs due to the paint cost which will dominate the profile cost and create areas of non-interest not existing in the unprotected case. As in the unprotected case, fire conditions will degrade the strength of the profiles.

The main conclusions regarding the economic value of protected tension members under fire conditions are listed below:

- The lower the η_{fire} value is, the lower the fire load applied for the same applied load N_{Ed}. It will thus be more advantageous to have a low η_{fire} in order to obtain a lower fire load for the considered N_{Ed}.
- Higher grade leads to higher fire resistance and thus increases the area of interest of the HSS grade. In addition, the higher the grade, the smaller the areas of non-interest.
- In the protected case only two product ranges are considered: the HEA range and the HEB range. The HEB range achieves a higher maximum strength and therefore a wider domain of interest. The HEB range will have a greater economic interest area of HSS steel compared to the HEA range due to the higher coating cost for less massive profiles; the cost plateau induced by the price of paint will not appear. Thus, the cost of the paint will have less influence on the total cost than for the HEA range and will therefore increase the areas of interest for the HSS grade.
- When the number of exposed faces is changed in the protected case, the results are different than in the unprotected case due to the introduction of the protection. When the element is protected on these 4 faces, the imposed temperature will be 500 °C whereas it will be 570 °C for 3 exposed faces. Thus, an element exposed on its 3 faces will have a lower strength as the strength degradation will be higher. The domain of interest will be smaller for 3 exposed faces. For 3 exposed faces, the required thickness of the HEA range is constant for any profile and no cost plateau will appear which will therefore not generate the large area of non-interest existing for the 4 faces exposure.
- When the price of S355 steel is lower, there will be more interest in using the HSS grade. When the S355 steel price is increased, the interest of the HSS grade will decrease. This is because the steel price will dominate the total price and therefore it will be more interesting to take a less massive profile with a higher protection.
- With a lower amplification factor of the intumescent paint the large non-interest area for an amplification factor of 10 will be drastically reduced. The raising cost of the intumescent coating will increase the non-interest areas of the HSS as the price of the paint will dominate the total cost. Around the area of the cost plateau, it will be more profitable to use a profile with the RS grade and use higher profiles from the catalogue than to use lower profiles that require more protection.

3.4 Optimal solutions at elevated temperature

This section will focus on the determination of optimal solutions taking into account various parameters. The main objective of this section is to have a first global overview of the impact of the different parameters.

3.4.1 Optimal solution: unprotected and protected

The objective of this section is to compare the different protected and unprotected solutions for the considered case study and thus to be able to determine the optimal solution according to the applied fire load. This section will compare Section 3.2 for an unprotected tensioned element with Section 3.3 for a protected tensioned element to determine the optimal solution between a protected or unprotected tensioned element of grade RS or HSS.

Firstly, the case study including the unprotected and protected results will be presented. Then, a decision support method will be developed in order to help the user to determine the optimal solution for given applied load and length, and thus choose whether the element will be protected or not and whether the grade is RS or HSS.

Case study results

The results of this section will consider the unprotected study case of Section 3.2.1 and the protected study case of Section 3.3.1. The evolution of the cost curves is shown in Figure 3.29 and the solutions considered are: unprotected RS and HSS as well as protected RS and HSS. The optimal solution for a fire load $N_{Ed,fire}$ will correspond to the solution with the lowest cost, i.e. the lowest cost curve.

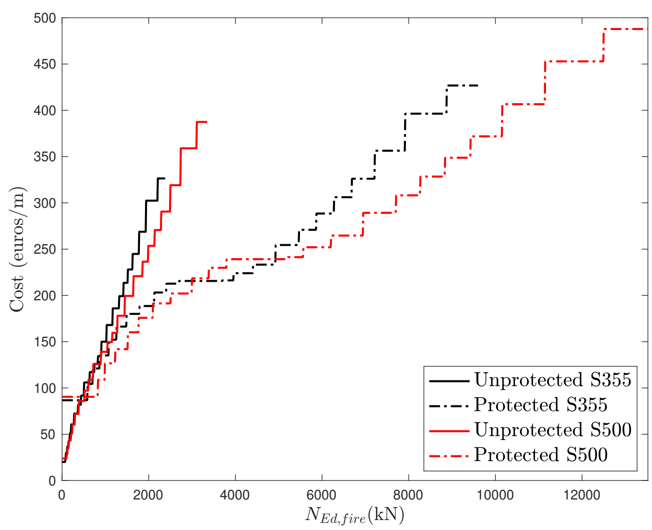


Figure 3.29: Case study for the optimal solution protected or unprotected in tension: cost evolution

A first observation based on Figure 3.29 is that the protection will allow to reach significantly higher fire loads than those reached without protection. This is also reflected in the fire resistance tables A.2 and A.4. This increase in profile strength is related to the lower temperature of 500 degrees after 30 minutes than in the unprotected case. Therefore, an unprotected member will have a stronger degradation of its mechanical properties.

On the basis of this figure, it is possible to determine load intervals defining an optimal solution among the 4 solutions studied. This will be done in Table 3.4.

Fire load interval [kN]	Protected?	Grade
0-75	NO	RS
75-160	NO	HSS
160-170	NO	RS
170-380	NO	HSS
380-433	NO	RS
433-513	NO	HSS
513-587	YES	RS
587-2099	YES	HSS
2099-2126	YES	RS
2126-2997	YES	HSS
2997-4928	YES	RS
4928-13520	YES	HSS

Table 3.4: Case study for the optimal solution protected or unprotected in tension: optimal solution results

The interest of using paint is clearly demonstrated in Table 3.4. Above a fire load of 513 kN, the optimal solution will be protected. Moreover, the clear benefit of HSS steels can be highlighted. Indeed, the HSS grade (S500) is mainly preferred in the domain, whether protected or not. This is due to the fact that the use of an HSS grade will increase the resistance and allow higher fire loads to be achieved for the same profile. The gain in resistance will therefore sufficiently outweigh the cost of using the HSS grade compared to the RS grade.

When the first profile (HEA 100) is protected, the price will be governed by the cost of the paint, which will quadruple the cost compared to the unprotected HEA 100 profile. Indeed, the unprotected HEA 100 profile for the RS grade is 20 € whereas it is 86.72 € for the same protected profile. It is therefore obvious that as long as the cost of the unprotected profiles does not exceed the protected cost of the first profile, protection will not be necessary, which corresponds to a fire load of 513 kN. In the case of the RS grade, it will be necessary to reach the HEA 260 profile before there is any interest in protection, whereas for the HSS grade, it will be the HEA 240 profile.

Method for determining the optimal solution

The method developed in this section is intended to help the user to determine which solution is optimal for a given load and length considering an element that is either protected or unprotected and either RS or HSS grade. In order to better understand how this routine can be used to determine the optimal solution, an example will be used to explain the procedure.

First, the routine will ask series of questions in order to define the situation the user wants to study. These questions are given in Figure 3.30.

```
Which applied load ?
1: Applied load at ambient temperature (Ned)
2: Applied load at elevated temperature (Ned,fire)
1
Enter the design value of the corresponding actions for normal temperature design (Ned in kN)
1500
Enter the value of the reduction factor for the design load level for the fire situation between 0.1 and 0.75
0.65
Enter the length of the member (in m)
3.5
Which product range do you want to study the economical interest?
1: HEA
2: HEB
1
Which high strength steel grade do you want to consider?
1: S420
2: S460
3: S500
4: S550
5: S620
6: S690
3
How many exposed faces to the fire ?
3: 3 faces exposed
4: 4 faces exposed
4
Enter the value of the step of the design actions for the fire situation en kN
1
```

Figure 3.30: Questions asked by the routine for the given tensioned example

The applied load can be an ambient load N_{Ed} with the corresponding factor η_{fire} or a fire load $N_{Ed,fire}$. The different questions asked by the routine will also give the limitations of this routine. Indeed, this routine can only be used for the HEA and HEB ranges of profiles, as the information of the painting cost of Section 2.4.2 is only provided for these ranges.

This routine will provide both graphical and numerical results to the user. The graphical output of the routine in Figure 3.31 represents the costs of the different solutions for the defined length as a function of the fire load. The chosen fire load is represented by the blue vertical line.

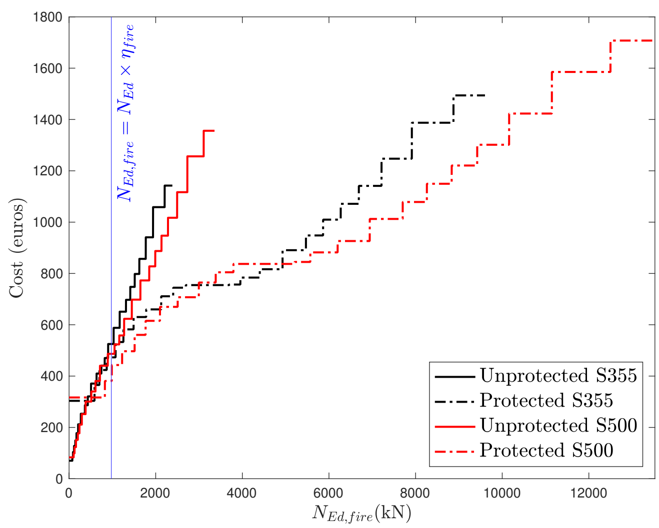


Figure 3.31: Optimal solution: protected or unprotected for the given tensioned example

In addition to this graph, this decision support tool will provide numerical results shown in Figure 3.32. The routine will thus output the most suitable solution, protected or not and RS or HSS grade, as well as the required profile for the defined load and length.

```
The cheapest solution for the given length and applied load is: Protected S500
The needed profile is: HEA120
```

Figure 3.32: Responses of the routine for the given tensioned example

3.4.2 Optimal solution: grades and product ranges

In this section, all the grades and ranges considered in this work will be compared to obtain the optimum profile, its grade and product range for a given length and fire load. The objective is to determine the economic interest of the grades and ranges. This section will therefore be a first attempt to take into account all the parameters by studying the protected and unprotected cases separately.

In this section, the graphical representation using red and green colours respecting the condition 2.8 will be used because of the large amount of information that prevents the use of the representations introduced in this work.

Unprotected members

In the case of an unprotected tension member, the economic interest of using HSS steels is shown in Figure 3.33 considering the 6 profile ranges and the 7 grades in the length range and fire load range considered. The end of the domain represented in this figure corresponds to the last profile of the HD range for a grade S690 which has a fire resistance of 114 174 kN for an element with 4 exposed faces as shown in Table A.2.

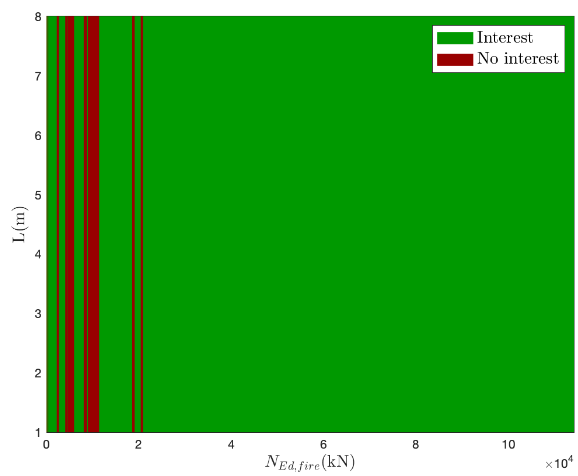


Figure 3.33: Unprotected member in tension: interest of HSS for the optimal solution

Based on Figure 3.33, it can be concluded that the economic interest of using an HSS grade for an unprotected element in tension is real. Indeed, above 20 000 kN, there will always be an interest in using HSS steels which will correspond to the HD product range which can reach much higher fire resistances than others product ranges. Before this value, the field is composed of zones of non-interest.

In order to clarify the results, the fire load range considered will be reduced to 0 to 5000 kN. This can be done because above this value, only the HD profile range will be considered as the optimal profile range. Thus, Figure 3.34 represents the optimum range of profiles and grade in the length range considered and the reduced fire load range considered. This figure will allow the definition of areas where certain ranges or grades are more suitable than others:

- HEAA: This HEAA range will be mainly preferred in the 0 - 200 kN range. The reason for the beginning of this range is that the strength of the first profile in the HEAA range for a RS grade has not yet been reached.
- HEA and HEB: These two ranges will be used in the 0 - 200 kN range. However, this area will not be mainly characterized by the use of these two ranges but by the HEAA range.
- HEC: This HEC range will be used in the 200 - 420 kN range. Then, in the range of 420 - 1360 kN, this range will be used partially.
- HEM: This HEM range will be used in the 420 - 1360 kN range together with the HEC range. Then, the 1360 - 4080 kN area will exclusively use the HEM range of profiles.
- HD: This HD range will be used in the range 4080 - 114174 kN.

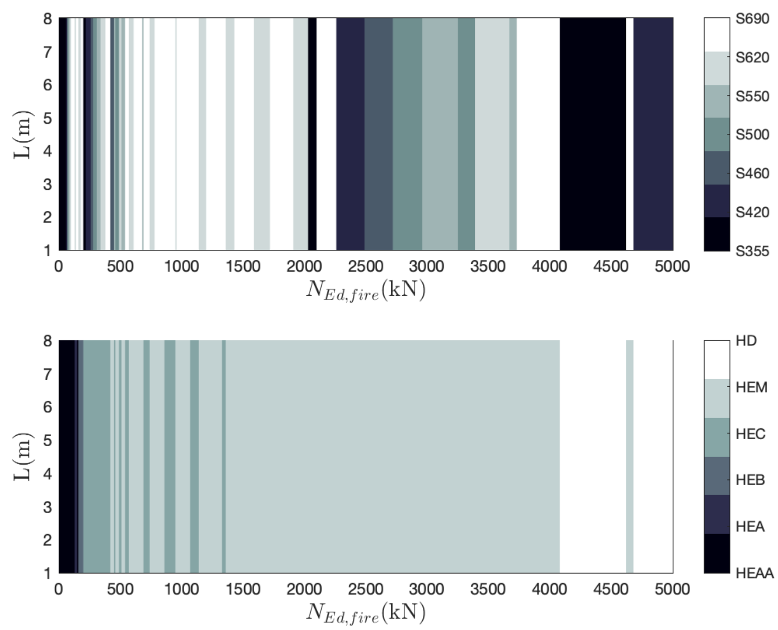


Figure 3.34: Unprotected member in tension: optimum product range and grade

By comparing the different ranges, it seems that the HEAA, HEA and HEB ranges are not to be preferred except for very low loads and that it is preferable to use the HEC, HEM and HD ranges. This can be explained by the high section factors for the HEAA, HEA and HEB ranges. This leads to a higher temperature of the steel at 30 minutes and therefore to a lower yield strength reduction factor which gives a higher strength degradation. This was already supported by Table 3.3 which showed that these ranges had a maximum reduction factor of about 0.2 whereas for the HEC, HEM and HD ranges the maximum value was 0.27, 0.41 and 1 respectively. Thus, these ranges are less fire-susceptible due to their greater mass than the HEAA, HEA and HEB ranges.

A further interesting observation can be drawn from these figures concerning the selection of the optimum grade. Indeed, for some fire loads, it is better to use another range of profiles with the RS grade than to use a certain range with an HSS grade. This brings complexity to the results. These graphs are therefore intended to help the reader to choose the most suitable grade and range for a given fire load and length.

Protected members

In the case of a protected tension member, the area of interest for HSS steels is almost the whole domain as shown in Figure 3.35 considering the 2 profile ranges (HEA and HEB) and the 7 grades in the length range and fire load range considered. The end of the domain represented in this figure corresponds to the last profile of the HEB range for a grade S690 which has a fire resistance of 21 528 kN for an element with 4 exposed faces as shown in Table A.4.

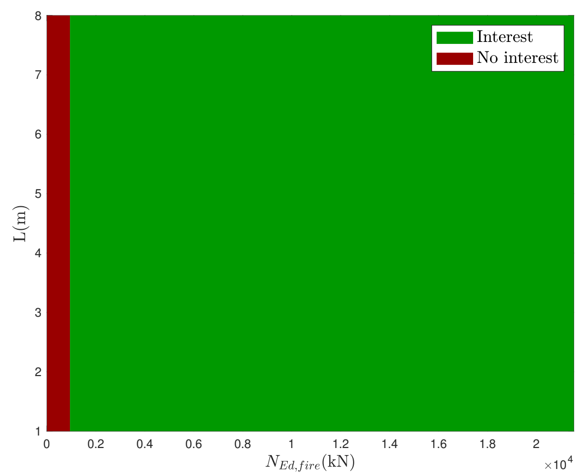


Figure 3.35: Protected member in tension: interest of HSS for the optimal solution

The price of the paint governs the results when the element is protected. As explained in Section 3.3.3, the profile range HEB will have a price that is less governed by the paint price as the protection required will be lower than for the HEA range which is less massive than the HEB range. Therefore, the HEB range will have a lower cost than the HEA range which explains why the area of interest is mainly an area where the optimum profile range is the HEB range as shown in Figure 3.36.

Furthermore, the unique zone of non-interest is at the beginning of the domain as shown in Figure 3.35. This zone corresponds to an area where the cost of the protected HEB profile for the RS grade is lower than the HEA range cost with the RS or HSS grade and also lower than the HEB range cost with the HSS grade. This is due to the range of profiles. In fact, for the HEB range, less paint is required and since the paint governs the price, the overall price is lower. Beyond this zone of no interest, there will always be interest in using an HSS grade.

Figure 3.36 also shows that high HSS grades such as S620 and S690 will be considered optimal. This can be justified by the fact that the price of the paint will govern the total cost. Therefore, it will be more interesting to increase the grade of steel than to change profiles and thus have a larger surface to protect leading to an increasing paint cost.

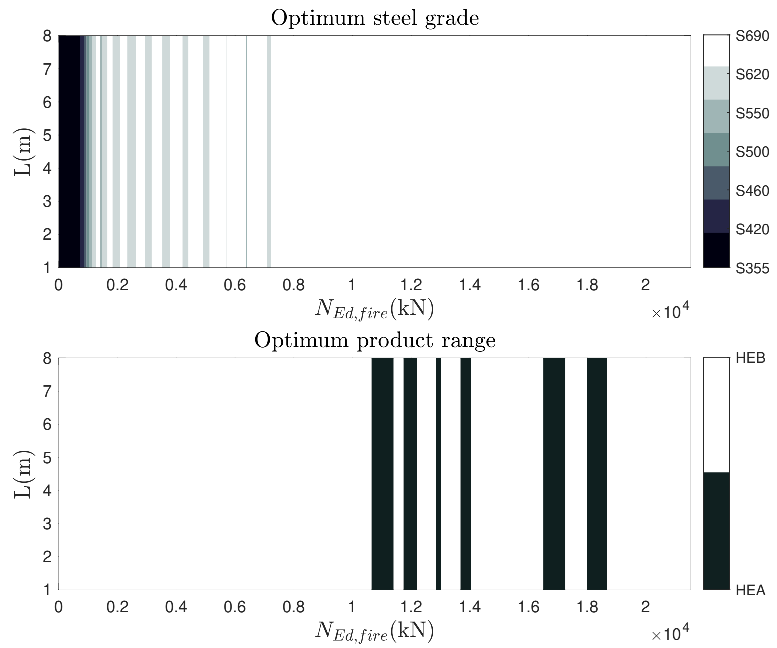


Figure 3.36: Protected member in tension: optimum product range and grade

3.4.3 Conclusion

The first optimal solution studied compared a protected or unprotected tensioned element of RS or HSS grade. A case study and a method allowing the user to determine the optimal solution for a given load and length were developed and can be summarised as follows:

- The protection will allow to reach significantly higher fire loads than those reached without protection because an unprotected member will have a stronger degradation of its mechanical properties. The case study clearly demonstrate the interest of using intumescent coating and a HSS grade. In addition, as long as the cost of the unprotected profiles does not exceed the protected cost of the first profile, protection will not be necessary.

- The method for determining the optimal solution is intended to help the user to determine which solution is optimal for a given load and length considering an element that is either protected or unprotected and either RS or HSS grade. This routine will provide both graphical and numerical results to the user. This decision support tool will output the most suitable solution, protected or not and RS or HSS grade, as well as the required profile for the defined load and length.

The second optimal solution studied compared all the grades and ranges considered for a unprotected element as well as for a protected element. It can be summarised as follows:

- In the case of an unprotected tension member, there is an important area of economic interest for HSS grade. By comparing the different ranges, it seems that the HEAA, HEA and HEB ranges are not to be preferred except for very low loads and that it is preferable to use the HEC, HEM and HD ranges. Indeed, the HEAA, HEA and HEB ranges of profiles will be less massive and consequently more fire-susceptible. It is therefore more interesting to use ranges that are less fire-susceptible and hence will have a lower degradation of the steel's mechanical properties.

- In the case of a protected tension member, the area of interest for HSS steels is almost the whole domain where the optimum profile range is the HEB range. This product range requires less painting as the profiles are more massive and since the paint governs the price, the overall price is lower. Therefore, it will be more interesting to increase the grade of steel by using a HSS grade than to change profiles and thus have a larger surface to protect leading to an increasing paint cost.

This optimal solution study brings complexity to the results. These graphs are therefore intended to help the reader to choose the most suitable grade and range for a given fire load and length. It is therefore a first attempt to take into account all the parameters.

4 Economical analysis: compression member

In this section, the economic interest of high yield strength steels in protected and unprotected compression members will be investigated. Modifications will be gradually introduced to understand the results better. As explained in Figure 2.1, all of these results will be given for a comparison between RS and HSS grades for a defined profile range.

A compressed member will take into account the instability of flexural buckling which will reduce the strength of the member. The use of high yield strength grades will allow the use of smaller cross-sections for the same load as the standard S355 grade. The interest of HSS grades should decrease as these elements will be more slender and therefore less resistant due to instabilities. The behaviour of the results is now influenced by the length of the column, which is logical since instabilities are now taken into account.

First, the results at ambient temperature [24] for a specific case study as well as the conclusions drawn from the sensitivity analysis will be summarized. Next, the fire conditions will be introduced with an unprotected element. The case study and the sensitivity study of the parameters will be developed and explained in detail. The same will be done for a protected element.

Then, the protected and unprotected case will be combined in a section that will study a specific case and will also provide an economic evaluation method to obtain the optimal solution. This method will allow the user to choose which solution (RS or HSS, unprotected or protected) is the cheapest and which profile to use for a given load.

Finally, an additional optimal solution study will be carried out. This will be done independently for the protected and unprotected elements, but all the ranges and grades considered will be combined. The objective will be to have a first overview of the optimal ranges and grades.

The designs are iterative processes progressing through the profile catalogue in order to determine the optimum profile for the length of the column and for the fire load considered. It should be noted that at each iteration the self-weight of the running profile is taken into account.

4.1 Ambient temperatures

The results in this section are based on the thesis studying the economic interest of HSS for steel structures [24]. The resistance of compressed members will be governed by their cross-sectional resistance depending on the grade considered and the instability of flexural buckling will be considered. The serviceability limit states are not considered.

The results are based on the design procedure for a member in compression only of Eurocode 3 part 1-1 [11]. The European buckling curves considered are those of the new version of Eurocode 3 part 1-1 [20] since the buckling curves are defined for steel grades up to S700.

4.1.1 Case study definition

In this section, the case study considered is the following:

- Grades: comparison between a RS S355 grade and an HSS S500 grade

- Profile range: HEA profile range
- Steel price for S355 grade: 1.2 €/kg
- Support conditions: Pinned ends
- Buckling axis: Strong axis

4.1.2 Case study results

The results of interest of the HSS grade for the study case defined in Section 4.1.1 for a compressed element at elevated temperature are given in Figure 4.1.

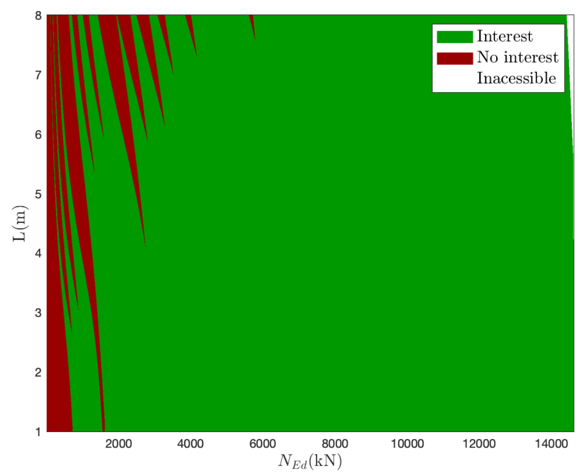
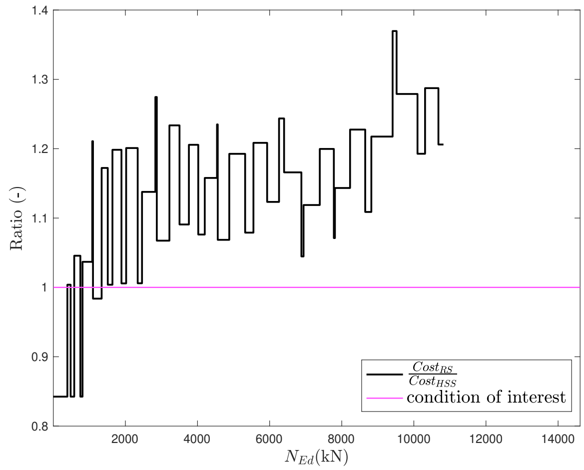


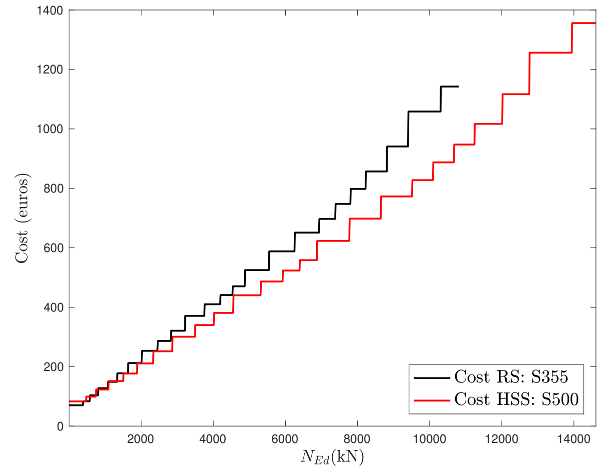
Figure 4.1: Case study for compressed members at ambient temperature: interest of HSS

As with the tension members, there is no point in switching to S500 until the resistance of the first RS steel section is reached. Then, for the rest of the field, the offsets between the European buckling curves for RS steel and HSS steel and the condition 2.10 lead to the areas of economic interest observed.

In order to compare the results, the cold results will be studied for the specific length of 3.5m corresponding to a column height considered as "standard" in multi-storey buildings. Figure 4.2 shows that for a length of 3.5m, the economic interest of the HSS grade is clear above 2000 kN. The cost of the HSS grade is 5 to 30% lower than the cost of the RS grade above 2000 kN.



(a) Condition of interest



(b) Cost evolution

Figure 4.2: Case study for compressed members at ambient temperature: L=3.5m

4.1.3 Key conclusions

The major conclusions drawn in the work [24] for elements in compression at ambient temperature are the following:

- The consideration of instabilities such as flexural buckling is detrimental to the interest of HSS steels because the more slender the element, the less interest there is in using the HSS grade. In fact, the gain in material generated by the change from RS to HSS is lower than in tension, since the greater the slenderness, the more equal the required cross-section is, regardless of the grade considered.

- The higher the yield strength of the HSS grade, the greater the relative cost compared to the RS grade and therefore the smaller the area in which the use of the HSS grade makes economic sense, as the additional cost is not compensated by the increased strength.

- Profile ranges such as HEM or HD in HSS steel are likely to be of greater interest. Indeed, due to their greater mass, they will be able to resist greater levels of loading.

- The smaller the buckling coefficient K, the greater the benefit of the HSS grade compared to the RS grade. In other words, the greater the risk of instability, the less likely it is that the use of HSS steel will be economically attractive because of the higher slenderness.

- The consideration of instabilities along the weak axis has a negative effect on the interest of HSS grades.

4.2 Unprotected member at elevated temperature

This section will investigate the economic interest of HSS for an unprotected compressed element subjected to fire. This section is based on the flowchart in Figure 2.6.

When a member is in compression, it is necessary to consider the flexural buckling instability as well as the fire conditions that will reduce the strength of the member. Under fire conditions, buckling will be more detrimental than at ambient temperature as the slenderness of the member will be higher to consider the degradation of the mechanical properties at high temperatures. In addition, a specific buckling curve will be used in these conditions and this will not have a horizontal plateau unlike in ambient conditions.

4.2.1 Case study definition

In this section, the case study considered is the following:

- Grades: comparison between a RS S355 grade and a HSS S500 grade
- Profile range: HEA profile range
- Number of exposed faces: 4 faces
- Steel price for S355 grade: 1.2 €/kg
- Support conditions: Pinned ends
- Buckling axis: Strong axis

4.2.2 Case study results

The results of the study case defined in Section 4.2.1 are obtained in Figure 4.3 for the entire length interval.

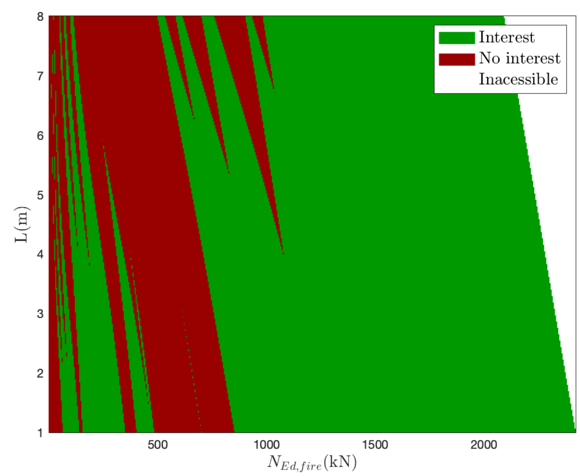
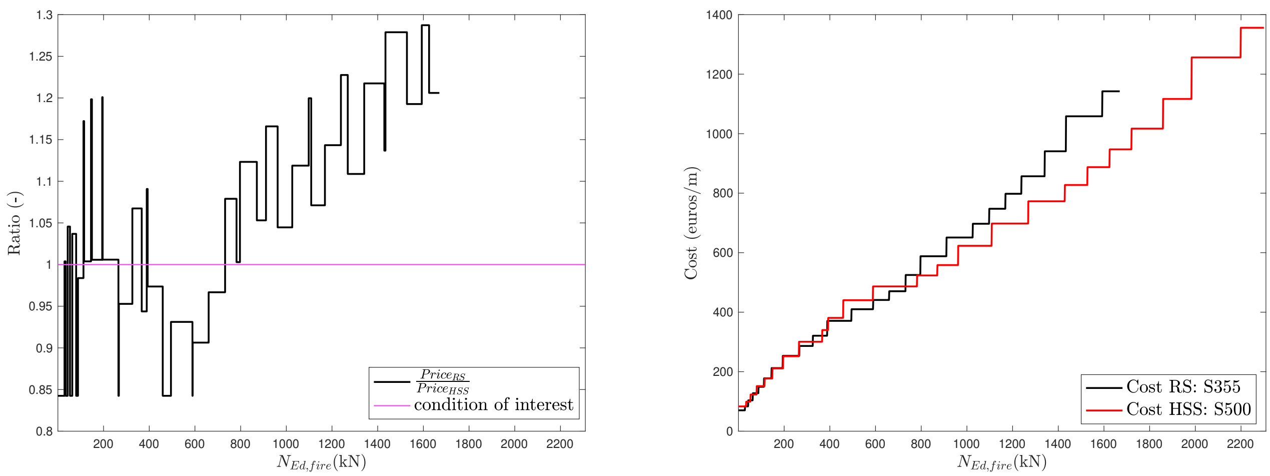


Figure 4.3: Case study for unprotected compressed members for all length: interest of HSS

Firstly, as with the tensioned elements and the ambient temperature case, there is no point in switching to S500 until the strength of the first RS steel section is reached. In a similar way to the pure tensile elements, an analysis of the number of profiles of difference between the two designs of the two grades compared can be carried out to understand the origin of the zones of non-interest in red on Figure 4.3 which are zones not respecting the condition 2.8. In section 3.2, a detailed analysis of the different zones of non-interest has been carried out for an unprotected tensioned element. In this section, this analysis will be considered as known and only the principle will be re-explained in the Appendix C.

In the rest of the section, a length of 3.5m will be used to study the results of the economic interest of HSS. The reason for choosing this value is that it corresponds to a height that can be described as standard for a compressed column in a building. This defined length will also allow to study the presence of the large red zone of non interest starting around a value of 500 kN for a length of 1m as shown in Figure 4.3. Thus, for further investigation of the interest of the HSS grade, the results for the 3.5m length are shown in Figure 4.4.



(a) Condition of interest HSS

(b) Cost Evaluation

Figure 4.4: Case study for unprotected compressed members, L=3.5m

On the basis of Figure 4.4, it can be seen that the interest of the HSS grade is limited below 800 kN. Indeed, although the condition 2.8 is respected in some places, the difference between the two costs is of the order of 1 to 5 % which is low.

Secondly, it is interesting to consider the origin of the large zone of HSS irrelevance that appears in the fire condition when it was not visible at ambient temperature. This zone can be identified in Figure 4.4(a) and is approximately between a fire load of 300 kN and 800 kN. Its origin lies in the classification of sections which becomes more severe by introducing fire conditions.

In this work, the classification of sections comes from the future version of Eurocode 3 part 1-1 [20] with the consideration of fire conditions through the use of a modified ϵ called ϵ_{fire} which is defined as such in the future Eurocode 3 part 1-2 [21]:

$$\epsilon_{fi} = 0.85\sqrt{\frac{235}{f_y}}$$

The ϵ_{fi} will have a reduction coefficient of 0.85 to take into account the degradation of the mechanical properties of the steel due to high temperatures. The grade considered will also have an impact on the cross-section classification. Indeed, the higher the grade, the lower the ϵ_{fi} and therefore the stricter the classification. For the two grades considered in this case study, the values of ϵ_{fi} are the following:

- For the RS grade:

$$\epsilon_{fi,RS} = 0.6916$$

- For the HSS grade:

$$\epsilon_{fi,HSS} = 0.5827$$

To determine whether a compressed part is Class 4, the following conditions must be checked:

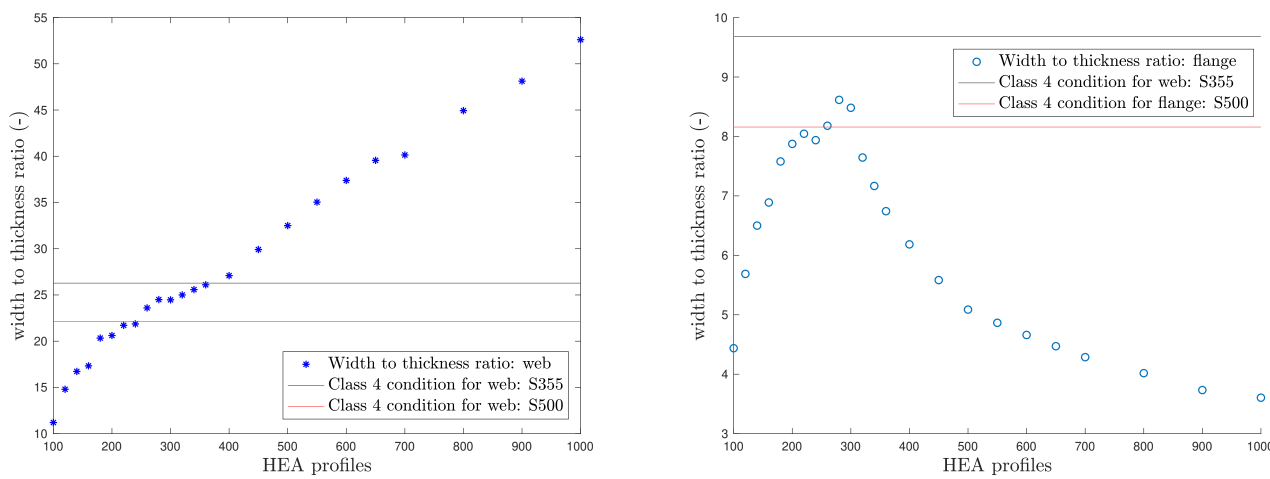
- For the compressed web, the Class 4 condition is as follows:

$$d/t_w \geq 38\epsilon_{fi}$$

- For compressed flanges, the Class 4 condition is as follows:

$$c/t_f \geq 14\epsilon_{fi}$$

Figure 4.5 will represent these two conditions for all the profiles in the HEA range. The profile is Class 4 for a given grade when the point representing the width to thickness ratio is above the condition represented in red for the HSS grade and in black for the RS grade.



(a) Class 4 condition: web

(b) Class 4 condition: flange

Figure 4.5: Case study for unprotected compressed members, L=3.5m: cross-section classification

In the case of the webs shown in Figure 4.5(a), there is more Class 4 for the HSS grade than for the RS grade. In the case of the flanges shown in Figure 4.5(b), there is no Class 4 for the RS grade whereas there is for the HSS grade. The two graphs in Figure 4.5 show that the higher the grade, the higher the number of Class 4 compressed elements. When ambient temperature conditions are considered, the lines corresponding to the conditions will be shifted upwards which will reduce the number of Class 4 compressed elements.

In order to determine the class of the cross-section, the worst class of the compressed elements is taken: the web and the flanges. It is thus possible to obtain Table 4.1 containing the classes of the profiles of the HEA range according to the RS grade or the HSS grade. This table confirms that an HSS grade will have more Class 4 sections.

HEA	S355	S500
Class 1	100,120	100
Class 2	140,160	120
Class 3	180,200,220,240,260,280,300,320,340,360	140,160,180,200,220,240
Class 4	400,450,500,550,600,700,800,900,1000	260,280,300,320,340,360,400,450,500,550,600,700,800,900,1000

Table 4.1: Case study for unprotected compressed members, L=3.5m: cross-section classification

When a cross-section is Class 4, it will use an effective reduced section A_{eff} to take into account the plate buckling behaviour by using effective widths.

$$A_{eff} = \beta_A \times A \tag{4.1}$$

Where β_A is 1 for Class 1,2 and 3 cross-sections and for a Class 4 $\beta_A < 1$. This reduction factor will take into account the reduction in cross-section related to plate buckling behaviour and will be represented in Figure 4.6.

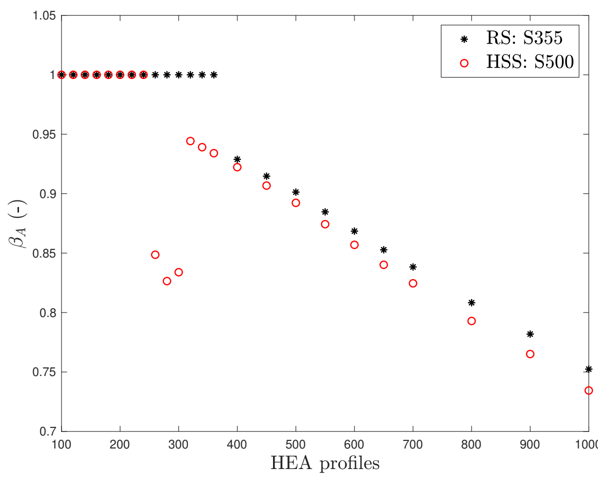


Figure 4.6: Case study for unprotected compressed members, L=3.5m: β_A

As shown in Figure 4.6, for the HSS grade, the HEA 260, HEA 280 and HEA 300 profiles will have a β_A value between 0.85 and 0.8. This low value is due to the fact that both the web and the flanges will buckle. Thus, the cross-sectional area will be more strongly reduced than if only the web was buckled. The resistance is proportional to the effective area, so a smaller β_A will result in a smaller cross-sectional area and therefore a lower fire resistance.

In Figure 4.7, the compressive fire resistance is given for each profile in the HEA range for the specific conditions of the unprotected case study and for the RS grade and the HSS grade. In the first profiles of the range up to HEA 300, the strengths for the RS and HSS grades are very close. Therefore, it is logical that the RS grade will be preferred as the small gain in strength will not justify the additional cost of the HSS grade. For HEA 260, HEA 280 and HEA 300, the small difference in strength is due to the fact that the cross-sections are Class 4 for the HSS grade and Class 3 for the RS grade. The impact of the effective cross-section is therefore significant and will generate a large area of non-interest between a fire load of $N_{Ed,fire}$ of 367 kN and 732 kN.

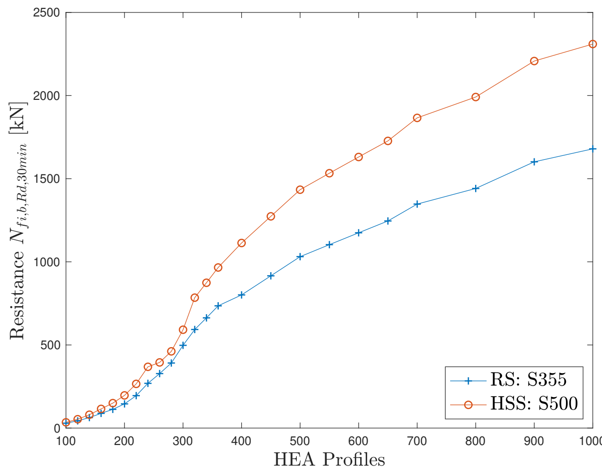


Figure 4.7: Case study for unprotected compressed members, L=3.5m: resistances

In conclusion, the zone of no interest is related to the later appearance of a Class 4 cross-section for a RS grade than for an HSS grade. A Class 4 cross-section will have a reduced effective cross-sectional area A_{eff} which will reduce the total compressive fire strength of the cross-section.

The detailed procedure for determining the cross-sectional class and the effective cross-sectional area is given in the Appendix B - 2. This appendix studies a specific case: the HEA 300 profile for the RS grade and the HEA 280 profile for the HSS grade in the case study. In addition, this example allows a better understanding of the values of β_A and to verify the values in Figure 4.6.

4.2.3 Sensitivity analysis of parameters

In this parameter sensitivity analysis section, tables of fire and ambient temperature compression strengths defined in Appendix A will be used. The ambient temperature resistances are represented in Table A.6 and will be used to compare it with the resistances at high temperatures.

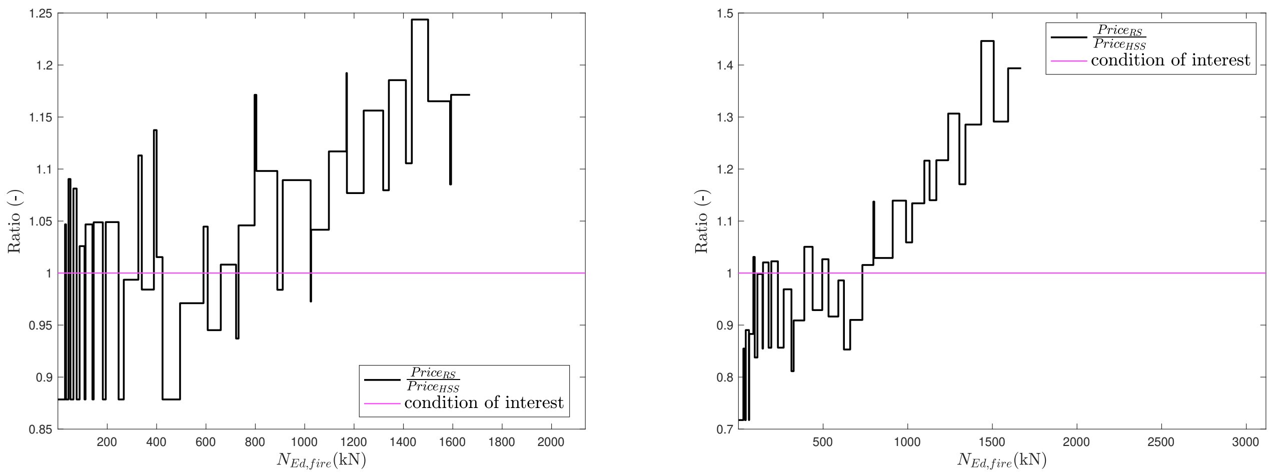
This section will focus on the influence of key parameters of this work: the reduction factor for the design load level for the fire situation η_{fire}, the grades, the profiles ranges, the length, the support conditions, the buckling axis, the exposed faces and the S355 steel price. In this parametric study, the case study will be kept and each parameter will be varied individually, i.e. only one parameter will be varied at a time.

Reduction factor η_{fire}

The lower the η_{fire} value is, the lower the fire load applied for the same applied load N_{Ed}. It will thus be more advantageous to have a low η_{fire} in order to obtain a lower fire load for the considered N_{Ed}. The impact of this reduction factor will be discussed in Section 5 which will aim to determine which design, at ambient or elevated temperature, will govern the optimal profile choice.

Grades

The results for grades S460 and S690 will be studied to determine the influence of the chosen HSS grade on the results. These are shown in Figure 4.8.



(a) Condition of interest for S460

(b) Condition of interest for S690

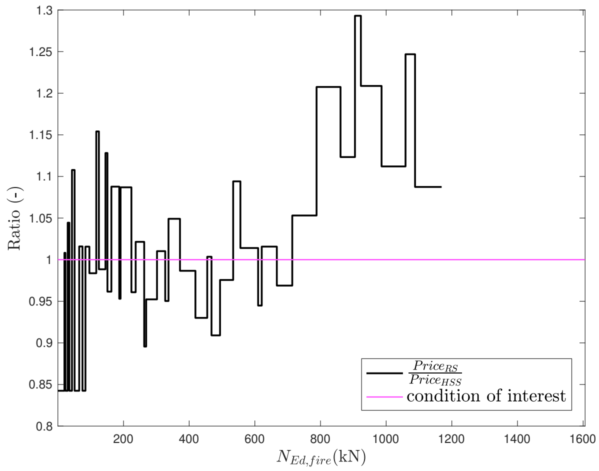
Figure 4.8: Unprotected compressed members, L=3.5m: Grades

Firstly, the same observation can be made as in tension (Section 3.2.3). As the yield strength increases, the areas with a single gap profile are no longer of economic interest (relative to the 2.10 condition). In other words, the higher the HSS grade, the higher the relative cost of the HSS grades and therefore the less economic interest there is in the single gap profile areas. The area where the use of the HSS grade makes economic sense is restricted to the early part of the load range. However, the use of a higher HSS grade will allow higher strengths to be achieved which will extend the load range accessible by a profile range.

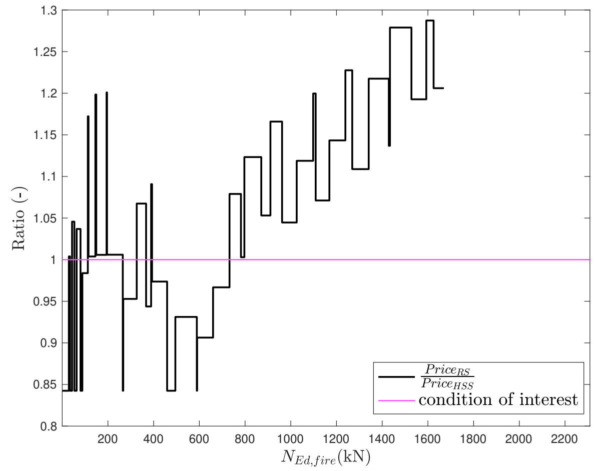
Another observation based on Figure 4.8 can be drawn and differs from the tension case. When introducing compression, the cross-section classification and the slenderness of the element must be taken into account. Indeed, the section classification will become more severe as the grade considered increases and there will be more Class 4 cross-sections which is unfavourable for the interest of the HSS grade considered. In addition, the higher the grade, the higher the slenderness, which is also unfavourable for the HSS grade. It is for these two reasons that more zones of non-interest will appear for the S690 grade than for the S460 grade. Thus, the higher the grade, the more the use of an HSS grade will be restricted in the beginning of the load interval. However, for massive and therefore not slender profiles, the interest of the higher HSS grade is real. This can be seen at the end of the load range as the percentage cost difference is higher for the S690 grade.

Product ranges

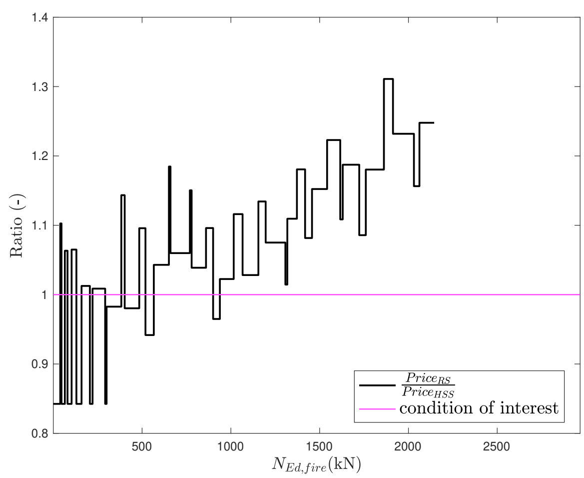
The study of the influence of the type of rolled profile used will be carried out on the basis of Figure 4.9 explaining the key differences with the tensile case of Section 3.2.3. In a similar way to the conclusions established in the section on elements in tension, the larger the cross-section of the first profile in the catalogue, the more the interest of the HSS grade is restricted at the beginning of the load range studied. Indeed, as long as the strength of the first profile in the range with grade S355 is not reached, there is no reason to switch to an HSS grade.



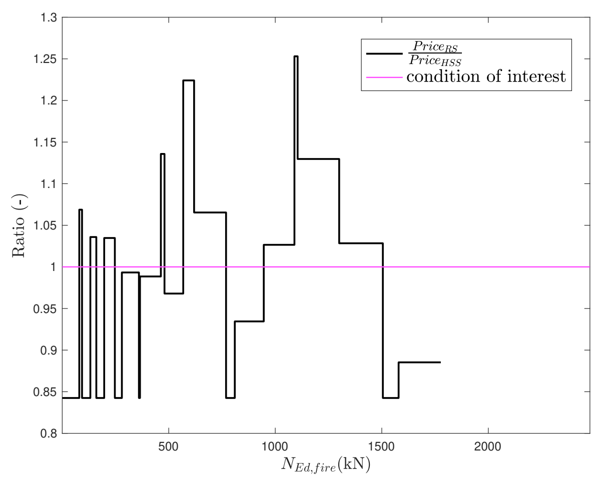
(a) HEAA



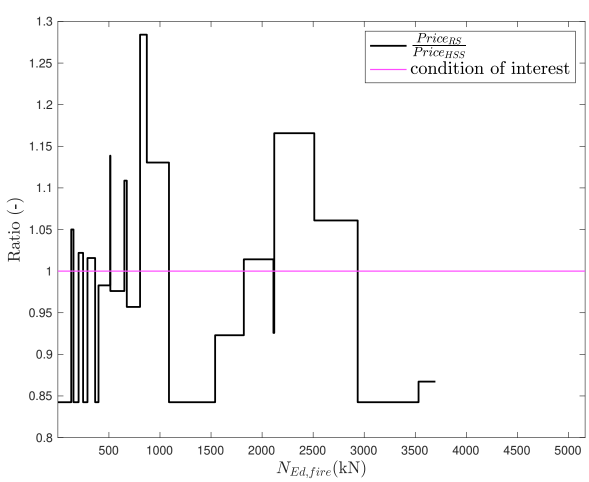
(b) HEA



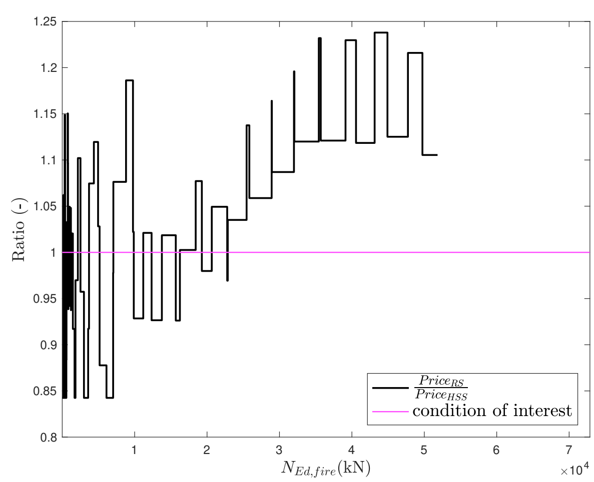
(c) HEB



(d) HEC



(e) HEM



(f) HD

Figure 4.9: Unprotected compressed members: product ranges

When the fire conditions are considered for a compressed element, the economic interest of HSS grades is reduced. However, this decrease does not impact in the same way the different studied ranges. In fact, the more massive the profiles are, the less the impact of fire will be felt in the computation of the fire resistance in compression of the element. When an element is not very massive, it will heat up faster and it will also be more slender, which is unfavourable for instabilities. Thus, the economic interest of the HSS grade for the HEAA range is rather weak since the elements will be slender and often of Class 4. Conversely, the HD range of profiles will be massive which will make it more economical to use the HSS grade as fire conditions and flexural buckling instability will have little impact on the strength of the element. For the HEB range of profiles it would appear that the use of the HSS grade is of great economic benefit compared to the HEAA and HEA ranges.

As a reminder, a profile at the beginning of the range will be less massive than a profile at the end. Thus, for the same range, it is logical that the zones of non-interest are concentrated at the beginning of the load interval, as this part will be covered by profiles from the beginning of the range and therefore less massive and more sensitive to compression and fire conditions. This is well illustrated for all ranges in Figure 4.9.

As already mentioned, the profiles in the HD range will be able to resist much higher load levels and the areas of interest for the HSS grade will be for much higher loads. In the case of the maximum strength of the HD range, the fire resistance in compression with all 4 faces of the member exposed is 100 221 kN (Table A.7) whereas it is 105 965 kN at ambient temperature (Table A.6). These two values are almost equivalent. However, the difference comes from the definition of the specific buckling curve under fire conditions which does not have a horizontal plateau. This specific buckling curve will also provide a different imperfection factor which will be higher in the case of fire conditions. There will therefore be a slight degradation in resistance due to the elevated temperature.

Length

Firstly, Figure 4.3 for the unprotected case can be used to show that the longer the length, the less interest there will be in using the HSS grade. This can be explained on the basis of the European buckling curves for RS and HSS. Indeed, depending on the grade considered, these curves will be shifted and it is this that will generate the curves in Figure 4.3. These shifts are shown in Figure 4.10 for a HEA100 profile. An essential difference with ambient temperature conditions comes from these buckling curves. Indeed, the fire conditions will have a specific buckling curve which will not have a horizontal plateau and therefore the fire resistance will always be impacted by the plate buckling.

Figure 4.10 clearly shows that the longer the length, the greater the slenderness and the more the axial fire resistance of the element becomes identical whatever the steel grade considered. This confirms that the consideration of instabilities such as flexural buckling is detrimental to the interest of HSS steels for elements with a high length, because the more slender the element, the less interest there is in using the HSS grade. In the case of the HEA 100 profile, using an HSS grade for an element length of more than 4m will not be useful.

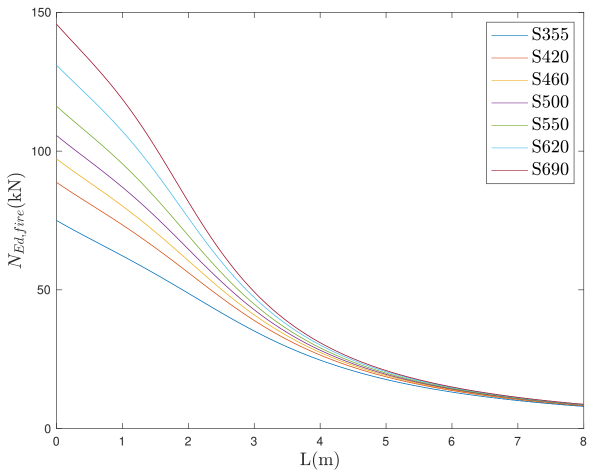
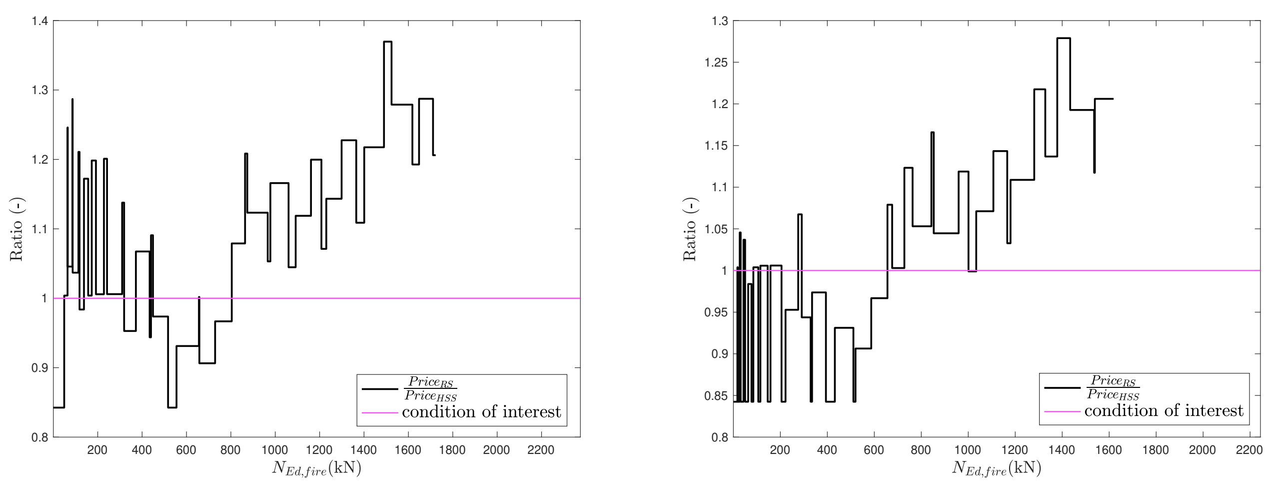


Figure 4.10: Offsets between the European buckling curves for a HEA100 profile in different grades (strong y-y axis) at elevated temperature for an unprotected member

In Figure 4.11, the condition of interest for a length of 2m and 5m is shown. When the profiles are at the end of range such as the HEA 1000 profile, the profile will be very massive and therefore the slenderness will be low which will only slightly modify the fire resistance of the profile. This explains the interest of the HSS grade at the end of the load range.

When the optimum profile is at the beginning of the range, the length will greatly influence the interest of the HSS grade as the slenderness of the profiles at the beginning of the range will be high. At the beginning of the load range, when the optimum profiles are slender, the longer the length, the more areas of non-interest will occur. This can be explained on the basis of Figure 4.10 for HEA 100. Indeed, as the length increases, the strength of the element becomes the same for all grades. Therefore, as the length increases, the cost difference between the two grades decreases as shown in Figure 4.11.



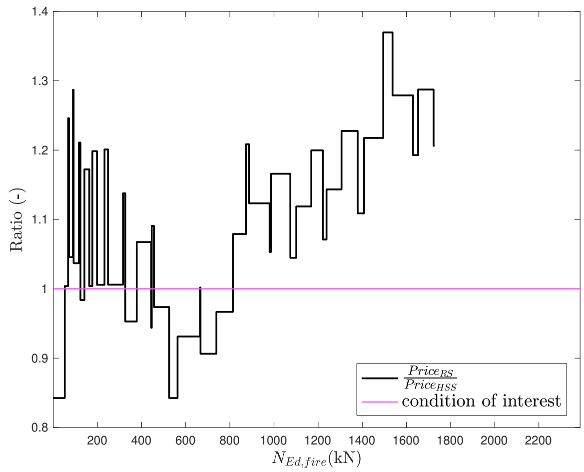
(a) L=2m

(b) L=5m

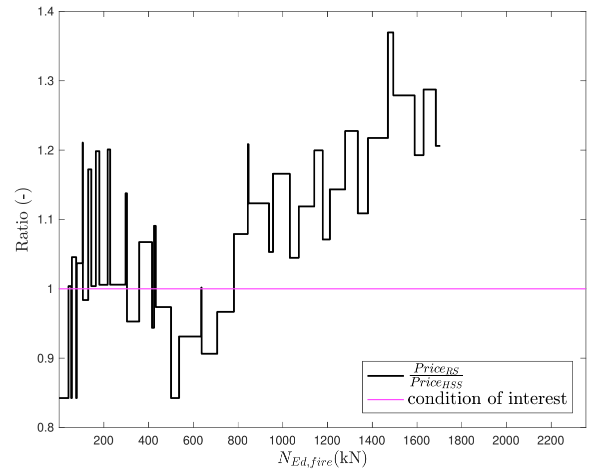
Figure 4.11: Unprotected compressed members: Length

Support conditions

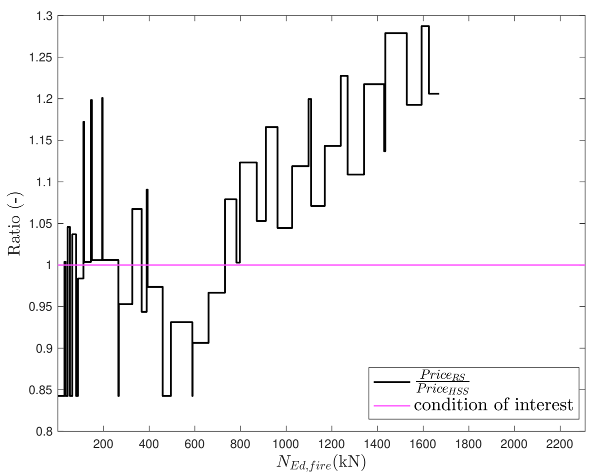
In this section, the impact of support conditions on the results will be studied. The support conditions will be translated into the buckling length coefficient K and the results for the different K's studied are given in Figure 4.12.



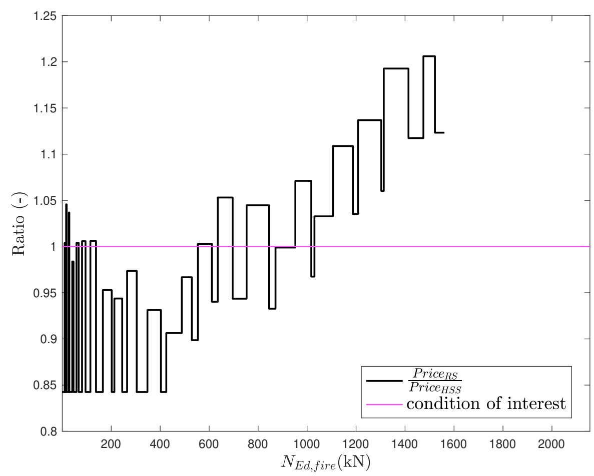
(a) K=0.5



(b) K=0.7



(c) K=1



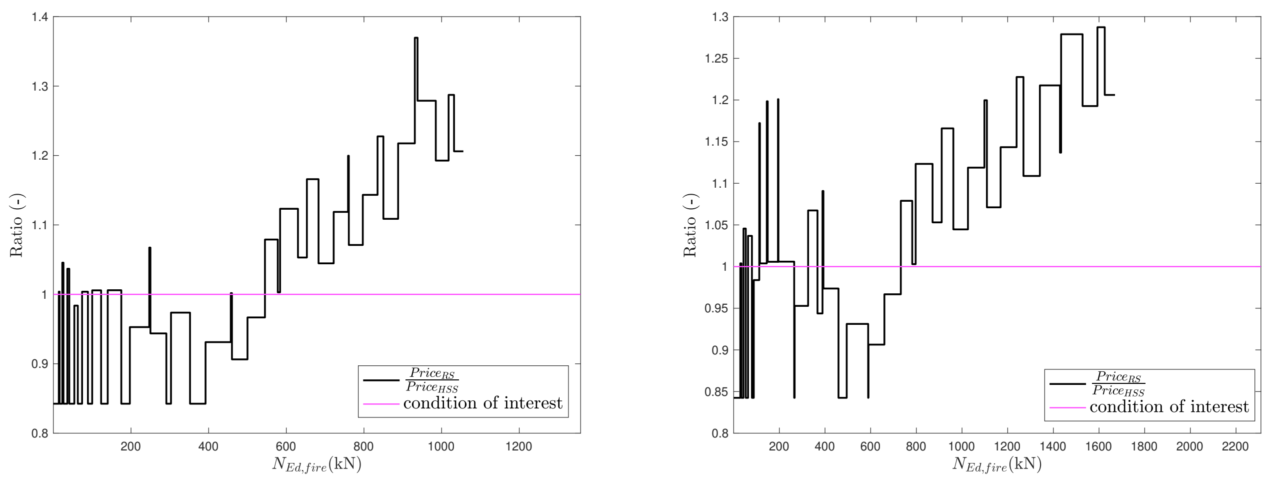
(d) K=2

Figure 4.12: Unprotected compressed members: Support conditions

The larger the K coefficient, the larger the part of the column that is susceptible to instability (flexural buckling) as the slenderness increases and, consequently, the resistance decreases. Figure 4.12 shows that as the K coefficient increases, the interest of the HSS grade compared to the RS grade decreases: the areas of non-interest increase and the difference between the cost of the grades decreases. In other words, the greater the slenderness, the less likely it is to be economically worthwhile to use HSS. In fact, the change from RS to HSS has the effect of reducing the cross-sectional area of the section required for the same applied load, but it increases the slenderness of the member and therefore the risk of buckling.

Buckling axis

So far, only strong axis buckling has been considered, considering that weak axis buckling was prevented at all times. The results obtained for the weak axis are shown in Figure 4.13.



(a) Weak buckling axis

(b) Strong buckling axis

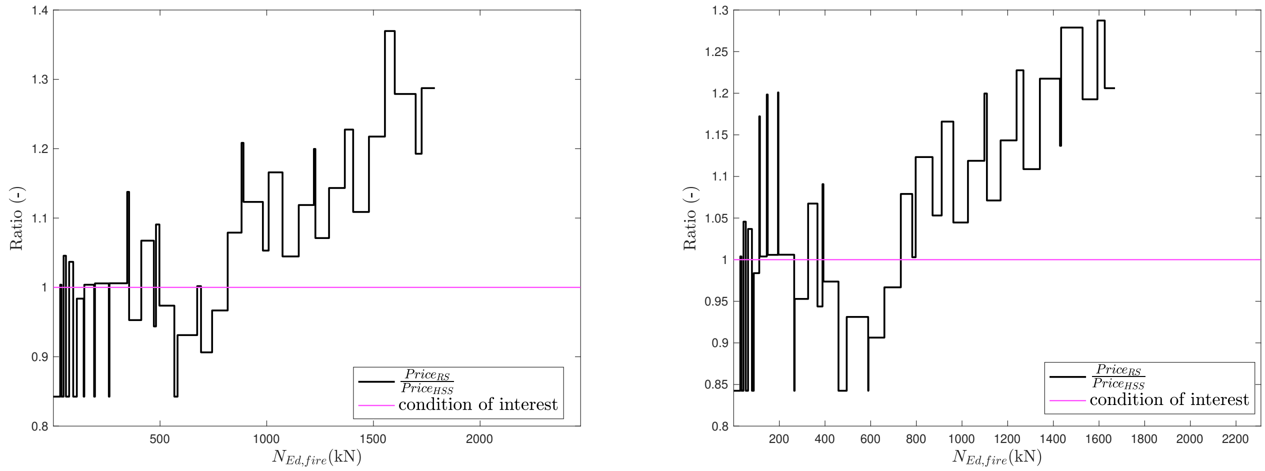
Figure 4.13: Unprotected compressed members: buckling axis

Based on Figure 4.13, it appears that there is less interest when buckling along the weak axis is not prevented. It must be noted that the strength of the various sections is less in the weak axis than in the strong axis.

Exposed faces

In Figure 4.14, the condition of interest of HSS defined by the condition 2.8 is shown for 3 and 4 exposed faces with the same conditions as the case study.

As in the case of tension, the number of exposed faces will change the temperature of the steel at 30 minutes. The temperature of the steel will decrease from a 4-sided exposed member to a 3-sided exposed member. This will result in the strength of the 3-sided sections being higher as they will be less degraded by the higher temperatures. The observations are similar to those of the unprotected tensioned element in Section 3.2.3. Therefore, when an element is exposed on 3 faces, the HSS grade will be of more interest than for an element exposed on 4 faces.



(a) Condition of interest for 3 faces exposed

(b) Condition of interest for 4 faces exposed

Figure 4.14: Unprotected compressed members: number of exposed faces

Steel price

In the results obtained for an unprotected compression member, only the cost curves will change as the price of S355 steel changes. Indeed, since the interest condition of an unprotected element can be written as represented by the condition 2.10, only the relative cost of the HSS grade compared to the RS grade will be needed for this condition. Thus, the interest condition of HSS steels will be similar whatever the price of the RS steel considered.

4.2.4 Conclusions

When the fire conditions are considered for a compressed member, the economic interest of HSS grades is reduced over in comparison to the tension results or to the compression ambient conditions. It is necessary to consider the flexural buckling instability as well as the fire conditions that will reduce the strength of the member.

Under fire conditions, buckling will be more detrimental than at ambient temperature as the slenderness of the member will be higher to consider the degradation of the mechanical properties at high temperatures. In addition, a specific buckling curve will be used in these conditions and this will not have a horizontal plateau unlike in ambient conditions. The classification of the cross-sections will be stricter when the fire conditions are considered as well as when considering a higher grade. There will be more Class 4 sections which will reduce the interest of HSS grades as the strength will be reduced due to the use of an effective cross-section. The zone of no interest is related to the later appearance of a Class 4 cross-section for a RS grade than for an HSS grade.

The main conclusions regarding the economic value of unprotected compression members under fire conditions are listed below:

- The lower the η_{fire} value is, the lower the fire load applied for the same applied load N_{Ed}. It will thus be more advantageous to have a low η_{fire} in order to obtain a lower fire load for the considered

N_{Ed}.

- As in tension, the higher the HSS grade, the higher the relative cost of the HSS grades and therefore the less economic interest there is in the beginning of the load interval. The use of a higher grade will allow higher strengths to be achieved which will extend the load range accessible by a profile range. In addition, the higher the grade, the stricter the cross-section classification and the higher the slenderness; this is detrimental to the interest of HSS grades.
- The interest in using HSS grades decreases when the range of profiles under consideration contains profiles that are not very massive and are therefore slender and susceptible to instability and fire.
- The longer the length, the greater the slenderness, the less interest there will be in using the HSS grade.
- As the buckling length coefficient K increases, the slenderness increases and the interest of the HSS grade compared to the RS grade decreases.
- There is less interest when buckling along the weak axis is considered.
- When an element is exposed on 3 faces, the HSS grade will be of more interest than for an element exposed on 4 faces.
- The interest condition of HSS steels will be similar whatever the price of the RS steel considered.

4.3 Protected member at elevated temperature

This section will investigate the economic interest of HSS for a compressed element subjected to fire and protected. This section is based on the flowchart in Figure 2.7.

With the introduction of protection, the element will have a lower temperature at 30 minutes and therefore the strength will be less degraded. However, the cost of a protected element will be higher and will be influenced by other factors such as the cost of paint and steel.

4.3.1 Case study definition

In this section, the case study considered is the following:

- Grades: comparison between a RS S355 grade and an HSS S500 grade
- Profile range: HEA profile range
- Number of exposed faces: 4 faces
- Steel price for S355 grade: 1.2 €/kg
- Amplification factor for the coating price: 10
- Support conditions: Pinned ends
- Buckling axis: Strong axis

4.3.2 Case study results

When a protected element is subjected to compression, the results of interest of the HSS grade will vary from those of the section 4.2 where the element is not protected. However, it is important to note that the finding based on the cross-section classification is the same in the protected case. The results of interest of the HSS grade for the study case with the full length interval are shown in Figure 4.15.

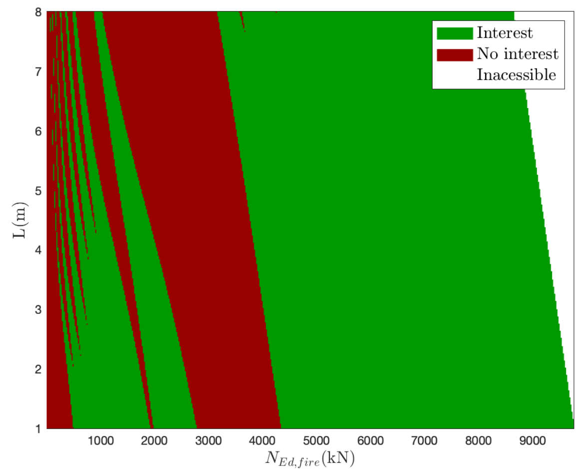
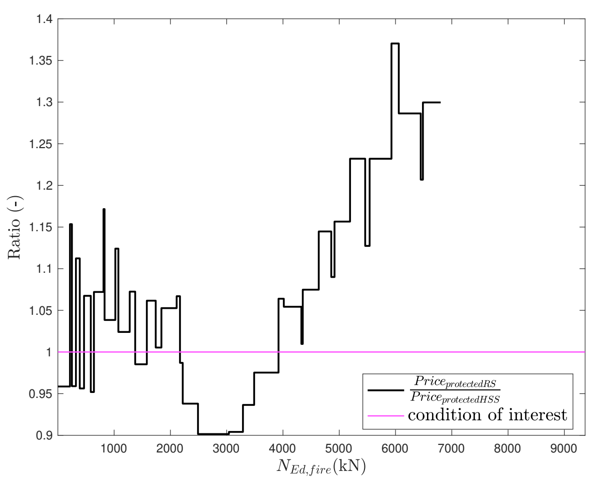
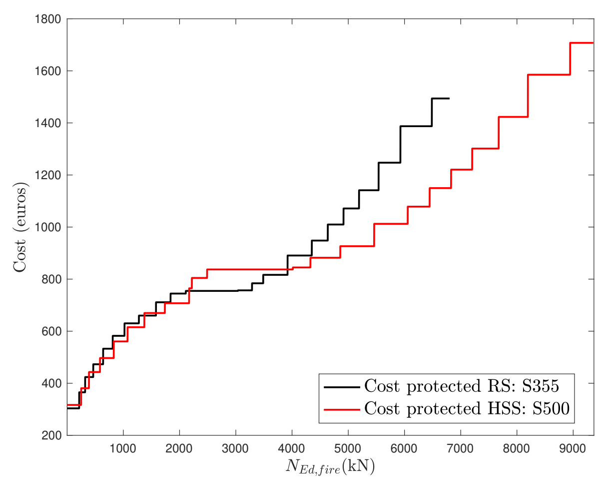


Figure 4.15: Case study for protected compressed members for all length: interest of HSS

This graph representing the zones of non-interest in red will have a similar appearance to the one of the unprotected element represented by Figure 4.3. However, a protected element will be able to achieve higher fire loads than the unprotected element. In addition, the area of non-interest is greater as the introduction of protection will result in an additional cost that will generate a plateau in cost as explained in tension in Section 3.3. In order to better understand the differences between the interest of an unprotected element (detailed in Section 4.2) and a protected element, it is interesting to use the so-called "standard" length of 3.5m. The results for this length are shown in Figure 4.16.



(a) Condition of interest



(b) Cost evolution

Figure 4.16: Case study for protected compressed members, L=3.5m

When introducing the protection, its cost must be taken into account, which will have a significant influence on the results. Indeed, when the optimal profile is chosen, it will be necessary to take a profile with a higher resistance than necessary but with a lower total cost, which will generate a large zone of non-interest in Figure 4.16(a). This zone of non-interest will have its origin in the cost plateau in Figure 4.16(b). The paint price will thus dominate the choice of profile and not the first resistant profile.

In addition, when the protection is introduced, the strength of the profiles will be increased. As already explained in Section 3.3 dealing with protected tensioned elements, the application of intumescent paint will allow the steel temperature to be reduced to 500 °C for 30 minutes for an element exposed on its 4 faces. This reduction in temperature will allow higher strengths to be achieved than in the unprotected case as the degradation of mechanical properties is smaller at lower temperatures.

In compression, the degradation of mechanical properties will be taken into account in two stages when computing the compressive fire resistance of the optimum profile for the considered grade. Firstly, the yield strength reduction factor will be higher as for a tension member. For instance, for a steel temperature of 500 °C, this factor is 0.78, whereas it is between 0.1 and 0.2 for an unprotected element, as the steel temperature fluctuates around 700 and 800 °C over the whole HEA range. Secondly, the lower temperature of the steel at 30 minutes will also affect the relative slenderness $\overline{\lambda}_\theta$ for the steel temperature at 30 minutes. Indeed, the relative slenderness will be modified to take into account the degradation of the mechanical properties linked to the high temperatures, which will result in the following equation:

$$\overline{\lambda}_\theta = \overline{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

Where $k_{y,\theta}$ is the relative slenderness at ambient temperature, $k_{y,\theta}$ is the yield strength reduction factor and $k_{E,\theta}$ is the Young's modulus reduction factor for the steel temperature θ_a. The square root of the ratio of the reduction factors will generally increase the slenderness of the element under consideration. This is shown in Figure 4.17.

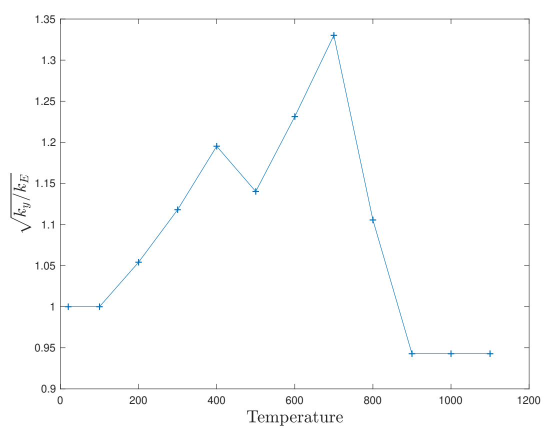


Figure 4.17: Evolution of the square root of the reduction factors ratio over the temperature

Figure 4.17 shows that for a temperature of 500 °C the slenderness is increased by 14% whereas for a temperature between 700 °C and 800 °C the slenderness is increased from 33% to 10%. It cannot be concluded that the decrease in temperature will always decrease the relative slenderness as this ratio is not increasing over all observed temperatures. Thus, the yield strength reduction factor k_y will be the parameter taking into account the temperature of the steel that will dominate the strength degradation.

Therefore, the large difference between the reduction factor k_y at 500 °C and the one for temperatures between 700 °C and 800 °C explains the high difference in resistance between the protected and unprotected case. This difference is expressed in Figure 4.16 and Tables A.7 and A.9 of Appendix A. Indeed, for a length of 3.5m, the HEA range for the HSS grade (S500) has a maximum fire resistance of 9369 kN in the protected case whereas in the unprotected case this value is 2310 kN.

4.3.3 Sensitivity analysis of parameters

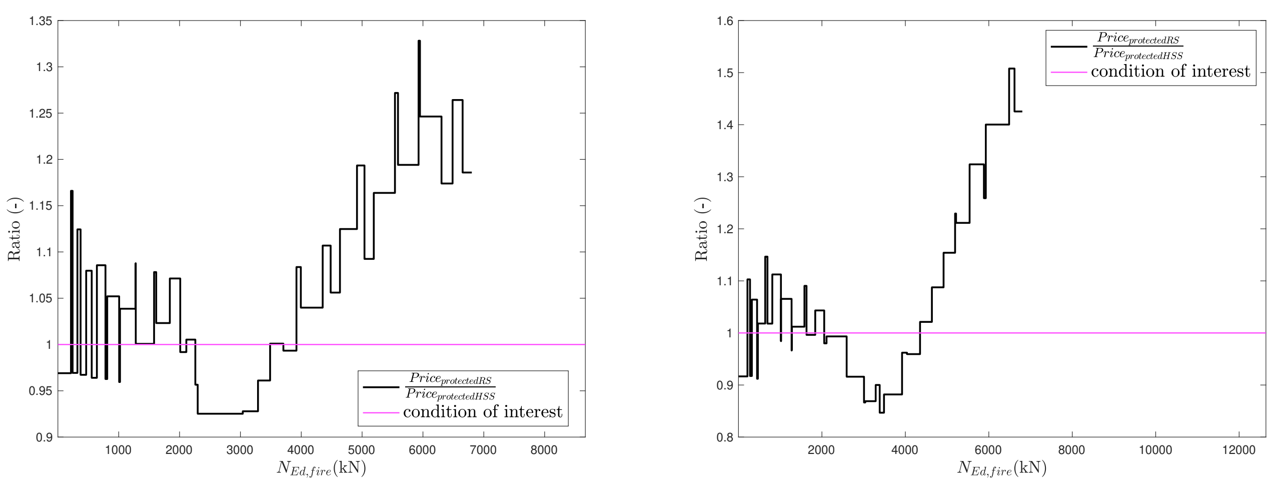
In this parameter sensitivity analysis section, tables of fire and ambient temperature compression strengths defined in Appendix A will be used. This section will focus on the influence of key parameters of this work: the reduction factor for the design load level for the fire situation η_{fire}, the grades, the profiles ranges, the length, the support conditions, the buckling axis, the exposed faces, the S355 steel price and the amplification factor of the paint price. In this parametric study, the case study will be kept and each parameter will be varied individually, i.e. only one parameter will be varied at a time.

Reduction factor η_{fire}

It will be more advantageous to have a low η_{fire} in order to obtain a lower fire load for the considered N_{Ed}. The impact of this reduction factor will be discussed in Section 5 which will aim to determine which design, at ambient or elevated temperature, will govern the optimal profile choice.

Grades

This section will investigate the influence of the chosen grade on the compression results for a protected element in Figure 4.18. The results will be similar to those in protected tension in Section 3.3.3 and so only the key observations will be highlighted.

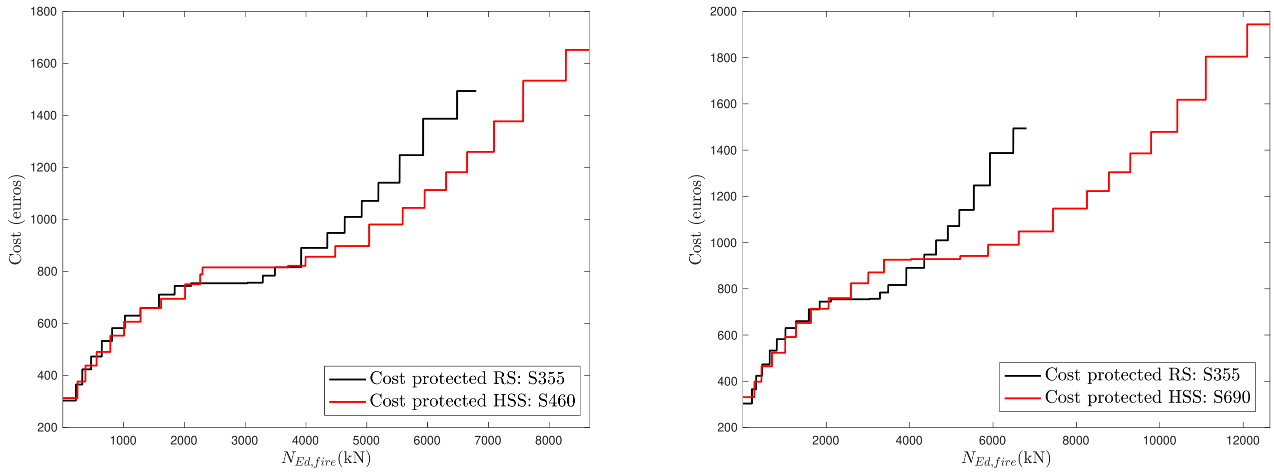


(a) Condition of interest for S460

(b) Condition of interest for S690

Figure 4.18: Protected compressed members, L=3.5m: Grades

As in tension, increasing the grade will lead to higher fire resistance and thus increase the area of interest of the HSS grade. In addition, the higher the grade, the smaller the areas of non-interest and this can be justified by the existence of a plateau in the cost curves. As the grade increases, the fire resistance of the element will increase and therefore the cost plateau will be shifted to the right as we can see in Figure 4.19. Furthermore, the higher the grade, the higher the difference between the cost curves.



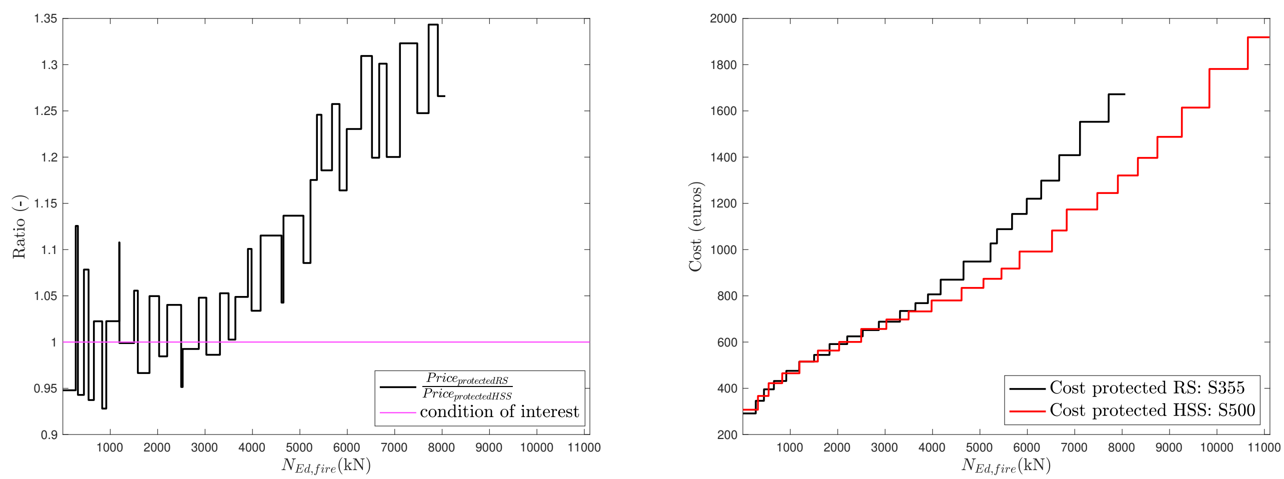
(a) Cost evolution

(b) Cost evolution

Figure 4.19: Protected compressed members, L=3.5m: Grades

Product ranges

In this section, the two ranges of profiles considered in the protected case will be compared: the HEA range and the HEB range. The conclusions will be similar to those for a tensioned element protected in Section 3.3.3.



(a) Condition of interest

(b) Cost evolution

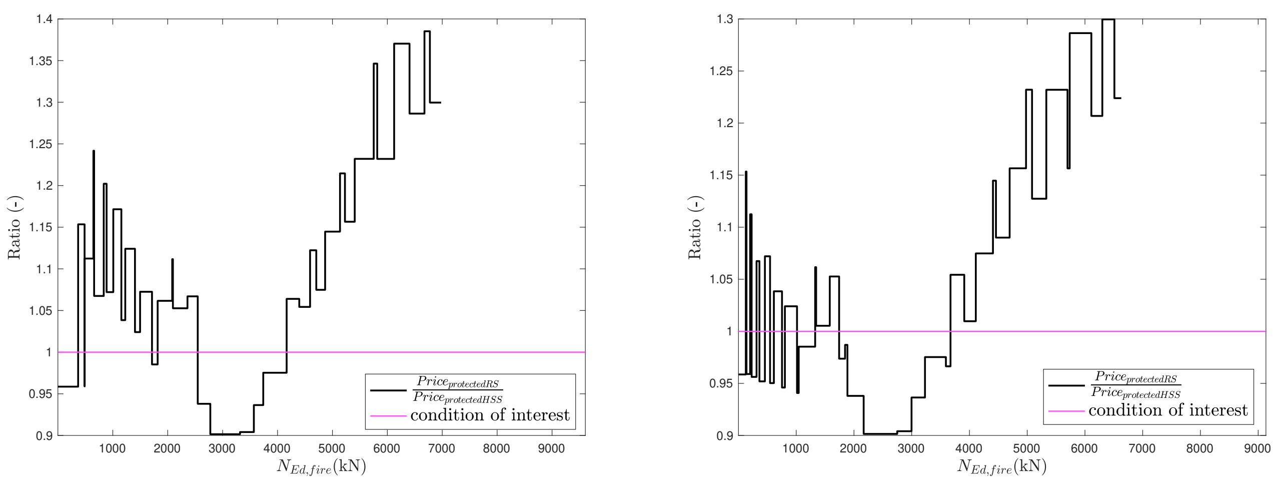
Figure 4.20: Protected compressed members, L=3.5m: HEB product range

Figure 4.20(a) shows that the HEB range will have a greater economic interest area of HSS steel compared to the HEA range which is represented in Figure 4.16(a). In addition, these two figures and Table A.9 show that the HEB range logically achieves a higher maximum strength and therefore a wider domain of interest.

As already mentionned, the areas of non-interest in the protected case will be due to the price of the paint which will strongly influence the total cost. When using the HEB range, less intumescent paint will be required to achieve a similar steel temperature than for HEA range profiles. The HEB range will have an increasing total cost with increasing profiles in the range and the cost plateau area identified in the study case will not appear. Therefore, the areas of non-interest relating to this plateau will not appear. Thus, the cost of the paint will have less influence on the total cost than for the HEA range and will increase the areas of interest for the HSS grade.

Length

As for the unprotected compressed member, the longer the length, the higher the slenderness, the less interest there will be in using the HSS grade as a result of the convergence of resistance regardless of the grade. The conclusions of the unprotected compressed element study are applicable to the protected elements which will have higher resistances as shown in Table A.9. Figure 4.15 shows the condition of interest for the entire load domain.



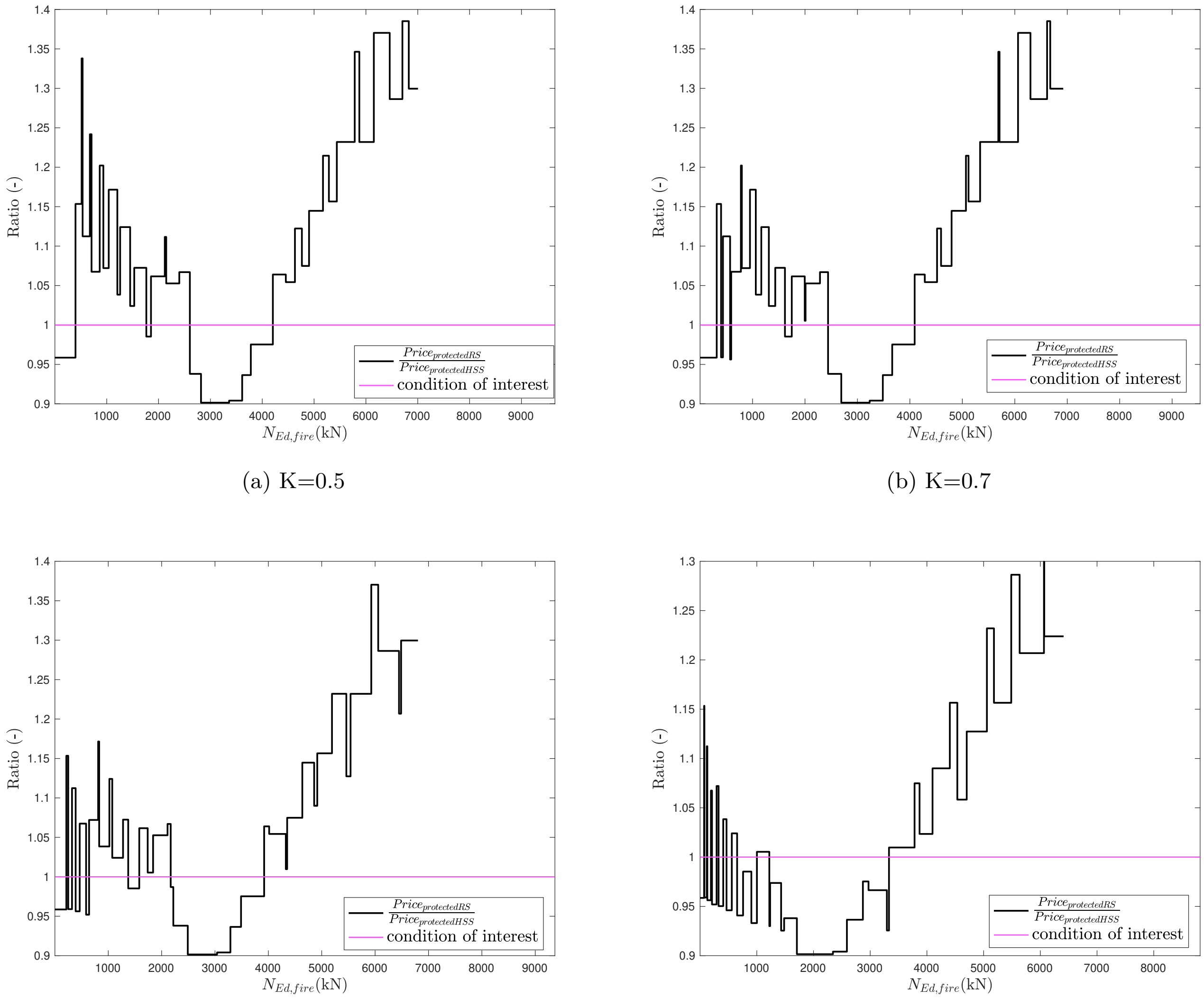
(a) L=2m

(b) L=5m

Figure 4.21: Protected compressed members: Length

Support conditions

The support conditions will be translated into the buckling length coefficient K and the results for the different K's studied are given in Figure 4.22.



(a) K=0.5

(b) K=0.7

(c) K=1

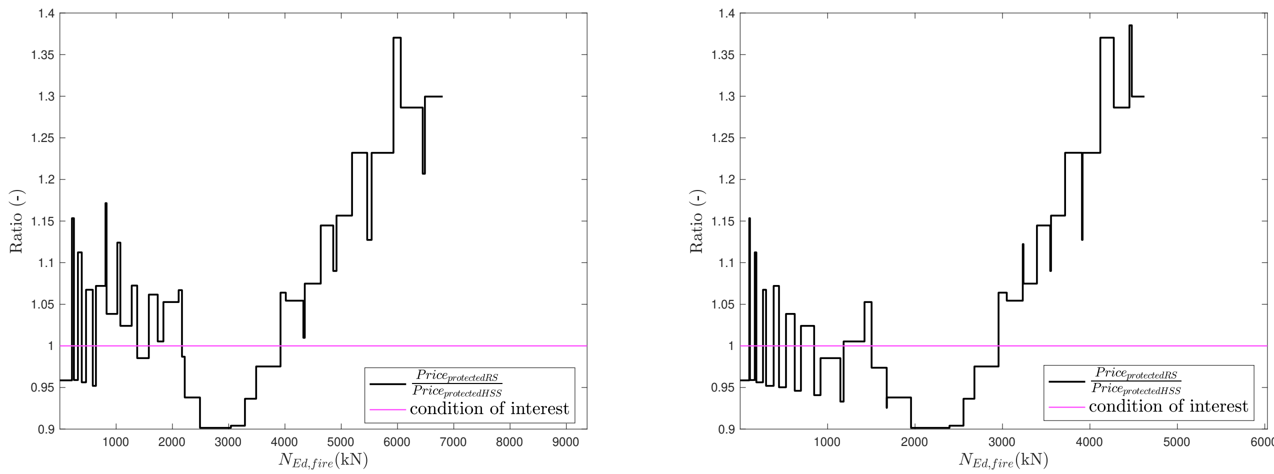
(d) K=2

Figure 4.22: Protected compressed members,L=3.5m: Support conditions

The conclusions will be similar to the unprotected case of Section 4.2.3. The larger the K coefficient, the larger the part of the column that is susceptible to instability as the slenderness increases and, the less interest of the HSS grade compared to the RS grade. In other words, the greater the slenderness, the less likely it is to be economically worthwhile to use HSS.

Buckling axis

As in the unprotected case in Section 4.2.3, when buckling along the weak axis is not prevented, the interest in using the HSS grade will decrease. Indeed, the maximum strength will decrease and the non-interesting zones will be increased.



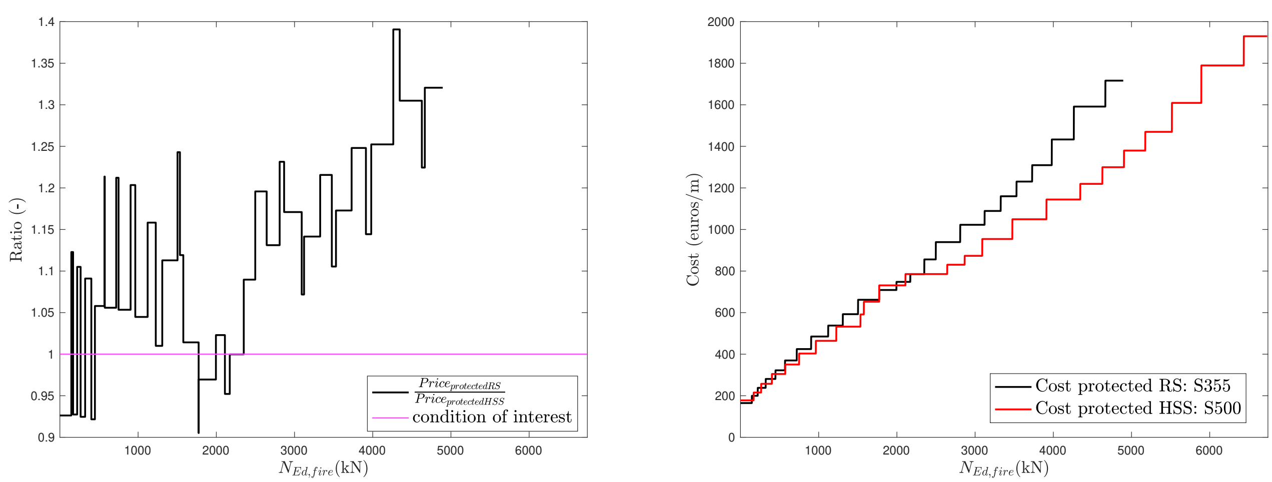
(a) Strong axis: condition of interest

(b) Weak axis: condition of interest

Figure 4.23: Protected compressed members, L=3.5m: Buckling axis

Exposed faces

The results for 3 exposed faces are given in Figure 4.24. These results will differ from those for an unprotected element due to the introduction of the protection. The conclusions drawn in tension will be similar with compression. Since the temperature for 3 exposed faces is higher, the strength of those protected elements exposed on 3 faces will be more degraded than those exposed on 4 faces. The domain size of interest will thus be smaller for 3 exposed faces.



(a) Condition of interest

(b) Cost evolution

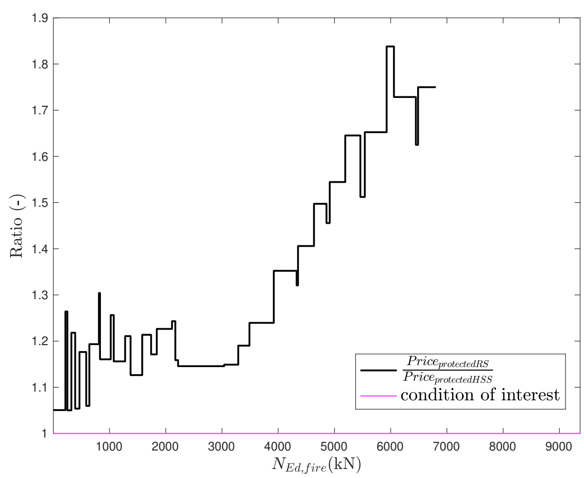
Figure 4.24: Protected compressed members, L=3.5m: 3 exposed faces

In addition, the cost plateau identified for an element exposed on 4 faces no longer appears. This can be explained in the same way as for tension (Section 4.3.3) and thanks to Figure 3.22. In the case of an element exposed on 3 faces, the thickness of paint required will be constant on all the profiles in the range. Thus, the price of the paint increases, unlike for an element exposed on 4 sides. The evolution of the total price will therefore be increasing and all the profiles in the range will be accessible. The cost plateau will not appear and the areas of non-interest will be drastically reduced.

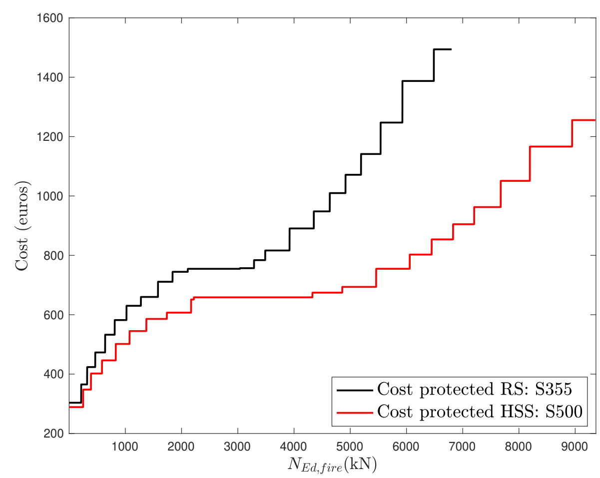
S355 steel price

The price of S355 steel will vary to determine the impact of this price on the results with a pre-crisis value of 0.8 €/kg and a high value of 1.6 €/kg will be studied in addition to the value of 1.2 €/kg corresponding to the current value in the middle of the economic crisis. In the case of a protected compressed member, the results will give similar conclusions to the observations made for a protected tensioned element in Section 3.3.3.

As shown in Figure 4.25, when the price of steel for a RS grade is lower, there will be more interest in using the HSS grade. This can be justified by the fact that it will be more interesting to take a more massive profile requiring a lower protection because of the high price of the intumescent paint.



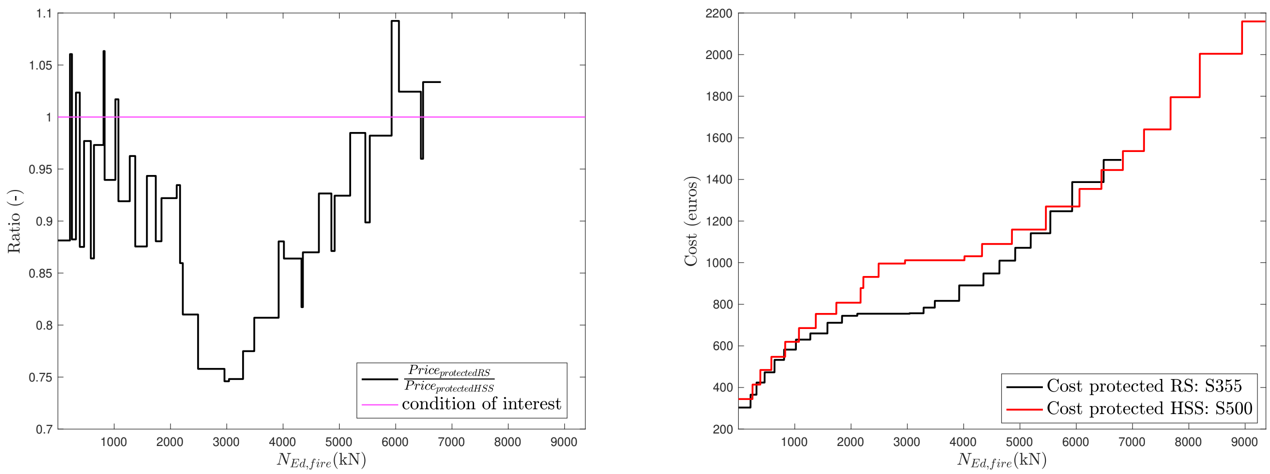
(a) Condition of interest of HSS



(b) Cost evolution

Figure 4.25: Protected compressed members: steel price=0.8 €/kg

In Figure 4.26, when the steel price for a RS grade is increased, the interest of the HSS grade will decrease. This is because the steel price will dominate the total price and therefore it will be more interesting to take a less massive profile with a higher protection.



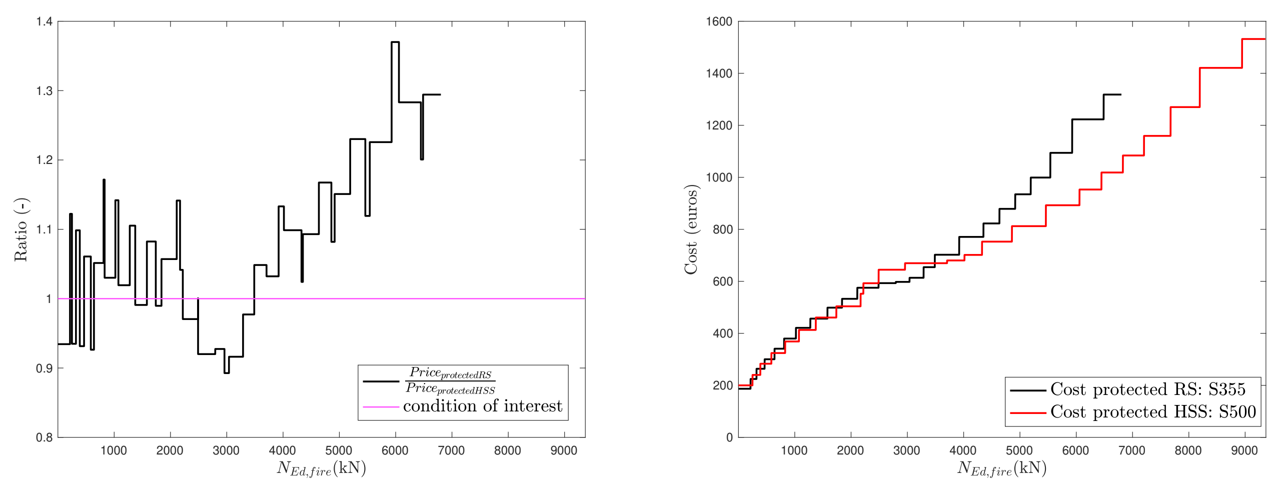
(a) Condition of interest of HSS

(b) Cost evolution

Figure 4.26: Protected compressed members: steel price=1.6 €/kg

Amplification factor

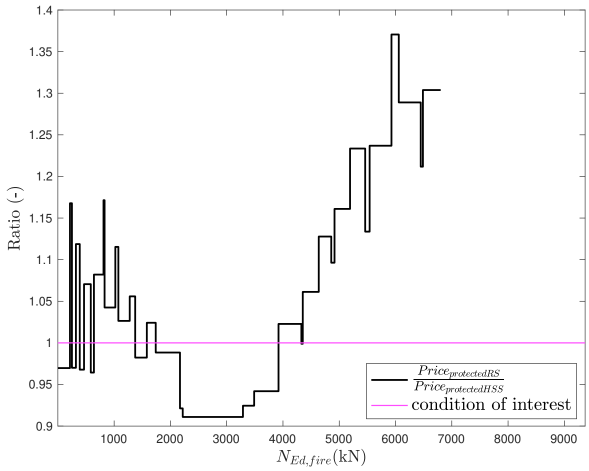
As mentioned in Section 3.3, the paint cost will have a negative influence on the domain of interest of HSS steels as it will generate a considerable area of non-interest in the middle of the domain of interest. This section will focus on the amplification factor which is involved in the intumescent coating price and has been defined as equal to 10 for the case study. The case study will be used with an amplification factor of the intumescent coating price of 5, 10 and 15. The findings will be similar to those for a protected tensioned member of Section 3.3.3.



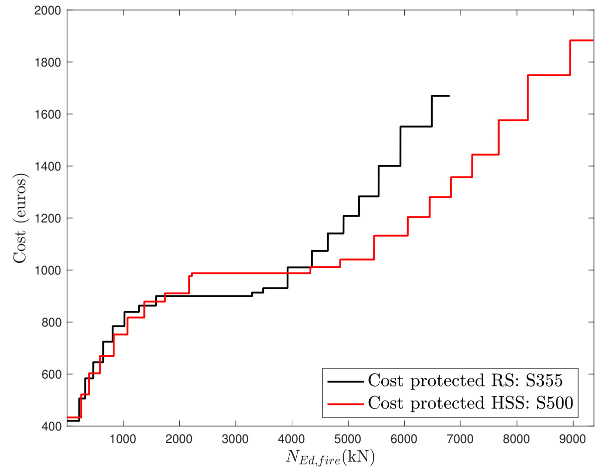
(a) Condition of interest of HSS

(b) Cost evolution

Figure 4.27: Protected compressed members: amplification factor = 5



(a) Condition of interest of HSS



(b) Cost evolution

Figure 4.28: Protected compressed members: amplification factor = 15

As Figure 4.27 shows, with an amplification factor of 5, the large area of non-interest for an amplification factor of 10 will be drastically reduced. If the amplification factor is 15, the zone of no interest will be larger due to the longer cost plateau as shown in Figure 4.28. The raising cost of the intumescent coating will increase the non-interest areas of the HSS as the price of the paint will dominate the total cost. Around the area of the cost plateau, it will be more profitable to use a profile with the RS grade and use higher profiles from the catalogue than to use lower profiles that require more protection.

4.3.4 Conclusions

The introduction of the protection will induce a large zone of non-interest in the case study. This area is linked to a plateau in the evolution of costs due to the cost of paint which will dominate the profile cost and create areas of non-interest not existing in the unprotected case. As in the unprotected case, fire conditions will degrade the strength of the profiles.

When a protected element is subjected to compression, the results of interest of the HSS grade will vary from those where the element is not protected. However, it is important to note that the finding based on the cross-section classification is the same in the protected case. Protected members will be able to achieve higher fire loads than the unprotected element. In addition, the area of non-interest is greater as the introduction of protection will result in an additional cost that will generate a plateau in cost as explained in tension.

The main conclusions regarding the economic value of protected compressed members under fire conditions are listed below:

- The lower the η_{fire} value is, the lower the fire load applied for the same applied load N_{Ed}. It will thus be more advantageous to have a low η_{fire} in order to obtain a lower fire load for the considered N_{Ed}.
- Like in tension, higher grade leads to higher fire resistance and thus increases the area of interest of the HSS grade. In addition, the higher the grade, the smaller the areas of non-interest.

- As in tension, the HEB range will have a greater economic interest area of HSS steel compared to the HEA range due to the higher coating cost for less massive profiles; the cost plateau induced by the price of paint will not appear for the HEB range. Thus, the cost of the paint for the HEB range will have less influence on the total cost than for the HEA range and will therefore increase the areas of interest for the HSS grade.
- As for the unprotected compressed member, the longer the length, the higher the slenderness, the less interest there will be in using the HSS grade. The protected elements will have higher resistances.
- As in tension, the domain size of interest will be smaller for 3 exposed faces due to the higher steel temperature. The evolution of the total price will be increasing and all the profiles in the range will be accessible in opposition with 4 exposed faces member. The cost plateau will not appear and the areas of non-interest will be drastically reduced.
- As with compressed unprotected element, the larger the coefficient K, the greater the slenderness, the less likely it is to be economically worthwhile to use HSS.
- As with compressed unprotected element, when buckling along the weak axis is not prevented, the interest in using the HSS grade will decrease.
- As tensioned protected element, when the S355 steel price is increased, the interest of the HSS grade will decrease. This is because the steel price will dominate the total price and therefore it will be more interesting to take a less massive profile with a higher protection.
- As tensioned protected element, with a lower amplification factor of the intumescent paint the large area of non-interest for an amplification factor of 10 will be drastically reduced. The raising cost of the intumescent coating will increase the non-interest areas of the HSS as the price of the paint will dominate the total cost. Around the area of the cost plateau, it will be more profitable to use a profile with the RS grade and use higher profiles from the catalogue than to use lower profiles that require more protection.

4.4 Optimal solutions at elevated temperature

This section will focus on the determination of optimal solutions taking into account various parameters. The main objective of this section is to have a first global overview of the impact of the different parameters.

4.4.1 Optimal solution: unprotected and protected

The objective of this section is to compare the different protected and unprotected solutions for the considered case study and thus to be able to determine the optimal solution according to the applied fire load. This section will compare Section 4.2 for an unprotected compressed element with Section 4.3 for a protected compressed element to determine the optimal solution.

Firstly, the case study including the unprotected and protected results will be presented. Then, a decision support method will be developed in order to help the user to determine the optimal solution for given applied load and length, and thus choose whether the element will be protected or not and whether the grade is RS or HSS.

Case study results

The results of this section will consider the unprotected case study of Section 4.2.1 and the protected case study of Section 4.3.1 with a member of 3.5m long. The evolution of the cost curves is shown in Figure 4.29 and the solutions considered are: unprotected RS and HSS as well as protected RS and HSS. The optimal solution for a fire load $N_{Ed,fire}$ will correspond to the solution with the lowest cost, i.e. the lowest cost curve.

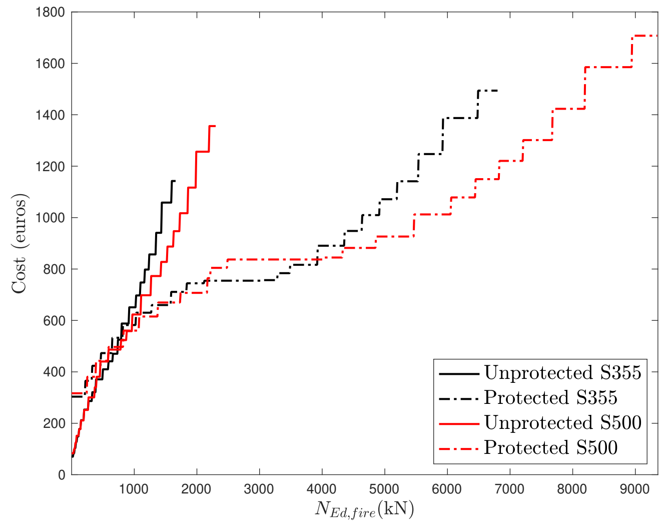


Figure 4.29: Case study for the optimal solution protected or unprotected in compression: cost evolution

A first observation based on Figure 4.29 is that the protection will allow to reach significantly higher fire loads than those reached without protection. This is also reflected in the fire resistance Tables A.7 and A.9. This increase in profile strength is related to the lower temperature of 500 degrees after 30 minutes than in the unprotected case. Therefore, an unprotected member will have a stronger degradation of its mechanical properties. In addition, higher loads can be achieved in tension than in compression, as the buckling instability in bending and the classification of cross-sections will be taken into account in compression.

On the basis of this figure, it is possible to determine load intervals defining an optimal solution among the 4 solutions studied. This will be done in Table 4.2. As in tension, this Table clearly demonstrates the interest of using paint. Indeed, above a fire load of 960 kN, the optimal solution will always be protected. Moreover, the clear benefit of HSS steels can be highlighted; the HSS grade (S500) is mainly preferred in the domain, whether protected or not. This is due to the fact that the use of an HSS grade will increase the resistance and allow higher fire loads to be achieved for the same profile. The gain in resistance will therefore sufficiently outweigh the cost of using the HSS grade compared to the RS grade.

It is obvious that as long as the cost of the unprotected profiles does not exceed the protected cost of the protected profiles, protection will not be necessary. In the case of the RS grade, it will be necessary to reach the HEA 360 profile before there is any interest in protection, whereas for the HSS grade, it will be the HEA 320 profile.

Fire load interval [kN]	Protected?	Grade
0-45	NO	RS
45-50	NO	HSS
50-65	NO	RS
65-75	NO	HSS
75-140	NO	RS
140-260	NO	HSS
260-325	NO	RS
325-365	NO	HSS
365-385	NO	RS
385-395	NO	HSS
395-730	NO	RS
730-780	NO	HSS
780-825	YES	HSS
825-960	NO	HSS
960-1370	YES	HSS
1370-1580	YES	RS
1580-2165	YES	HSS
2165-3920	YES	RS
3920-9350	YES	HSS

Table 4.2: Case study for the optimal solution protected or unprotected in compression

Method for determining the optimal solution

The method developed in this section is intended to help the user to determine which solution is optimal for a given load and length considering an element that is either protected or unprotected and either RS or HSS grade. In order to better understand how this routine can be used to determine the optimal solution, an example will be used to explain the procedure.

First, the routine will ask series of questions in order to define the situation the user wants to study.

```
Which applied load ?
1: Applied load at ambient temperature (Ned)
2: Applied load at elevated temperature (Ned,fire)
1
Enter the design value of the corresponding actions for normal temperature design (Ned in kN)
1500
Enter the value of the reduction factor for the design load level for the fire situation between 0.1 and 0.75
0.65
Enter the length of the member (in m)
3.5
Which product range do you want to study the economical interest?
1: HEA
2: HEB
1
Which high strength steel grade do you want to consider?
1: S420
2: S460
3: S500
4: S550
5: S620
6: S690
3
How many exposed faces to the fire ?
3: 3 faces exposed
4: 4 faces exposed
4
Which axis do you want to consider?
1: Strong axis
2: Weak axis
3: Both
1
What are the support conditions?
1: Pinned ends
2: Fixed, anchored ends
3: Pinned and fixed ends
4: Fixed and free ends
1
Enter the value of the step of the design actions for the fire situation en kN
1
```

Figure 4.30: Questions asked by the routine for the given tensioned example

The applied load can be an ambient load N_{Ed} with the corresponding factor η_{fire} or a fire load $N_{Ed,fire}$. The different questions asked by the routine will also give the limitations of this routine. Indeed, this routine can only be used for the HEA and HEB ranges of profiles, as the information of the painting cost of Section 2.4.2 is only provided for these ranges.

This routine will provide both graphical and numerical results to the user. The graphical output of the routine in Figure 4.31 represents the costs of the different solutions for the defined length as a function of the fire load. The chosen fire load is represented by the blue vertical line.

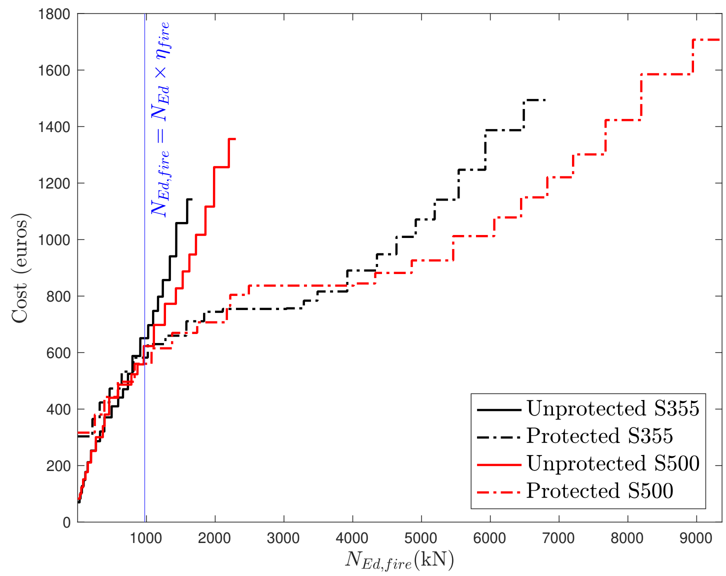


Figure 4.31: Optimal solution: protected or unprotected for the given compressed example

In addition to this graph, this decision support tool will provide numerical results shown in Figure 4.32. The routine will thus output the most suitable solution, protected or not and RS or HSS grade, as well as the required profile for the defined load and length.

```
The cheapest solution for the given length and applied load is: Protected S500
The needed profile is: HEA180
```

Figure 4.32: Responses of the routine for the given compressed example

4.4.2 Optimal solution: grades and product ranges

In this section, all the grades and ranges considered in this work will be compared to obtain the optimum profile and its grade and range of profiles for a given length and fire load. The objective is to determine the economic interest of the grades and ranges. This section will therefore be a first attempt to take into account all the parameters by studying the protected and unprotected cases separately. This section will consider a bi-supported element exposed on its 4 faces and the strong axis of buckling.

The graphical representation using red and green colours respecting the condition 2.8 will be used because of the large amount of information that prevents the use of the representations introduced in this work.

Unprotected members

In the case of an unprotected compressed member, the economic interest of using HSS steels is shown in Figure 4.33 considering the 6 profile ranges and the 7 grades in the length range and fire load range considered. In this graphical representation, it has been chosen to limit the fire load range to 8000 kN, as above this value only the HD range can be considered as the maximum resistance of the other ranges is reached. These maximum fire resistance values can be found in Table A.7.

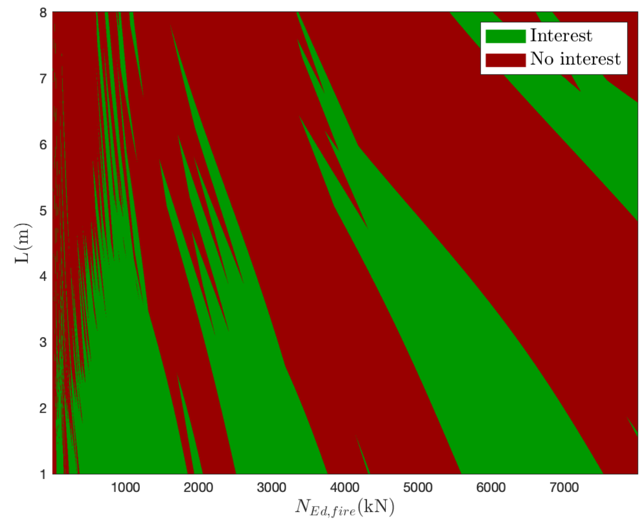


Figure 4.33: Unprotected member in compression: interest of HSS for the optimal solution

Based on Figure 4.33, it can be concluded that the economic interest of using an HSS grade for an unprotected element in compression is limited due to the introduction of the instability.

In order to clarify the interest results, Figure 4.34 represents the optimum range of profiles and grade in the length range considered and the reduced fire load range considered. This figure will allow the definition of approximate areas where certain ranges or grades are more suitable than others:

- HEAA: this HEAA range is preferred in the first area where the RS grade is to be used, which corresponds to an area where the strength of the first HEAA range profile with a RS grade is not reached. The HEAA range is used with a RS grade at the very beginning of the range.
- HEA: the HEA range is preferred for fire loads from the beginning of the range up to a maximum of 1300 kN for lengths of 5 to 8 m with a RS grade.
- HEB: the HEB range will be preferred for lengths from 3m to 5m for fire loads up to 1500 kN. This range will use HSS grades.
- HEC: the HEC range will be preferred for lengths from 0m to 3m for loads up to 1600 kN. This range will use HSS grades.
- HEM: the HEB range will be preferred for lengths from 1m to 8m for loads from 1600 to 3500 kN for 1m and 1200 to 2000 kN for 8m. Another area using this range can be defined for 8m length from 2500 kN to 3700 kN. This range will use HSS grades as well as RS grade.

- HD: this HD range will be used for the remaining field as it is the range that can achieve the maximum compressive fire resistance. This range will use HSS grades as well as RS grade.

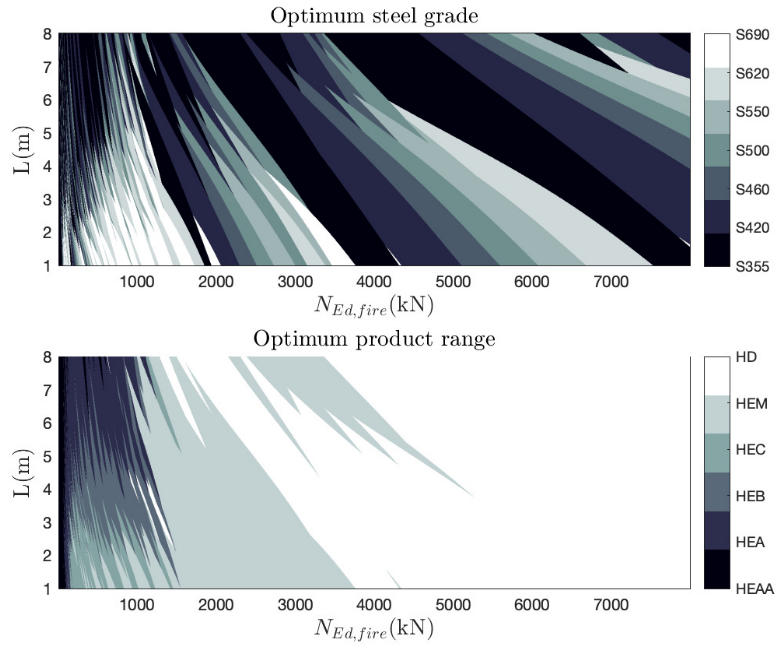


Figure 4.34: Unprotected member in compression: optimum product range and grade

The introduction of flexural buckling will reduce the interest of the HSS grade. Indeed, the higher the slenderness, the more limited the use of HSS grades will be, as the resistances will converge whatever the grade, as explained in Figure 4.10. This phenomenon will be even more pronounced the more slender the profile considered is and therefore more susceptible to instabilities.

The HEAA range or the HEA range are ranges that are highly susceptible to fire conditions as well as to flexural buckling, as the profiles are less massive than those of the other ranges. Therefore, these will be preferred with a RS grade as the profiles in these ranges will be more slender and more profiles will be Class 4 than the other ranges studied. In these ranges, the increased strength of the profile due to the use of an HSS grade will not compensate for the increased cost. As the other ranges are more massive, they will be less susceptible to flexural buckling and fire and therefore are able to use HSS grades.

By comparing the different ranges, it seems that the HEAA, HEA, HEB and HEC ranges are not to be preferred except for very low loads and that it is preferable to use the HEM and HD ranges. These 2 ranges are less fire-susceptible and instability-susceptible due to their greater mass than the HEAA, HEA, HEB and HEC ranges.

A further interesting observation can be drawn from these figures concerning the selection of the optimum grade. Indeed, for some fire loads, it is better to use another range of profiles with the RS grade than to use a certain range with an HSS grade. This brings complexity to the results. These graphs are therefore intended to help the reader to choose the most suitable grade and range for a given fire load and length.

Protected members

In the case of a protected compressed members, the interest of an HSS grade compared to the RS grade is given in Figure 4.35. In this section, all the ranges considered (HEA and HEB) as well as the 7 grades of this work will be compared to determine which solution is the most optimal in the whole range of length and fire load considered. The end of the range will correspond to the last profile in the HEB range for a grade S690.

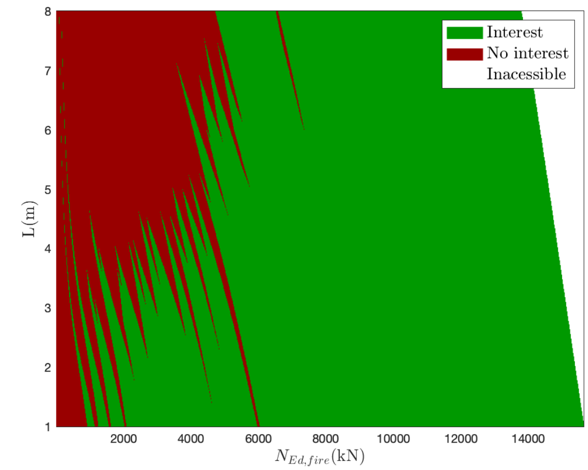


Figure 4.35: Protected member in compression: interest of HSS for the optimal solution

First, similar findings to the tension protected case in Section 3.4.2 can be made. As a recall, the price of the paint governs the results when the element is protected and the profile range HEB will have a price that is less governed by the paint price than for the HEA range. Therefore, area of interest is mainly an area where the optimum profile range is the HEB range as shown in Figure 4.36.

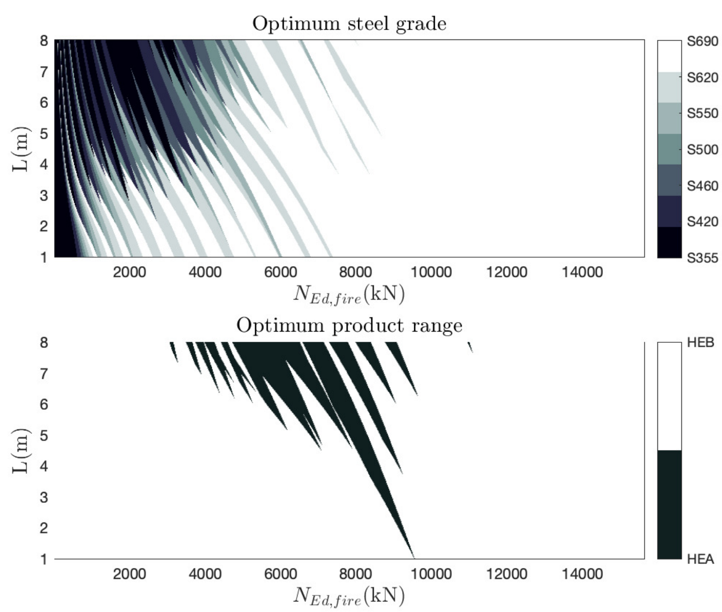


Figure 4.36: Protected member in compression: optimum product range and grade

When the results take into account compression and thus flexural buckling in addition to fire conditions, the interest of HSS grades will be limited. Different observations can be drawn from these figures. The zones of non-interest are greater when the length increases since the slenderness will increase. By increasing the slenderness, the interest of using HSS will be reduced because of the convergence of resistances whatever the grade.

These zones are present at the beginning of the load range in a more pronounced way. On the one hand, the first zone of non-interest is linked to the fact that the strength of the first profile of the HEB range with the RS grade is not yet reached. On the other hand, the more the load will increase, the more a massive profile will be required, whereas this one will be less slender and therefore less susceptible to instability. Thus, for the same length, as the fire load increases, the profile required will increase in the catalogue and become more massive, the sectional strength of the profile will therefore be less degraded. Therefore, the interest of the HSS grade will increase.

It can also be seen that the S690 grade is largely favoured over other grades. This is because the cost of the paint dominates the price, so it is better to increase the grade used than to increase the profile as the cost of the paint will increase more than the cost of the profile, and therefore of the steel.

An important detail can be highlighted concerning the protected results. Indeed, these results have been obtained with rather approximate cost assumptions. These results should therefore be taken with great caution.

4.4.3 Conclusion

The first optimal solution studied compared a protected or unprotected compressed element of RS or HSS grade. A case study and a method allowing the user to determine the optimal solution for a given load and length were developed and can be summarised as follows:

- The protection will allow to reach significantly higher fire loads than those reached without protection. In addition, higher loads can be achieved in tension than in compression, as the buckling instability in bending and the classification of cross-sections will be taken into account in compression. There is a clear benefit of HSS for the case study. This is due to the fact that the use of an HSS grade will increase the resistance and allow higher fire loads to be achieved for the same profile under the same solicitation.

- The method for determining the optimal solution is intended to help the user to determine which solution is optimal for a given load and length considering an element that is either protected or unprotected and either RS or HSS grade. This routine will provide both graphical and numerical results to the user. This decision support tool will output the most suitable solution, protected or not and RS or HSS grade, as well as the required profile for the defined load and length.

The second optimal solution studied compared all the grades and ranges considered for a unprotected element as well as for a protected element. It can be summarised as follows:

- In the case of an unprotected compressed member, the economic interest of using an HSS grade is limited due to the introduction of the fire conditions and the flexural buckling. Less massive profiles will have a higher slenderness which will limit the use of HSS as the strength will converge regardless of grade. Thus, less massive profiles such as those in the HEAA range will not be recommended for

HSS. It seems that the HEAA, HEA, HEB and HEC ranges are not to be preferred except for very low loads and that it is preferable to use less fire-susceptible and instability-susceptible ranges with more massive profiles: the HEM and HD ranges.

- In the case of a protected compressed members, similar findings to the tension protected case can be made. The profile range HEB will have a price that is less governed by the paint price than for the HEA range. Therefore, the area of interest is mainly an area where the optimum profile range is the HEB. For profiles of low mass and therefore susceptible to fire and instabilities, the interest of HSS is limited because of the convergence of the strength for all grades for a high slenderness. In addition, the cost of the paint dominates the price. Therefore, it is better to increase the grade used than to increase the profile as the cost of the paint will increase more than the profile cost.

This optimal solution study brings complexity to the results. These graphs are therefore intended to help the reader to choose the most suitable grade and range for a given fire load and length. It is therefore a first attempt to take into account all the parameters.

5 Ambient and elevated temperatures: governing design

The objective of this section is to combine the cold and hot results, i.e. the design at ambient or elevated temperature (fire conditions). It will be necessary to determine which design governs the final choice of the optimal profile for a given load and length: cold, hot or both. The influence of the reduction factor of the applied load η_{fire} will be taken into account in this section.

To determine which design governs the required profile selection for a given length and load, it is necessary to determine which design needs the highest profile in the catalogue between the cold or hot design. If both designs require the same profile, then both will govern. It is important to note that the choice of cold and hot profile does not use the same applied load but an ambient temperature load for the cold design and a corresponding fire load for the hot design.

The results of this section will be obtained from the following two conditions corresponding to the choice of the optimal hot and cold profiles for a given load and length. In order to establish the optimal cold profile, the following condition must be met:

$$N_{Ed} \leq R_{Rd} \tag{5.1}$$

where R_{Rd} is the design resistance of the steel member for the ambient temperature design which is represented by N_{Rd} for a tension member and $N_{b,Rd}$ for a compression member, and N_{Ed} is the design value of the corresponding force for normal temperature design.

In order to obtain the optimum hot profile, the following condition must be met:

$$N_{Ed,fi} = \eta_{fire} N_{Ed} \leq R_{fi,30min,Rd} \tag{5.2}$$

Where $R_{fi,30min,Rd}$ is the design resistance of the steel member for the fire design situation after 30 minutes which is represented by $N_{fi,30min,Rd}$ for a tension member and $N_{b,fi,30min,Rd}$ for a compression member, $N_{Ed,fi}$ is the design effect of actions for the fire design situation and η_{fire} is the reduction factor for the design load level for the fire situation.

First, the results will be given for a specific case study and then a sensitivity analysis of the parameters will be performed. This will be done for both protected and unprotected tensioned elements and for protected and unprotected compressed elements. The case study will be the same as for the Sections 3 (S355 and S500, HEA range, ...) and 4 (S355 and S500, HEA range, strong axis, pinned ends, ...). The results will only be developed for an element exposed on these 4 faces. Indeed, it is rare to have a column exposed on 3 faces, this is more recurrent for beam elements. In addition, a length of 3.5m will be used for all the results in tension and compression. It was also chosen to study the results for a η_{fire} of 0.1 which is a low value of this reduction factor that can be associated with metal frames with light roofs and a value of 0.65 corresponding to the value recommended by the Eurocode [13].

5.1 Tension members

In this section, both protected and unprotected tensioned elements will be studied. As a reminder, the tension will not affect the length in the results. Only the cost will be increased proportionally to the length.

To obtain the results of this section, it will be necessary to use the condition 5.1 for a cold design and the condition 5.2 for a hot design. To have both conditions in the same form, the conditions can be rewritten for tension. The cold condition 5.1 can be written as such:

$$N_{Ed} \leq N_{Rd} \tag{5.3}$$

While the condition 5.2 for hot design can be rewritten as such:

$$N_{Ed,fi} = \eta_{fire} \times N_{Ed} \leq N_{fi,30min,Rd} = k_{y,30min} \times N_{Rd}$$

$$N_{Ed} \leq \frac{k_{y,30min}}{\eta_{fire}} \times N_{Rd} \tag{5.4}$$

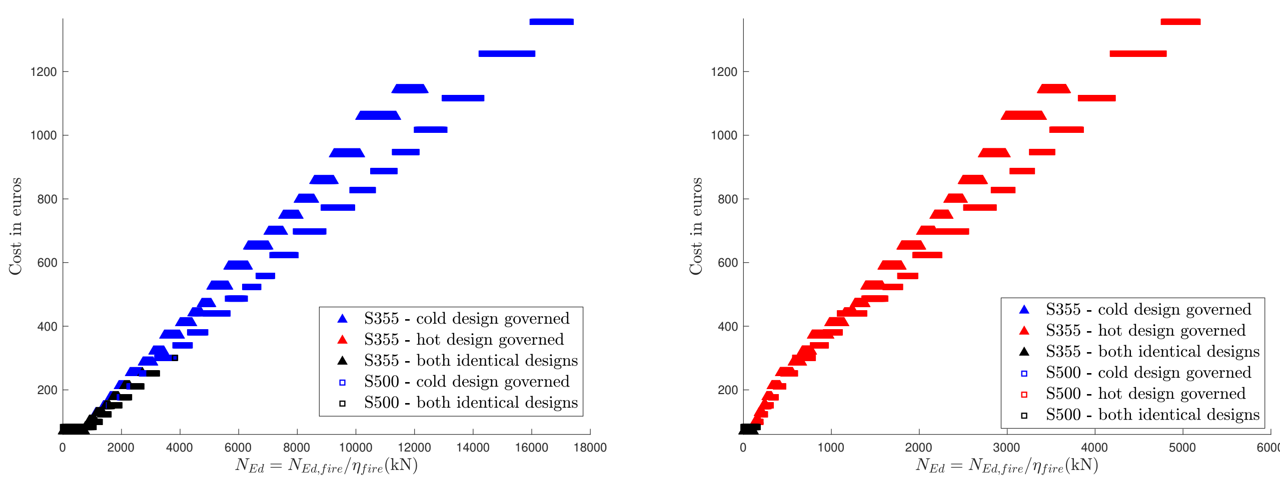
The hot condition will therefore depend on two parameters: $k_{y,30min}$ and η_{fire}. As a reminder, the cold tensile strength of the profiles will only be degraded by the reduction factor k_y of the considered profile to obtain the fire strength of the tensioned element.

5.1.1 Unprotected members

Case study results

This section will give the results of the case study which will be defined by Section 3.1.1 for the cold design by Section 3.2.1 for the hot design. Figure 5.1 gives the results of the case study for a η_{fire} of 0.1 and 0.65.

The graphical representation of the results will be explained on the basis of Figure 5.1 and will then be taken as understood. In order to have a common representation between the hot and cold design, it was necessary to choose the reference applied load on the horizontal axis. Thus, it was chosen to use the cold applied load N_{Ed} as a reference and the fire load $N_{Ed,fire}$ will be directly linked to the cold load through the η_{fire}. The horizontal axis will represent the cost of the optimal profile for the two grades considered. When the cold design will govern, the point will be blue, red for the fire design and black if both designs govern. When the point is red, i.e. the fire design governs, the fire load will be equivalent to the cold load N_{Ed} shown on the horizontal axis multiplied by the reduction factor η_{fire}. Each cost step will represent a profile in the range under consideration, starting with the first profile in the range.



(a) η_{fire}=0.1 (b) η_{fire}=0.65

Figure 5.1: Ambient and elevated temperatures for an unprotected tensioned member: Case study

Based on Figure 5.1(b), it can be concluded that fire governs the choice of profile for the HEA range with a η_{fire} of 0.65 (recommended value of the Eurocode). It can also be seen that for the first profile in the catalogue both designs govern (area with the lowest cost for HSS and RS grades). This is due to the fact that in this area, both designs require the first profile of the HEA 100 range as the strength of this profile is not yet reached.

In Figure 5.1(a), the results are given for a η_{fire} of 0.1. On this one, the cold design governs mainly. However, there are areas where both designs govern at the same time: at the first profile level (HEA 100) as well as for early range profiles.

To better understand the results, it is necessary to use the condition 5.4 and the condition 5.3 for the specific case of tension which have the same form. To establish which design governs, it is sufficient to determine which condition is stricter. Indeed, a stricter condition will lead to a faster increase of the optimal profile in the considered product range and the cost curve will be steeper. To determine the strictest condition, the following condition can be used:

$$\text{Strictest condition} = min\left(\underbrace{1}_{\text{Cold design governs}} \quad ; \quad \underbrace{\frac{k_{y,30min}}{\eta_{fire}}}_{\text{Hot design governs}} \right) \tag{5.5}$$

The most severe condition will be at elevated temperature when $k_{y,30min} < \eta_{fire}$. In the case of Figure 5.1(b), the reduction factor $k_{y,30min}$ will always be less than the value of η_{fire} of 0.65 as the values of $k_{y,30min}$ for the HEA range from 0.1 to 0.19, thus the fire governs well over the whole range. In Figure 5.1, the η_{fire} is 0.1 which is less than or equal to the values of $k_{y,30min}$ for the HEA range and therefore the cold design will govern as the cold condition is the most stringent and the increase of the optimal profile for the cold design will rise faster than the hot one.

To complete this explanation, it is interesting to consider the case where the η_{fire} is 0.2 which is done in Figure 5.2. On this one, the fire design mainly governs. However, there are areas where both designs govern at the same time: at the first profile (HEA 100) as well as at higher loads.

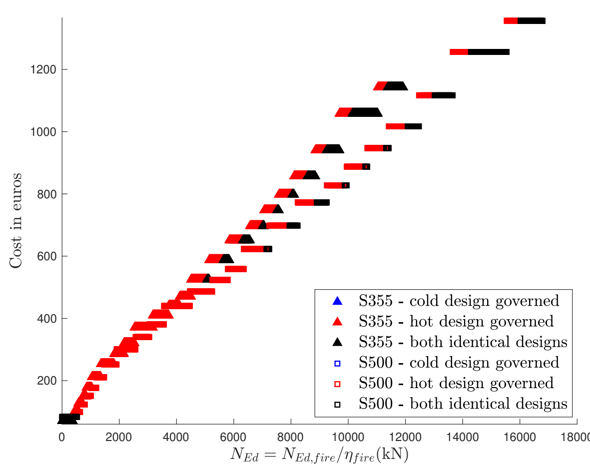


Figure 5.2: Ambient and elevated temperatures for an unprotected tensioned member: Case study with $\eta_{fire} = 0.2$

These areas where the two designs govern appear at the end of the cost steps for high loads and therefore for profiles at the end of the range. The fire resistance will be less degraded for these profiles as they have a lower section factor and therefore a higher reduction factor $k_{y,30min}$ close to the η_{fire} value of 0.2 as shown in Table 3.3. This will imply that for profiles at the end of the range, the Condition 5.4 is less restrictive than at the beginning of the range. Thus, the progression of the optimal profile through the range will be almost similar, resulting in areas where the same optimal profile will be required for both the hot and cold design for a corresponding applied load. These areas shown in black will occur where the hot and cold optimum design intersect and therefore at the end of the cost step.

Based on the hot and cold conditions, it can be concluded that only two parameters will modify the results: $k_{y,30min}$ and η_{fire}. Indeed, if the grade is increased, both conditions will increase proportionally and it will not change which one is more severe and therefore the definition of the governing design zones will remain the same. It is interesting to study the variation of the parameter $k_{y,30min}$ and thereby study the different ranges of the study.

Variation of product range

The same study was carried out for the other profile ranges. The graphical results for the HEAA, HEC and HEM ranges can be found in Appendix D - 1 while those for the HEB and HD ranges will be presented in this section in Figures 5.4 and 5.5.

The governing design will have the strictest condition, which translates into the Condition 5.5 taking into account $k_{y,30min}$ and η_{fire}. The values of the yield strength reduction factor are shown for all HEA, HEB and HD profiles in Figure 5.3.

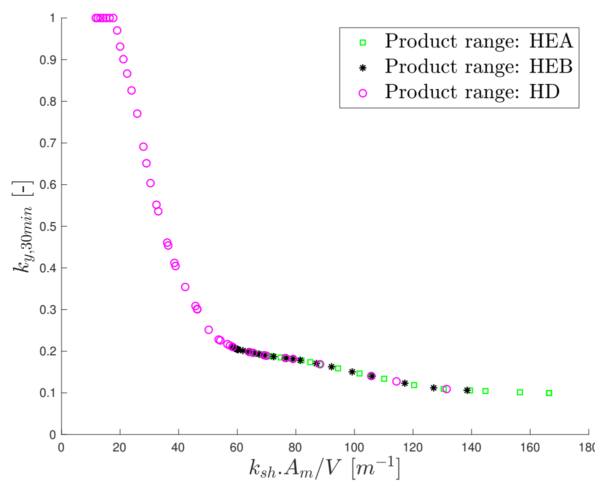
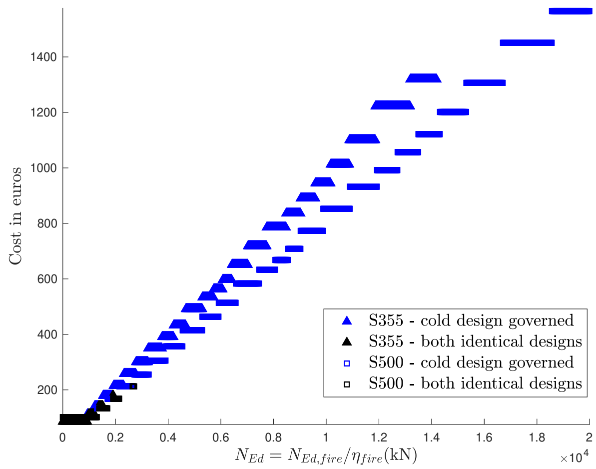
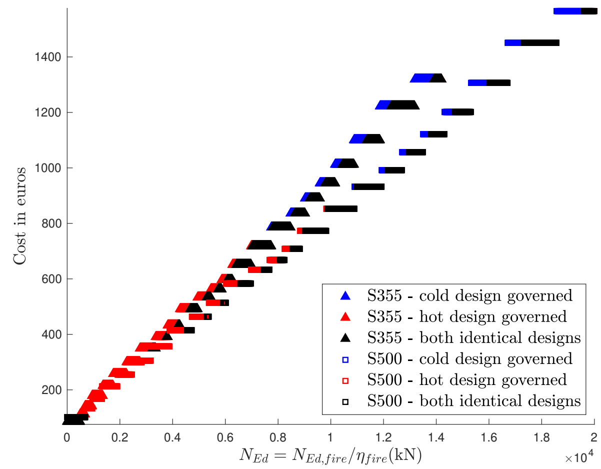


Figure 5.3: Evolution of the reduction factor of the yield strength for the product ranges HEA, HEB and HD

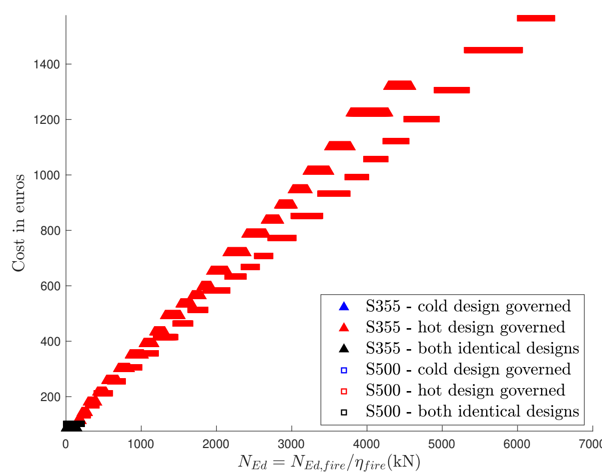
In the case of the HEB product range, the values of $k_{y,30min}$ are between 0.1 and 0.21, so the results and their explanation will be quite similar to those explained above for the HEA range. The difference between the two ranges will come from the values of $k_{y,30min}$ and the results for a $\eta_{fire} = 0.2$. As shown in Figure 5.3, the HEB range profiles will have overall higher $k_{y,30min}$ values than the HEA range since the HEB range will have most of its $k_{y,30min}$ values around 0.2 which is not the case for the HEA range. Thus, for a $\eta_{fire} = 0.2$, the HEB range will have areas where the cold design governs where the profiles have a value around $k_{y,30min}$ 0.2, these are end of range profiles that are less susceptible to fire.



(a) η_{fire}=0.1



(b) η_{fire}=0.2

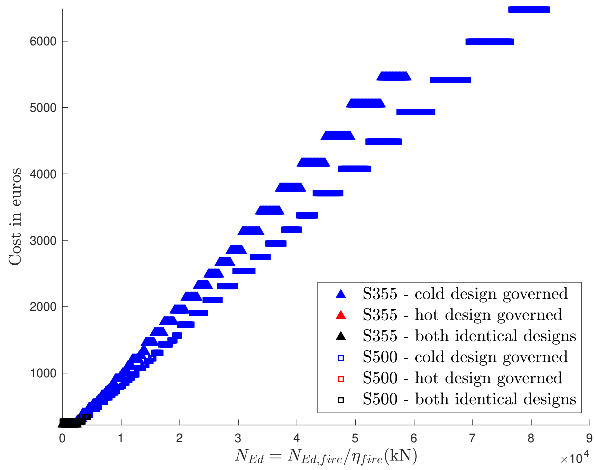


(c) η_{fire}=0.65

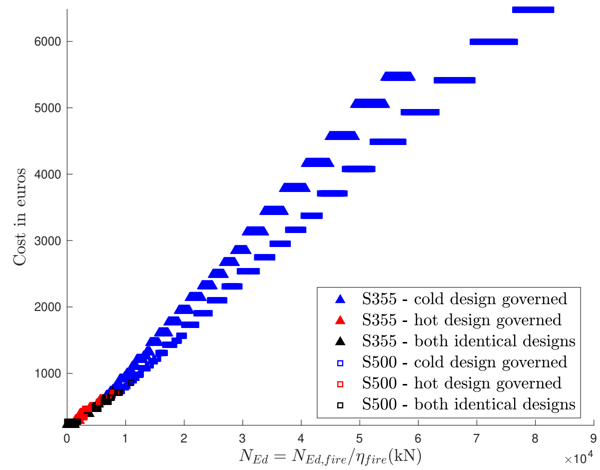
Figure 5.4: Ambient and elevated temperatures for an unprotected tensioned member: HEB product range

In the case of the HD product range, the values of $k_{y,30min}$ are between 0.1 and 1. The values are therefore much higher than the HEA and HEB ranges for most profiles as shown in Figure 5.3. In Figure 5.5 with $\eta_{fire} = 0.65$, the choice of profile is mainly governed by the cold design and only the profiles at the beginning of the range will be governed by the hot design. This is due to the fact that the early range profiles are more susceptible to fire and therefore their $k_{y,30min}$ values are lower than 0.65.

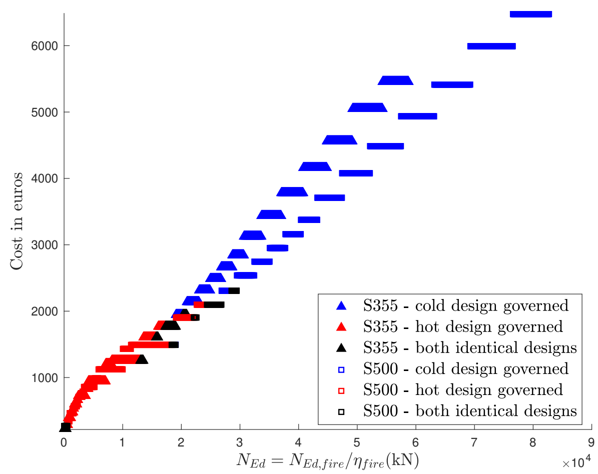
As shown in Figure 5.5, the higher the η_{fire}, the more the cold design fire governs as fewer profiles will have a $k_{y,30min}$ lower than η_{fire}. Profiles with a $k_{y,30min}$ greater than 0.75 will never be governed by the hot design since the maximum value of η_{fire} is this value. Thus, the thermal degradation of the profile strength will be less than the reduction of the load applied to consider the fire condition, which results in the governing cold condition.



(a) η_{fire}=0.1



(b) η_{fire}=0.2



(c) η_{fire}=0.65

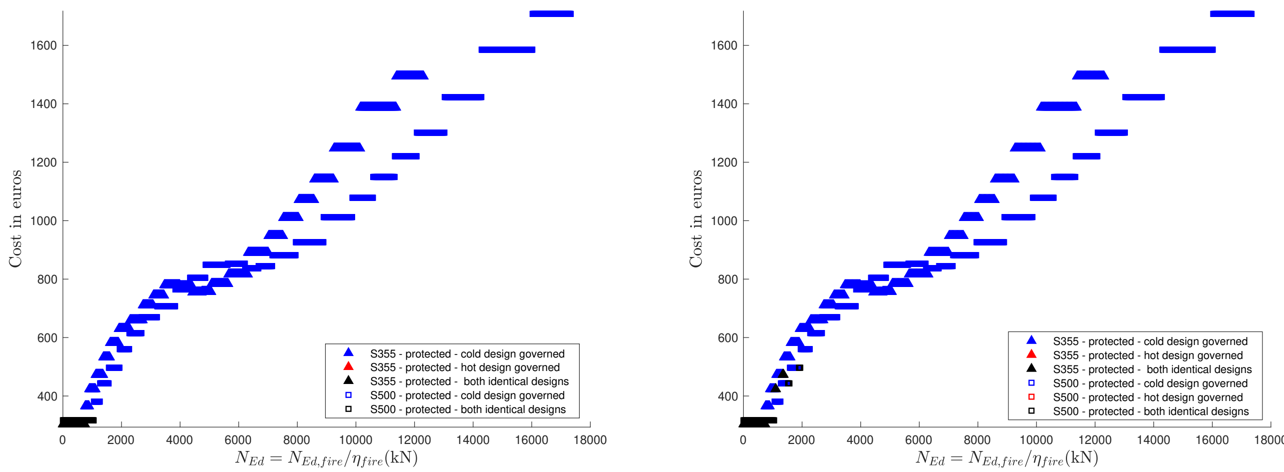
Figure 5.5: Ambient and elevated temperatures for an unprotected tensioned member: HD product range

5.1.2 Protected members

When protection is considered, the hot and cold price will take into account the price of this protection as well as the price of the optimal profile. In addition, in the case of the hot design, an imposed steel temperature on all the profiles in the range of 500°C will be used for an element with 4 exposed faces. Thus, all the profiles will have a single yield strength reduction factor $k_{y,30min}$ which is 0.78. The hot condition 5.4 can therefore be rewritten as such:

$$N_{Ed} \leq \frac{0.78}{\eta_{fire}} \times N_{Rd} \tag{5.6}$$

This condition will be valid for the HEA and HEB range and only the value of η_{fire} will influence the results.



(a) η_{fire}=0.1 (b) η_{fire}=0.65

Figure 5.6: Ambient and elevated temperatures for a protected tensioned member: HEA product range

The condition 5.6 as well as the Figure 5.6 allow to conclude that the cold design will govern the choice of the optimal profile. This comes from the imposed high value of $k_{y,30min}$ of 0.78 which will make the cold condition the strictest under all circumstances. Indeed, the η_{fire} has a maximum value of 0.75 which is lower than 0.78. Thus, the evolution of the optimal profile increase in cold condition will be faster than in hot condition. By taking a value of η_{fire} of 0.75 which corresponds to the maximum possible value, several zones where both designs govern appear as the condition 5.6 will be almost equivalent to the cold condition.

5.1.3 Conclusion

In the case of tensioned elements, the thermal degradation of the resistance will depend on the value of $k_{y,30min}$ while the load applied under fire conditions will be the design load at ambient temperature reduced by the factor η_{fire}. The design governing the profile selection will depend on the most stringent condition and will thus depend on these two parameters.

Different conclusions can be drawn for the unprotected elements under tension:

- By taking a product range with more massive profiles (and so a lower section factor), the cold design will govern more for the same η_{fire} since the values of $k_{y,30min}$ will be higher and therefore the fire condition will be less strict.
- By taking a lower η_{fire} for the same range of profiles, the more cold design can govern as the η_{fire} will more easily be lower than the $k_{y,30min}$ of the profiles in the range considered.
- Within a given profile range, profiles at the end of the range are more likely to have a governing cold design than those at the beginning of the range as these will have higher yield strength reduction factors and therefore be more likely to be superior to the η_{fire}.

For the protected elements under tension, the protection will be of interest when the hot design alone is considered, but this interest will clearly be outweighed by taking into account the cold design. Indeed, the cold design will govern the choice of the optimal profile and not the hot design. This is due to the reduced load considered in the fire conditions and the unique yield strength reduction factor: the reduction in applied load under fire conditions will be greater than the thermal degradation of the strength, resulting in a slower increase in the optimum profile under elevated temperature than at ambient temperature.

5.2 Compression members

In this section, both protected and unprotected compressed elements will be studied. In compression, the length will be involved in the strength computation because of the introduction of flexural buckling.

As a reminder, to obtain the results of this section, it will be necessary to use the condition 5.1 for a cold design and the condition 5.2 for a hot design. These can be rewritten for compression and in the same form. The cold condition 5.1 can be written as such:

$$N_{Ed} \leq N_{b,Rd} = \chi \times \beta_A \times N_{Rd}$$

The cold condition will thus depend on the bending buckling reduction factor χ and the section reduction factor β_A which is relative to the section classification (Class 4: β_A<1). The hot condition 5.2 can be rewritten as such:

$$\begin{aligned} N_{Ed,fi} = \eta_{fire} \times N_{Ed} \leq N_{b,fi,30min,Rd} &= \chi_{fi} \times A_{eff} \times k_{y,30min} \times f_y \\ &= \chi_{fi} \times \beta_{A,fi} \times N_{Rd} \times k_{y,30min} \end{aligned}$$

$$N_{Ed} \leq \frac{\chi_{fi} \times \beta_{A,fi} \times k_{y,30min}}{\eta_{fire}} \times N_{Rd}$$

The hot condition will therefore depend on 4 parameters which will modify the cross-sectional resistance of the element: $k_{y,30min}$, η_{fire}, the reduction factor for bending buckling in a fire situation χ_{fi} and the cross-sectional reduction factor $\beta_{A,fi}$ which is relative to the classification of the cross-sections (Class 4: β_A<1) under fire conditions.

In tension, thermal degradation was only taken into account with the factor $k_{y,30min}$. In compression, the thermal degradation will take into account many different parameters. It is therefore interesting to use the compressive strength at ambient temperature $N_{b,Rd}$ as a mutual term between the two conditions in addition to N_{Ed}. To do this, a reduction factor $k_{b,fi}$ will be introduced and will quantify the impact of the thermal degradation of the element resistance. This reduction factor will be expressed as such:

$$k_{b,fi} = \frac{N_{b,fi,30min,Rd}}{N_{b,Rd}} = \frac{\chi_{fi} \times \beta_{A,fi} \times N_{Rd} \times k_{y,30min}}{\chi \times \beta_A \times N_{Rd}} = \frac{\chi_{fi} \times \beta_{A,fi} \times k_{y,30min}}{\chi \times \beta_A}$$

Based on this new factor, the cold condition can be written as such:

$$N_{Ed} \leq N_{b,Rd} \tag{5.7}$$

Whereas the hot condition can be written as follows:

$$N_{Ed} \leq \frac{k_{b,fi}}{\eta_{fire}} \times N_{b,Rd} \tag{5.8}$$

This makes it possible to write a condition as in tension, which will allow to obtain the strictest condition:

$$\text{Strictest condition} = min\left(\underbrace{1}_{\text{Cold design governs}} \quad ; \quad \underbrace{\frac{k_{b,fi}}{\eta_{fire}}}_{\text{Hot design governs}} \right) \tag{5.9}$$

This condition will determine which condition is the most severe and therefore help to determine which design is most likely to govern the profile selection. It is important to note that even if a condition is considered the strictest for a certain profile, the governing design may not correspond to this condition. Indeed, the governing design will also depend on the evolution of the optimal profile selection over the entire range of profiles.

5.2.1 Unprotected members

Case study results

This section will give the results of the study case which will be defined by Section 4.1.1 for the cold design by Section 4.2.1 for the hot design. Figure 5.8 gives the results of the case study for a η_{fire} of 0.1, 0.2 and 0.65.

In order to explain the results, it is necessary to know the behaviour of the reduction factor $k_{b,fi}$ which will reduce the compressive strength at ambient temperature to obtain the fire resistance. This factor will therefore represent the thermal degradation of the strength due to the introduction of fire conditions. The values of this factor for the HEA range of profiles for grades S355 and S500 are given in Figure 5.7.

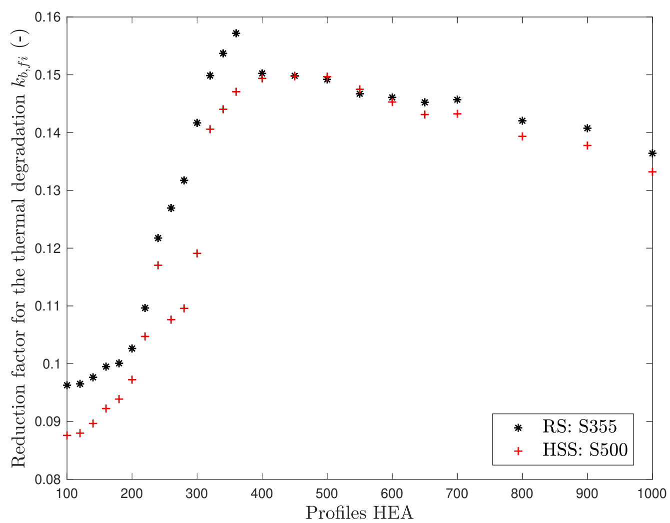
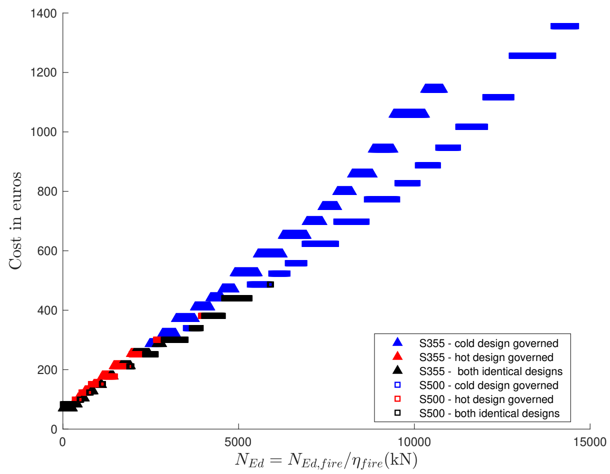
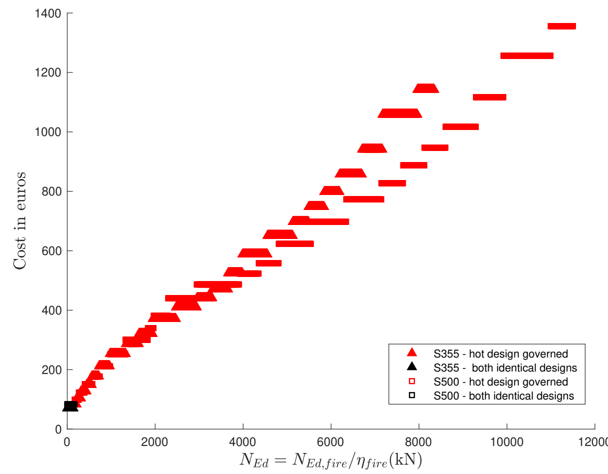


Figure 5.7: Reduction factor for the thermal degradation $k_{b,fi}$ of the unprotected compressed members of the HEA range

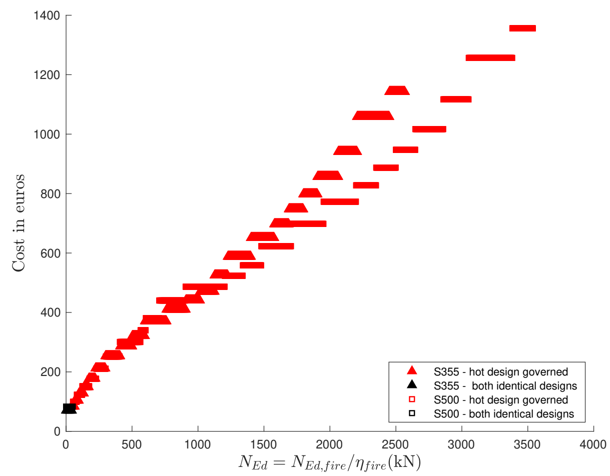
The reduction factor will therefore reflect different phenomena related to the introduction of fire conditions. Firstly, the classification of the sections will be more unfavourable for a fire situation than for an ambient temperature. This will result in a higher Class 4 cross-sections. In addition, the relative slenderness will be increased by introducing high temperatures which will lead to a lower reduction factor for fire buckling under fire conditions. These two phenomena are accentuated as the grade increases.



(a) η_{fire}=0.1



(b) η_{fire}=0.2



(c) η_{fire}=0.65

Figure 5.8: Ambient and elevated temperatures for an unprotected compressed member: HEA range

In order to explain these results, it is necessary to use the Condition 5.9 which will take into account this new reduction factor. The explanations of the results are comparable to those for tension, except that the introduction of instabilities linked to compression will degrade the strength at ambient temperature more than in the tension. Hence, the reduction factor $k_{b,fi}$ is less than the factor $k_{y,30min}$. It is therefore logical that the results in compression will be more governed by the fire design than in tension.

In compression, the fire condition will be stricter if $k_{b,fi} < \eta_{fire}$. As shown in Figure 5.7, the factor $k_{b,fi}$ never exceeds 0.16 for the HEA product range. Thus, it is logical that for values of η_{fire} greater than 0.16, the fire condition will always govern since the increase in the optimal profile will be the fastest for the fire design. This observation confirms the results obtained for a η_{fire} of 0.2 and 0.65.

Then, for results obtained with a η_{fire} of 0.1, the early range profiles will have a thermal degradation characterised by $k_{b,fi}$ which is less than the value of η_{fire}. The fire condition will therefore govern and the increase in the optimum profile at elevated temperature will be faster than at ambient temperature. From HEA 180 for RS and HEA 200 for HSS, the cold condition will be stricter and therefore the increase in profile choice will be stronger for the cold condition. This will lead to the cold design governing the end of the range where the profiles are less susceptible to fire.

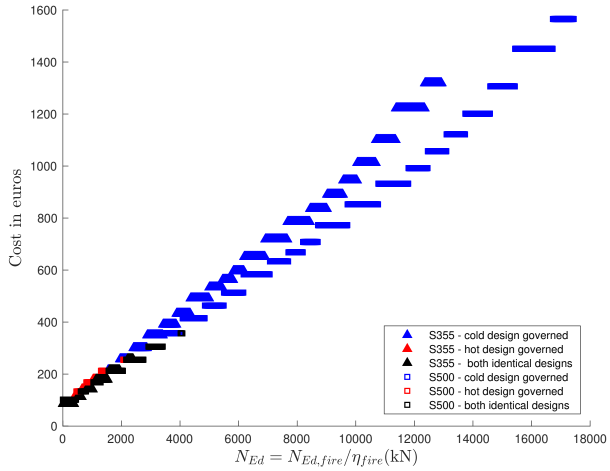
Another observation can be drawn from the results with a η_{fire} of 0.1. Indeed, when the HSS grade is used, the hot design will govern longer than for the RS grade. This is due to the increase in thermal degradation with the grade considered as shown in Figure 5.7. Thus, a higher grade will have a stricter fire condition which will make the fire design more likely to govern the choice of the optimal profile.

Variation of product range

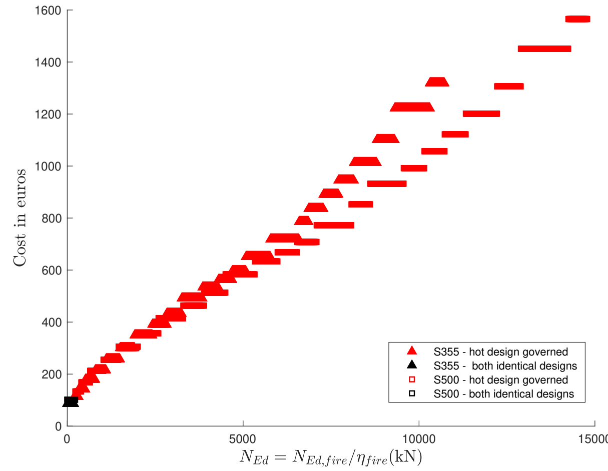
The same study was carried out for the other profile ranges. The results for the HEAA, HEC and HEM ranges can be found in Appendix D while those for the HEB and HD ranges will be presented in this section in Figures 5.9 and 5.10.

The governing design will have the strictest condition, which translates into the Condition 5.9 taking into account $k_{b,fi}$ and η_{fire}. The values of the reduction factor $k_{b,fi}$ are given in Figure 5.9 (d) for the HEB range and in Figure 5.10 (d) for the HD range.

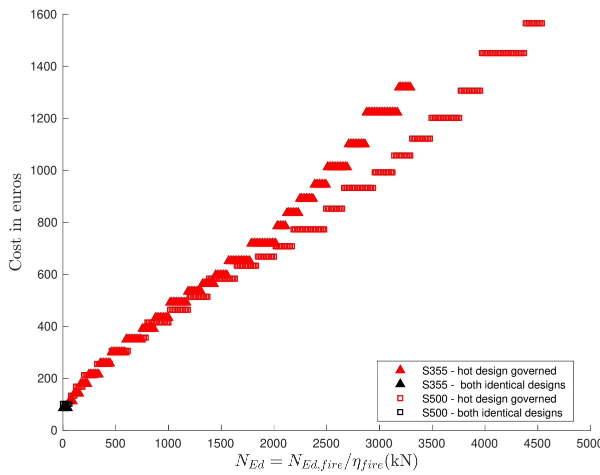
In the case of the HEB product range, the values of $k_{b,fi}$ are between 0.09 and 0.18, so the results and their explanation will be quite similar to those explained above for the HEA range. When $\eta_{fire} = 0.1$, there will be less areas where the fire design governs than for the HEA range. This is due to the $k_{b,fi}$ values being higher for the HEB range. This range therefore has profiles that are less susceptible to fire due to their lower section factor.



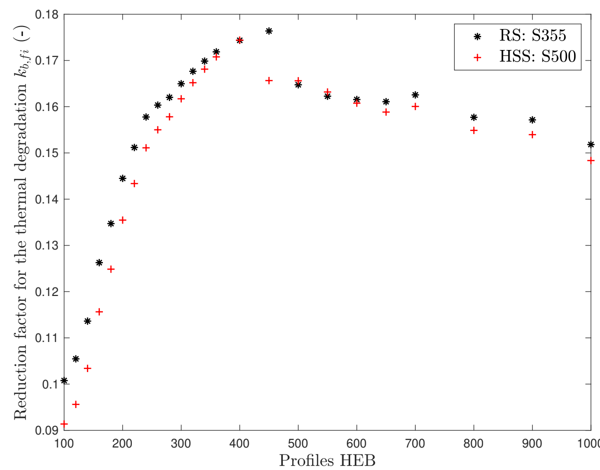
(a) η_{fire}=0.1



(b) η_{fire}=0.2



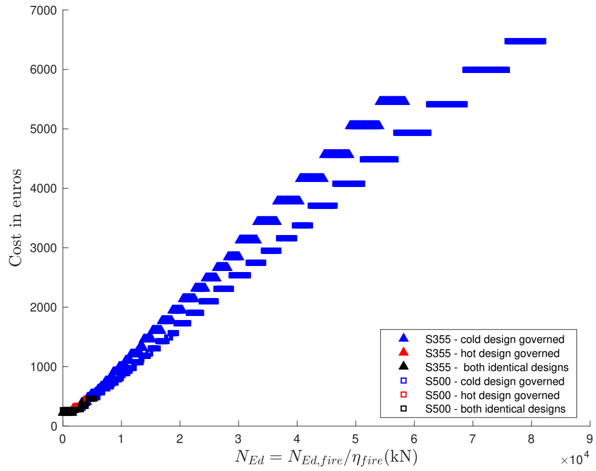
(c) η_{fire}=0.65



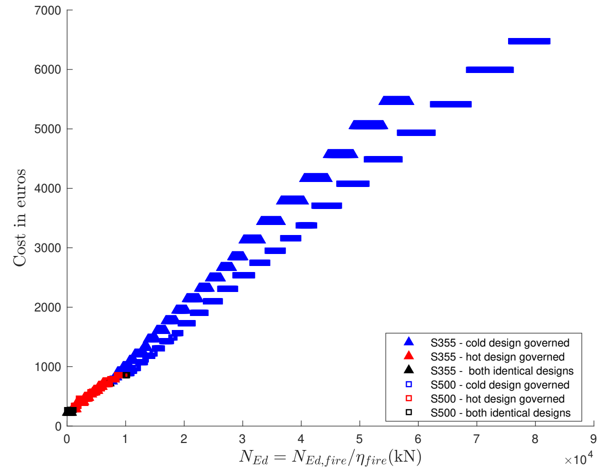
(d) Reduction factor for the thermal degradation $k_{b,fi}$

Figure 5.9: Ambient and elevated temperatures for an unprotected compressed member: HEB range

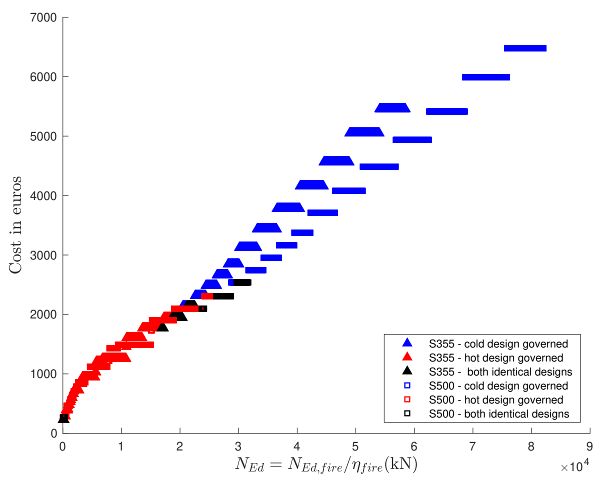
In the case of the HD product range, the values of reduction factor $k_{b,fi}$ are between 0.09 and 0.9. The values are therefore much higher than the HEA and HEB ranges but the thermal degradation in compression of this range is higher than in tension. The higher the η_{fire}, the more the cold design fire governs as fewer profiles will have a $k_{b,fi}$ lower than η_{fire}. Therefore, the thermal degradation of the profile strength will be less than the reduction of the load applied to consider the fire condition, which results in the governing cold condition.



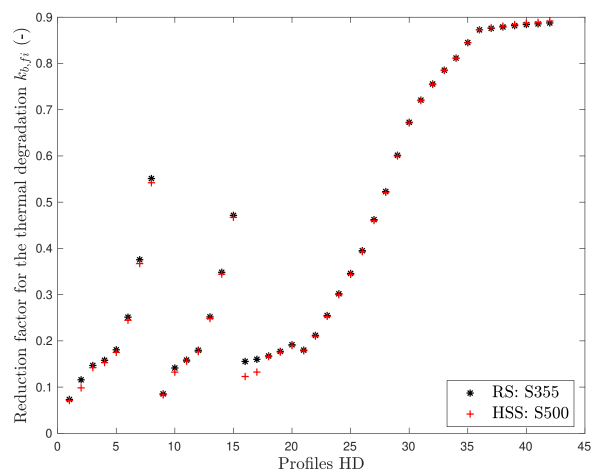
(a) η_{fire}=0.1



(b) η_{fire}=0.2



(c) η_{fire}=0.65



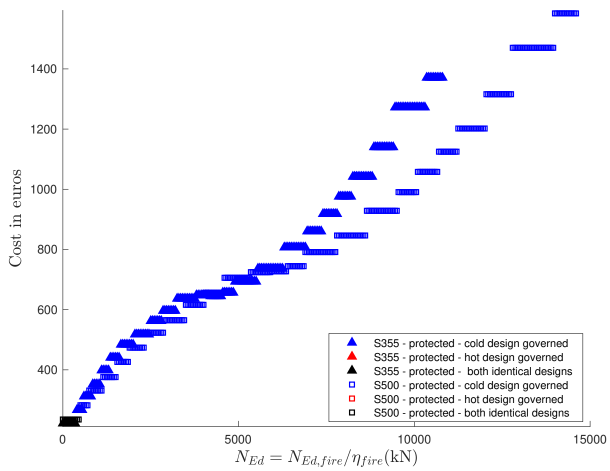
(d) Reduction factor for the thermal degradation $k_{b,fi}$

Figure 5.10: Ambient and elevated temperatures for an unprotected compressed member: HD product range

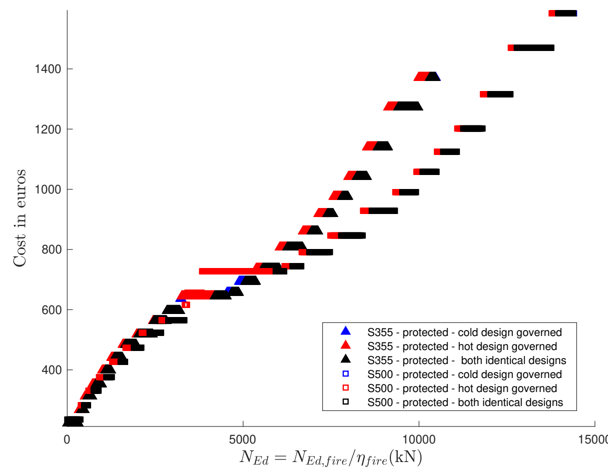
5.2.2 Protected members

For the protected tensile case, the cold design governed the choice of the optimal profile as $k_{y,30min} > \eta_{fire}$ with a constant value of $k_{y,30min}$ equal to 0.78 over the whole range. This observation cannot be extended to the compression case as the compressive strength will be degraded by instabilities. This thermal degradation of the compressive strength $k_{b,fi}$ for a protected element will be higher than in tension as it depends on the flexural buckling of the element as well as its section classification which will be more unfavourable at elevated temperatures. This thermal degradation will therefore give different results where the fire design will be more likely to govern the choice of the optimal profile. This is because the hot condition will become more strict than in protected tension. It is important to note that introducing paint also allows for less thermal degradation and therefore the cold design will be more likely to govern than in the unprotected compressed case.

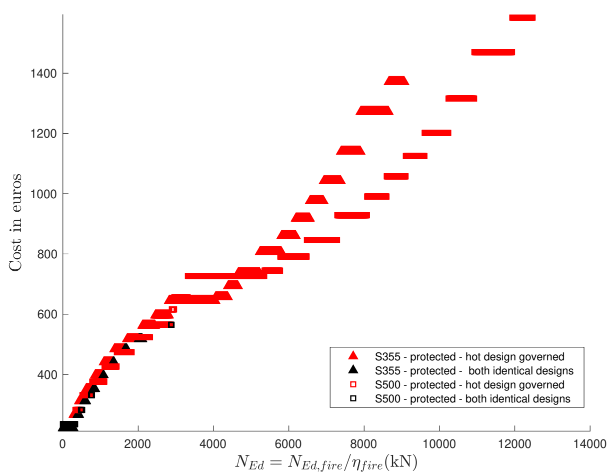
As a recall, the governing design will have the strictest condition, which translates into the Condition 5.9 taking into account $k_{b,fi}$ and η_{fire}. The values of the reduction factor $k_{b,fi}$ are given in Figure 5.11 (d) for the HEA range. The results obtained for a protected compressed element for the HEA range are given in Figure 5.11 for η_{fire}=0.1, η_{fire}=0.65 and η_{fire}=0.75.



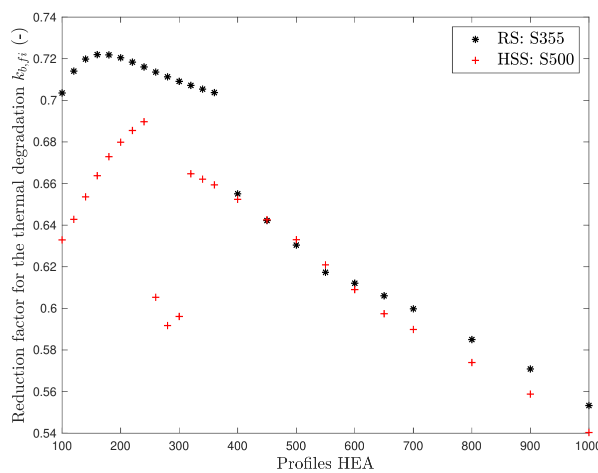
(a) η_{fire}=0.1



(b) η_{fire}=0.65



(c) η_{fire}=0.75



(d) Reduction factor for the thermal degradation $k_{b,fi}$

Figure 5.11: Ambient and elevated temperatures for a protected compressed member: HEA product range

To justify these results, the same explanation will be given as in the unprotected compressed case based on Condition 5.9. As a reminder, the fire condition will be stricter if $k_{b,fi} < \eta_{fire}$. As shown in Figure 5.11 (d), the values of $k_{b,fi}$ are between 0.72 and 0.56. Thus, it is logical that for values of η_{fire} higher than 0.72, the fire condition will be dominant since the increase of the optimal profile will be the fastest for the fire design. This observation confirms the results obtained for a η_{fire} of 0.75.

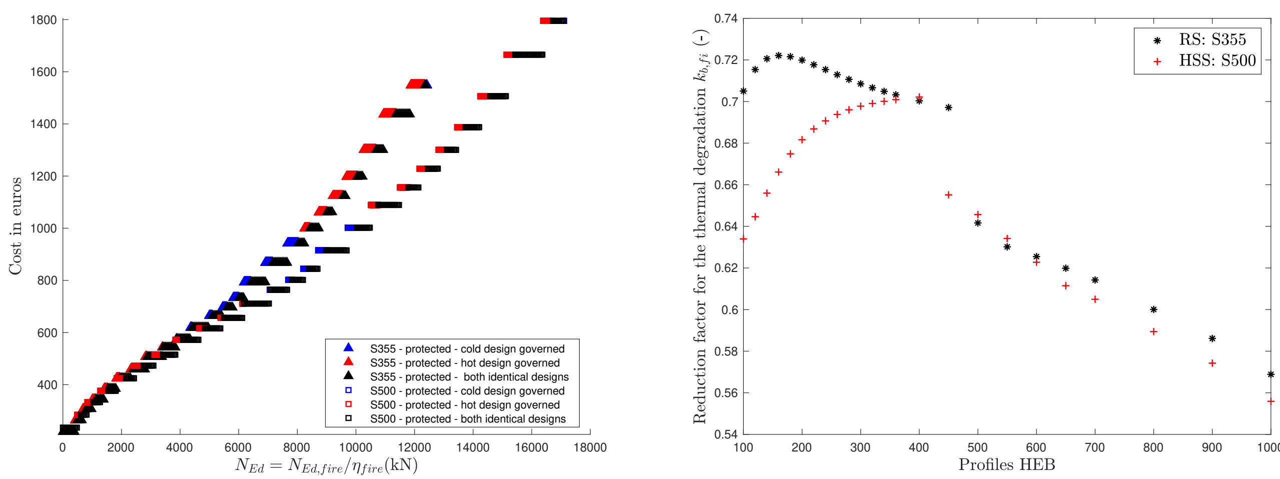
For a η_{fire} of 0.1, the cold design will govern as the thermal degradation is less than the η_{fire} value and therefore the fire condition is less strict than the ambient temperature condition. Thus, the evolution of the optimal profile at ambient temperature will be faster than at elevated temperature.

For a η_{fire} of 0.65, the evolution of the optimal profile increase for the hot design and for the cold design are quite close given the high number of black areas where both designs have the same optimal profile. Indeed, the conditions will be almost similar due to the values of $k_{b,fi}$ being around the value of η_{fire}.

In addition, the thermal degradation will be higher when the HSS grade is used, so the $k_{b,fi}$ values are lower for the HSS grade. This is because the degradation is much higher up to HEA 360 due to the stricter cross-section classification and higher slenderness. The HSS grade will therefore be more susceptible to fire and the fire will govern more than for the RS grade which will have a less strict fire condition.

Variation of product range

For the HEB range, the profiles are less susceptible to fire as shown by the values of $k_{b,fi}$ in Figure 5.12 (b). The results for a η_{fire} of 0.1 and 0.75 are similar to those for the HEA range. For a η_{fire} of 0.65, the results vary since the values of $k_{b,fi}$ will belong to an interval of values similar to the HEA range but the distribution of values in this interval leads to higher values for the HEB range. Furthermore, the cross-section classification will no longer generate lower values of $k_{b,fi}$ as with the HEA 260, HEA 280 and HEA 300 profiles for the HSS grade. Thus, more areas where the cold design governs will appear in the middle of the range. The HSS grade will be more susceptible to fire than the RS grade due to the higher thermal degradation.



(a) η_{fire}=0.65

(b) Reduction factor for the thermal degradation $k_{b,fi}$

Figure 5.12: Ambient and elevated temperatures for a protected compressed member: HEA product range

5.3 Conclusion

When compression is taken into account, the thermal degradation will not be limited to the yield strength reduction factor as in tension. Indeed, compression will induce a higher thermal degradation than in tension and will include instabilities that will be more unfavourable in fire conditions due to the stricter section classification and the higher slenderness. This thermal degradation is represented by a reduction factor $k_{b,fi}$ of the compressive strength at ambient temperature.

Since thermal degradation is higher in compression, the results will be more governed by the choice of the optimal profile of the fire design than in tension results. However, the general conclusions in protected tension can be extended to compression. Thus, the following conclusions can be drawn for unprotected compressed elements:

- By taking a range of products with less fire-susceptible profiles, the cold design will govern more for the same η_{fire} since the thermal degradation will be lower and therefore the fire condition will be less strict.
- By taking a lower η_{fire} for the same range of profiles, the more cold design can govern as the η_{fire} will more easily be lower than the reduction factor for the thermal degradation of the profiles in the range considered.
- Within a given range of profiles, profiles at the end of the range are more likely to have a governing cold design than those at the beginning of the range.
- When the HSS grade is used, the thermal degradation will be higher than for a RS grade. Thus, a higher grade will have a stricter fire condition which will make the fire design more likely to govern the optimal profile selection.

For protected compressed elements, the tension results are no longer valid. Indeed, the introduction of instabilities will make the thermal degradation of the profiles higher than in tension. Thus, the design in fire will be more likely to guide the choice of the optimal profile than in tension. It is important to note that introducing paint also allows for less thermal degradation and therefore the cold design will be more likely to govern than in the unprotected compressed case. The conclusions for unprotected compressed elements are thus applicable to protected elements.

6 Validity assessment of Eurocodes recommendations

This study is carried out for high yield strength steels and therefore for grades below S700. The results of this work were based on a Eurocode recommendation: «The standard is applicable to steels with grades greater than S460 up to S700 without further additional rules» [12]. The validity of this recommendation is therefore the subject of this section and will be verified through available literature by comparing the results of this literature with the results of the Eurocode 3.

The literature reviewed focuses on the mechanical behaviour of high strength steel at elevated temperatures. Two factors were questioned in this literature review: the yield strength reduction factor k_y and the Young's modulus reduction factor k_E. As a reminder, the reduction factors represent the degradation of the mechanical properties of steel at elevated temperatures.

It is important to note that the reduction factor values are similar between the actual Eurocode version [13] and the future version [21]. The values of the reduction factors are defined in Table 5.3 of the future version of the Eurocode 3 part 1-2 [21] and have to be linearly interpolated to generate a curve representing the evolution of the factor according to the steel temperature.

6.1 Yield strength reduction factor

For the yield strength reduction factor, according to the considered documents, the conclusion varies: the Eurocode overestimates or underestimates the real values. However, a general trend of overestimation seems to dominate which may lead to unsafe fire design.

The different documents' conclusions on the yield strength reduction factor can be synthesised as follows:

- **Modeling elevated-temperature mechanical behavior of high and ultra-high strength steels in structural fire design [18]:**
  Eurocode overestimates the reduction factor k_y espicially between 400 °C and 800 °C. However, the k_y values for regular steels are overestimated in a similar way as for high yield steels and these values are considered applicable despite the unsafe side. The authors suggest adjusting the Eurocode curve by making the curve fit the weighted centrelines resulting from their comparative analysis. It does not give a simplified model but just a suggestion for improvements.

- **Mechanical properties of High and Very High Strength Steel at elevated temperatures and after cooling down [17]:**
  Eurocode curve underestimates the reduction factor. A simplified non linear model is proposed to predict the reduction factor k_y. Two alternative equations are proposed using expontential or summation of sines forms. However, the author points out that Equation 6.1, in exponential form, is the one that can be considered ideal. Indeed, the sine equation introduces a sudden drop in the reduction factor at 100 °C which does not represent the behaviour of the experimental data. The selected model is the following:

$$k_y = a_{y,1} \exp\left[-\left(\frac{x - b_{y,1}}{c_{y,1}}\right)^2\right] + a_{y,2} \exp\left[-\left(\frac{x - b_{y,2}}{c_{y,2}}\right)^2\right] \tag{6.1}$$

  The parameters were found using a non linear fitting method and are detailed in Figure 6.1.

parameter	k_y	k_u	k_E
a_1	−85.81	0.9878	0.1871
b_1	184.4	40.68	−12.96
c_1	297.7	469.1	132
a_2	86.73	0.3482	0.9199
b_2	184.2	437.9	181.6
c_2	299.8	205.9	483.9

Figure 6.1: Maraveas eq 1: parameters of the proposed model [17]

- **Experimental studies on mechanical properties of S700 MC steel at elevated temperatures [26]:**
  The reduction factor decreases from 100 °C while the Eurocode have no decrease up to 400 °C. The authors compared their experimental data with the literature and observed a wide dispersion of results between 200 °C and 700 °C. However, the results are typically lower than the reduction factors provided by the Eurocode between 200 °C and 400 °C. A proposed model of the yield strength reduction factor is given based on the tests for S700 MC (thermomechanically rolled for cold-forming):

$$\begin{aligned} k_y &= 1.02 - 4 \times 10^{-4}\theta + 4.5 \times 10^{-7}\theta^2 && 20^\circ \leq \theta < 300^\circ \\ k_y &= 1.07 - 4 \times 10^{-4}\theta - 2.7 \times 10^{-6}\theta^2 && 300^\circ \leq \theta < 600^\circ \\ k_y &= 3.55 - 8.34 \times 10^{-3}\theta + 5 \times 10^{-6}\theta^2 && 600^\circ \leq \theta \leq 800^\circ \end{aligned} \tag{6.2}$$

- **Temperature-Dependent Material Modeling for Structural Steels: Formulation and Application [25]:**
  The US National Institute of Standards and Technology (NIST) developed an elevated-temperature stress-strain model for structural steels taking into account many literature data and tests. The following equation is used to predict the yield strength reduction factor:

$$k_y = r_5 + (1 - r_5)\exp\left[-\frac{1}{2}\left(\frac{T-20}{r_3}\right)^{r_1} - \frac{1}{2}\left(\frac{T-20}{r_4}\right)^{r_2}\right] \tag{6.3}$$

  The parameters of the NIST model are calibrated to fit the whole data set.

Parameter	Value (Ord.)	Value (FR)	Value (plate)	Value (bolt)	Units	Eq.
r_1	7.514	9.782	10.143	4.967		(2.4)
r_2	1.000	1.000	1.000	1.000		(2.4)
r_3	588	625	589	456	°C	(2.4)
r_4	676	1334	837	2040	°C	(2.4)
r_5	0.090	0	0	0	°C	(2.4)
k_1	7.820	9.814	10.616			(2.10)
k_2	540	616	811		°C	(2.10)
k_3	1006	5835	959		MPa	(2.10)
k_4	0.759	15.846	0.766			(2.10)
n	0.503	0.456	0.349			(2.10)
m_0	0.0108					(2.9)
m_1	7.308					(2.9)
m_2	613				°C	(2.9)
m_3	0.126					(2.9)
$\dot{\epsilon}_0$	8.333×10^{-5}				s^{-1}	(2.9)
E_0	206.0				GPa	(2.2)
e_1	3.768					(2.2)
e_2	1.000					(2.2)
e_3	639				°C	(2.2)
e_4	1650				°C	(2.2)

Figure 6.2: NIST model: values of parameters [25]

- **Behavior and Design of High-Strength Constructional Steel [16]:**
  Eurocode overestimates the reduction factor k_y. The authors propose to use the model developed by the US National Institute of Standards and Technology (NIST). The equation used in this paper is the same as Equation 6.3 from [25]. However, the parameters are different because they are calibrated to fit their own experimental data given in Figure 6.3.

	Q550	Q690	Q890	All
e_1	1.421	8.308	2.076	7.026
e_2	3.803	2.684	6.442	2.723
e_3	782°C	656°C	1044°C	657°C
e_4	580°C	1035°C	620°C	810°C
r_1	6.239 (4.963)	6.245 (5.953)	8.031 (7.734)	6.700 (5.98)
r_2	1.815 (6.866)	0.461 (0.3328)	0.758 (0.9486)	0.945 (1.168)
r_3	576°C (512°C)	547°C (541°C)	575°C (574°C)	563°C (546°C)
r_4	729°C (1910°C)	7921°C (184,000°C)	1207°C (1359°C)	1256°C (1932°C)
r_5	0	0	0	0

Figure 6.3: Calibrated NIST model: values of parameters in NIST model for curve fitting [16]

- **Rules on high strength steel (RUOSTE) : final report [10]:**
  The yield strength reduction factors of the Eurocode proofed to be optimistic, which can be also found for regular steels. The behaviour of high strength steels is very similar to that of regular steels and therefore the same reduction factors could be used for both. It is therefore assumed that the Eurocode yield strength reduction factors might be applicable for high strength steels.

- **High strength steel design and execution guide [9]:**
  «The strength reduction factors for conventional strength steel given in EN 1993-1-2 can be safely applied to HSS up to and including S700.»

In these documents, four of them provide a simplified model which, according to the document authors, seems to be a better approximation to obtain the yield strength reduction factor. The 4 models will be displayed on the same graph with the Eurocode curve in order to compare them and identify whether one curve seems more relevant.

In Figure 6.4, the different curves can be described as follows: The Maraveas curve eq1 corresponds to Equation 6.1. The Saani Shakil, Weir Lu, Jari Puttonen curve corresponds to Equation 6.2. The NIST model (all) curve corresponds to Equation 6.3 with the parameters in the "All" column in Table 6.3, this column corresponds to the parameters determined for all of the grades experimentally tested by the document [16]. The NIST model curve (ordinary) corresponds to Equation 6.3 with the parameters in the "Ord" column in Table 6.2, this column corresponds to the parameters for all their data relating to ordinary structural steels.

On the basis of Figure 6.4 (A), the Saani Shakil, Weir Lu, Jari Puttonen curve can be rejected. Indeed, it is limited to a temperature of 800 °C, on top of that the curve is not smooth, and finally, it is not recommended to have several equations for a single model. The NIST model (all) curve can also be rejected because it uses a limited data set to establish its parameters. By discarding these two curves, only the Maraveas eq1 and NIST model (ordinary) curves remain suitable as shown in Figure 6.4 (B). However, the Maraveas eq1 curve [17] is based on an opposite finding compared to the literature, Eurocode underestimates the reduction factors, so the curve seems unreliable.

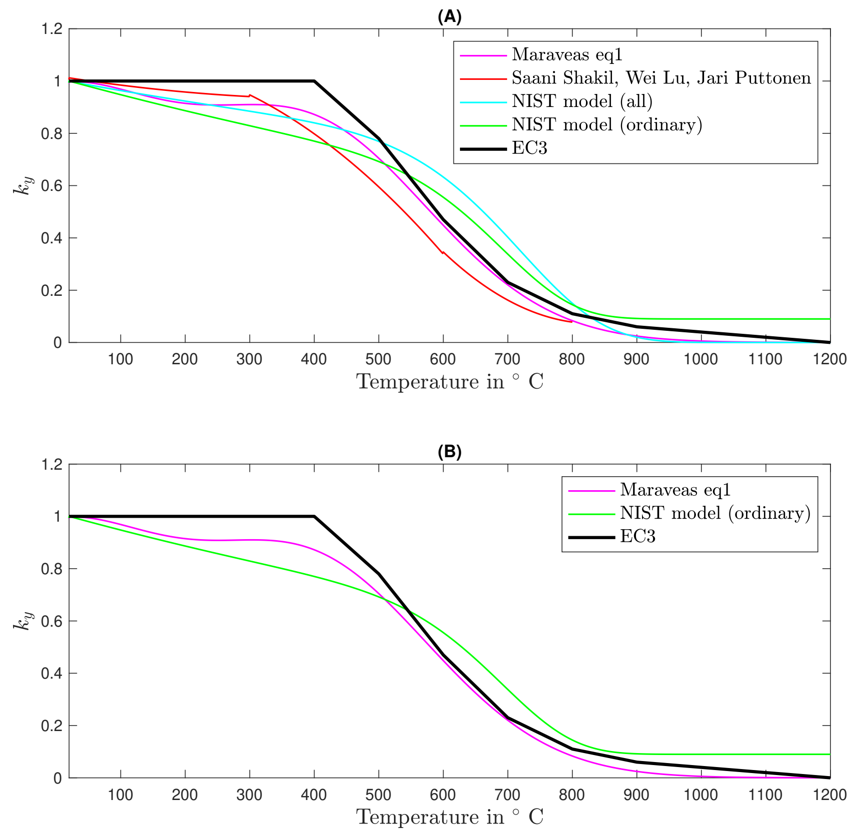


Figure 6.4: Yield strength reduction factor: Maraveas eq1 [17]; Saani Shakil, Weir Lu, Jari Puttonen [26]; NIST model (all) [16]; NIST model (ordinary) [25]; EC3 [21]

As most of the literature has pointed out [18], [26], [25], [16], [10], Eurocode overestimates the yield strength reduction factors mainly between 200 °C and 600 °C for high yield strength steels, however, the RUOSTE project developed by the European Commission [10] states that there is no need to modify the k_y reduction factors and that the Eurocode is applicable. In fact, this overestimation of k_y is already existing for regular steels and does not prevent the Eurocode from being applicable even if it is on the unsafe side. The documents [18] and [9] supports the observation related to the similar behaviour of HSS and RS. The assumption of considering the Eurocode reduction factors for HSS is therefore validated.

6.2 Young's modulus reduction factor

In this section, the Young's modulus reduction factor literature will be reviewed in the same manner as in Section 6.1. In the literature, a general trend appears: the Young's modulus reduction factors are underestimated which can lead to an overconservative fire design and which risks to lead to failure modes related to instabilities [18].

The different documents' conclusions on the Young's modulus reduction factor can be synthesised as follows:

- **Modeling elevated-temperature mechanical behavior of high and ultra-high strength steels in structural fire design [18]:**

Eurocode underestimates the reduction factor k_E especially between 550 °C and 800 °C. The authors argue that it is difficult to establish the reduction factor because the data are highly scatter and suggest adjusting the Eurocode curve by making the curve fit the weighted centrelines resulting from their comparative analysis. It does not give a simplified model but just a suggestion for improvements.

- **Mechanical properties of High and Very High Strength Steel at elevated temperatures and after cooling down [17]:**
  Eurocode is overconservative especially between 350 °C et 600 °C. A simplified non linear model is proposed to predict the reduction factor k_E. As in Section 6.1, Equation 6.4 in exponential form is the one that can be considered ideal. The selected model is the following:

$$k_E = a_{E,1} \exp\left[-\left(\frac{x - b_{E,1}}{c_{E,1}}\right)^2\right] + a_{E,2} \exp\left[-\left(\frac{x - b_{E,2}}{c_{E,2}}\right)^2\right] \tag{6.4}$$

  The parameters were found using a non linear fitting method and are detailed in Figure 6.1.

- **Material properties of high strength steel under fire conditions [27]:**
  Above 100 °C, Eurocode underestimates the Young's modulus reduction factor.

- **Experimental studies on mechanical properties of S700 MC steel at elevated temperatures [26]:**
  Even if there is a high dispersion of the value, Eurocode underestimates the reduction factors k_E especially around 400 °C. The reduction factor k_E should be revised on the entire temperature range. A proposed model of the yield strength reduction factor is given based on the tests for S700 MC (thermomechanically rolled for cold-forming):

$$\begin{aligned} &k_E = 1\theta + 4.5 \times 10^{-7}\theta^2 && 20° \leq \theta < 200° \\ &k_E = 1.14 - 6.7 \times 10^{-4}\theta && 200° \leq \theta < 400° \\ &k_E = 7.64 - 3.26 \times 10^{-2}\theta + 4.95 \times 10^{-5}\theta^2 - 2.55 \times 10^{-8}\theta^3 && 400° \leq \theta \leq 800° \end{aligned} \tag{6.5}$$

- **Temperature-Dependent Material Modeling for Structural Steels: Formulation and Application [25]:**
  Eurocode underestimates the reduction factor values. The US National Institute of Standards and Technology (NIST) developed an elevated-temperature stress-strain model for structural steels taking into account many literature data and tests. The following equation is used to predict the Young's modulus reduction factor:

$$k_E = \exp\left[-\frac{1}{2}\left(\frac{T - 20}{e_3}\right)^{e_1} - \frac{1}{2}\left(\frac{T - 20}{e_4}\right)^{e_2}\right] \tag{6.6}$$

  The parameters of the NIST model are calibrated to fit the whole data set and can be found in Figure 6.2.

- **Behavior and Design of High-Strength Constructional Steel [16]:**
  The Eurocode underestimates the reduction factor values. The authors propose to use the model developed by the US National Institute of Standards and Technology (NIST). The equation used in this paper is the same as the equation 6.6 from [25]. However, the parameters are differents because they are calibrated to fit their own experimental data given in the Figure 6.3.

- **High strength steel design and execution guide [9]:**
«The stiffness reduction factors for conventional strength steel given in EN 1993-1-2 can be safely applied to HSS up to and including S700.»

For the reduction factor of the Young's modulus, all the documents tend towards the same conclusion: The Eurocode understimates the performance of HSS between 100 °C and 800 °C. Therefore, it could be interesting to use another model to predict the reduction factor for the Young modulus at elevated temperature.

As in Section 6.1, four documents provide a simplified model and will be displayed on one graph in order to compare them and identify whether one curve seems more relevant. In Figure 6.5, the different curves can be described as follows: The Maraveas curve eq1 corresponds to Equation 6.4. The Saani Shakil, Weir Lu, Jari Puttonen curve corresponds to Equation 6.5. The NIST model (all) curve corresponds to Equation 6.6 with the parameters in the "All" column in Table 6.3, this column corresponds to the parameters determined for all of the grades experimentally tested by the document [16]. The NIST model curve (ordinary) corresponds to Equation 6.6 with the parameters in the "Ord" column in Table 6.2, this column corresponds to the parameters for all their data relating to ordinary structural steels.

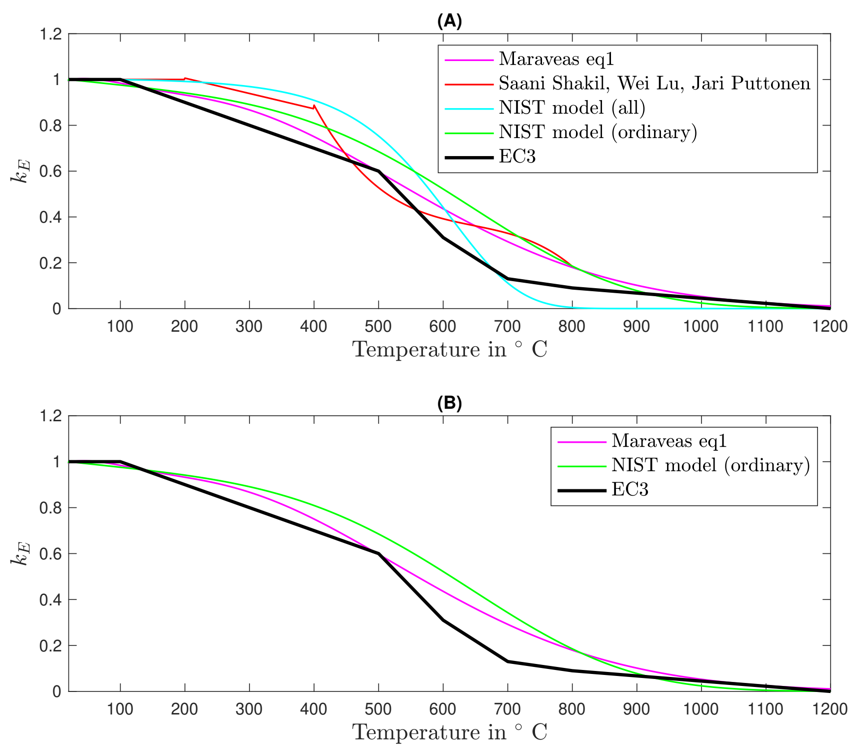


Figure 6.5: Young's modulus reduction factor: Maraveas eq1 [17]; Saani Shakil, Weir Lu, Jari Puttonen [26]; NIST model (all) [16]; NIST model (ordinary) [25]; EC3 [21]

Based on the literature, the reduction factors are underestimate by the Eurocode curve, and so, underestimates the simplified model curves. As already mentioned and based on Figure 6.5 (A), the Saani Shakil, Weir Lu, Jari Puttonen curve can be rejected. Indeed, it is limited to a temperature of 800 °C, on top of that the curve is not smooth, and finally, it is not recommended to have several equations for a single model. The NIST model (all) curve can also be rejected because it uses a limited data set to establish its parameters. By discarding these two curves, only the Maraveas eq1 and NIST model (ordinary) curves remain suitable as shown in Figure 6.4 (B). Two curves could be interesting. However, the NIST model (ordinary) curve [25] seems more appropriate because it is based on a large amount of data from their multiple tests but also from the available literature.

The high strength steel design and execution guide [9] states that the Eurocode k_E reduction factors is applicable. Solely this document validate the Eurocode recommendations, therefore, the assumption of considering the Eurocode reduction factors for HSS could be misleading. The use of one of the simplified models could be a solution to avoid this underestimation of the k_E reduction factors.

6.3 Conclusion

For the yield strength reduction factor, even if the Eurocode overestimates the yield strength reduction factors, the behavior of HSS is believed to be the same as the regular steels. Therefore, the Eurocode reduction factors for HSS can validated even if it is on the unsafe side.

For the reduction factor of the Young's modulus, all the documents tend towards the same conclusion: The Eurocode understimates the performance of HSS. Therefore, it could be interesting to use another model to predict the reduction factor for the Young modulus at elevated temperature. One model was considered relevant: NIST model (ordinary) [25] corresponding to Equation 6.6. However, further reasearch should be made before being able to revise the Eurocode model.

7 Conclusions and perspectives

The main objective of this work was to determine the economic interest of using an HSS grade compared to an RS grade taking into account 30 minutes fire conditions which will degrade the mechanical properties of the steel. This work will be based on the development of appropriate calculation methods incorporating fire resistance at 30 minutes exposure in the process of selecting the optimal profile. These codes were used to obtain the results of this study but can also be used for a specific situation belonging to the field of application defined in this work.

Some key conclusions on the study of the interest of HSS grades at high temperatures can be highlighted:

- A member subjected to tension will have large zones of economic interest of HSS grades. When the member is subjected to compression with flexural buckling, these areas of interest will be reduced due to the consideration of instabilities which will be amplified with fire conditions. The more slender the member, the less interest there will be in using an HSS grade as the strength of the profile converges for all grades with increasing slenderness.

- In both tension and compression, the use of passive protection (intumescent paint) will allow significantly higher 30 minute fire resistances to be achieved. However, a large area of non-interest will arise due to the paint cost dominating the overall cost and generating an area where some profiles will not be accessible (higher cost than a larger profile in the range). Outside of this area, the HSS grade will be of interest as it is more interesting to increase the grade than to increase the profile and therefore to have more paint required.

- The use of a higher grade will allow higher strengths to be achieved which will extend the the field of interest of HSS. When a member is compressed and subjected to flexural buckling, the higher the grade, the stricter the cross-section classification and the higher the slenderness; this is detrimental to the interest of HSS grades, especially for profiles from the beginning of the range.

- The results will depend on the section factor corresponding to the ratio between the exposed surface area and the volume of steel. The lower the section factor, the lower the degradation of the element and the less susceptible it is to fire. It is therefore preferable to use profiles with low section factor under fire conditions.

In addition to the study of the economic interest of HSS grades, routines have been developed to determine which design, between ambient and elevated temperature, will govern the element dimensioning, and thus the selection of the optimal profile. This will depend on the thermal degradation of the element as well as the reduced fire load considered which will be obtained based on the applied load at ambient temperature degraded by the reduction factor for design load level in the fire situation η_{fire}.

In the case of tensioned elements, the thermal degradation of the resistance will depend only on the value of the reduction factor of the yield strength. When compression is taken into account, and therefore instabilities, the thermal degradation is higher than the one in tension. Consequently, the results in compression will be more governed by the fire design than in tension.

The introduction of the protection will result in less thermal degradation and therefore the cold design will be more likely to govern. For protected tensioned elements, the design at ambient temperature will be the dimensioning design in any considered case. However, this conclusion does not extend to protected tensioned elements which will have higher thermal degradation. Hence, the fire design will be more likely to govern for a compressed protected element than one in tension.

The following general conclusions apply to unprotected tensioned elements as well as to unprotected and protected compressed elements:

- By taking a range of products with less fire-susceptible profiles, the cold design will govern more for the same η_{fire} since the thermal degradation will be lower.
- By taking a lower η_{fire} for the same range of profiles, the cold design will govern more as the η_{fire} will more easily be lower than the reduction factor for the thermal degradation of the profiles in the range considered.
- Within a given range of profiles, profiles at the end of the range are more likely to have a governing cold design than those at the beginning of the range.
- In compression, a higher grade will make the fire design more likely to govern due the higher thermal degradation for HSS grade.

To complete this work, an existing literature review was carried out to validate the assumptions used by Eurocode 3 part 1-2, and therefore of this work. Indeed, the Eurocode uses the same reduction factors for yield strength and Young's modulus for all the considered grades (RS and HSS) which the literature seemed to contradict. Based on the literature, for the yield strength reduction factor, the Eurocode reduction factors for HSS can be validated. However, for the reduction factor of the Young's modulus, the Eurocode understimates the performance of HSS and therefore it could be interesting to use another model to predict the reduction factor for the Young modulus at elevated temperature. One model was considered relevant: NIST model (ordinary) [25]. However, further reasearch should be made before being able to revise the Eurocode model.

The economic study carried out in this work is based on several simplifying assumptions which give first results, but further research should be carried out in order to quantify more precisely the economic interest of these steels and thus to have a more accurate cost of those. Research is currently underway at the University of Liège on this subject and this work is part of its developments.

An important detail can be highlighted concerning the protected results. Indeed, these results have been obtained with rather approximate cost assumptions. These results should therefore be taken with great caution. One perspective would be to improve the definition of intumescent paint costs through further research and also to extend the use of passive protection to other profile ranges or even to use other passive protection techniques.

In this work, a very precise and limited field of study has been defined. It could be interesting to extend this domain by using more profile ranges and also by widening the length range studied, especially for ranges reaching much higher strengths such as the HD range. Another obvious perspective would be to extend this study to other loadings such as bending. As mentioned in the ambient temperature work, it would also be interesting to carry out a global study of the interest of HSS grades under fire conditions using simple steel structures, e.g. frames.

Finally, this work was carried out to determine the suitability of HSS steels for a 30-minute fire load. It would therefore be interesting to carry out the same study for a 60 minute or 120 minute fire exposure. It is obvious that this additional study will be limited to ranges that are not very fire-susceptible or to protected elements.

A Fire resistance tables

A - 1 Under tension

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEAA	554	10018	655	11852	718	12981	780	14110	858	15521	967	17496	1076	19472
HEA	753	12311	890	14566	975	15953	1060	17340	1166	19074	1314	21502	1463	23929
HEB	923	14200	1092	16800	1196	18400	1300	20000	1430	22000	1612	24800	1794	27600
HEC	1395	8410	1651	9950	1808	10897	1965	11845	2162	13030	2437	14688	2712	16346
HEM	1889	15769	2234	18656	2447	20433	2660	22210	2926	24431	3298	27540	3671	30650
HD	2450	58742	2898	69497	3174	76116	3450	82735	3795	91009	4278	102591	4761	114174

Table A.1: N_{Rd} in kN for an unprotected member in tension

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEAA	53	1795	62	2124	68	2326	74	2529	81	2781	92	3135	102	3489
HEA	75	2385	89	2821	97	3090	106	3359	116	3695	131	4165	146	4635
HEB	98	2981	116	3527	127	3863	138	4199	152	4619	171	5207	190	5795
HEC	214	2238	253	2647	277	2900	301	3152	331	3467	374	3908	416	4349
HEM	347	4564	410	5399	449	5914	488	6428	537	7071	606	7971	674	8871
HD	267	58742	316	69497	346	76116	376	82735	414	91009	466	102591	519	114174

Table A.2: $N_{fi,30min,Rd}$ in kN for an unprotected member in tension with 4 faces exposed

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEAA	55	1882	66	2226	72	2438	78	2650	86	2915	97	3286	108	3657
HEA	87	2554	102	3022	112	3310	122	3598	134	3957	151	4461	168	4965
HEB	520	7995	615	9458	673	10359	732	11260	805	12386	908	13962	1010	15539
HEC	259	3651	307	4320	336	4731	365	5142	401	5657	452	6377	504	7097
HEM	396	6949	469	8222	514	9005	558	9788	614	10766	692	12137	770	13507
HD	376	58742	444	69497	487	76116	529	82735	582	91009	656	102591	730	114174

Table A.3: $N_{fi,30min,Rd}$ in kN for an unprotected member in tension with 3 faces exposed

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEA	587	9603	695	11361	761	12443	827	13525	909	14878	1025	16771	1141	18665
HEB	720	11076	852	13104	933	14352	1014	15600	1115	17160	1257	19344	1399	21528

Table A.4: $N_{fi,30min,Rd}$ in kN for a protected member in tension with 4 faces exposed

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEA	424	6931	501	8200	549	8981	597	9762	656	10739	740	12105	824	13472
HEB	520	7995	615	9458	673	10359	732	11260	805	12386	908	13962	1010	15539

Table A.5: $N_{fi,30min,Rd}$ in kN for a protected member in tension with 3 faces exposed

A - 2 Under compression

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEAA	272	8501	286	9801	322	10586	327	11363	333	12323	339	13649	343	14957
HEA	390	10830	413	12545	467	13586	476	14617	485	15893	494	17661	502	19411
HEB	493	12950	523	14997	594	16237	606	17465	618	18983	631	21084	642	23159
HEC	796	8048	850	9417	973	10485	996	11350	1020	12422	1045	13907	1065	15372
HEM	1142	14753	1230	17090	1417	18504	1456	19903	1496	21631	1540	24021	1575	26379
HD	1695	55510	1853	64933	2145	72594	2216	78548	2292	85905	2381	96038	2454	105965

Table A.6: $N_{b,Rd}$ in kN for an unprotected member in compression

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEAA	20	1176	22	1371	22	1489	23	1607	24	1752	25	1954	26	2154
HEA	29	1679	32	1964	33	2137	35	2310	36	2524	37	2821	39	3117
HEB	39	2156	42	2522	44	2745	46	2967	48	3242	50	3625	51	4004
HEC	80	1783	87	2097	91	2288	94	2478	97	2712	101	3036	104	3354
HEM	132	3705	143	4363	149	4764	154	5163	160	5657	166	6342	171	7017
HD	164	51874	192	61302	209	67094	226	72876	246	80092	275	90170	303	100221

Table A.7: $N_{fi,b,30min,Rd}$ in kN for an unprotected member in compression with 4 faces exposed

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEAA	21	1231	22	1436	23	1560	24	1683	25	1835	26	2047	27	2256
HEA	32	1797	35	2101	37	2287	38	2471	39	2700	41	3019	42	3335
HEB	47	2464	51	2883	53	3138	55	3391	57	3706	59	4143	60	4576
HEC	91	2946	99	3468	102	3786	106	4101	109	4493	113	5034	117	5567
HEM	145	5718	157	6738	163	7362	168	7981	174	8751	181	9819	186	10876
HD	225	52065	263	61534	286	67351	308	73160	336	80410	374	90539	411	100641

Table A.8: $N_{fi,b,30min,Rd}$ in kN for an unprotected member in compression with 3 faces exposed

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEA	215	6812	233	7966	242	8670	250	9369	259	10238	269	11445	277	12643
HEB	272	8078	295	9450	307	10287	318	11118	329	12150	343	13583	354	15004

Table A.9: $N_{fi,b,30min,Rd}$ in kN for a protected member in compression with 4 faces exposed

	S355		S420		S460		S500		S550		S620		S690	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
HEA	146	4904	158	5735	164	6242	169	6745	174	7370	181	8239	186	9101
HEB	186	5815	201	6803	208	7405	215	8004	222	8746	231	9778	238	10801

Table A.10: $N_{fi,b,30min,Rd}$ in kN for a protected member in compression with 3 faces exposed

B Complete design

This appendix aims to detail a complete design in tension and compression. This will allow a better understanding and verification of the procedure used by the code that has been developed in this work.

B - 1 Tension member

In this illustrative example, the unprotected situation with 4 faces fire exposed is considered. The optimum profiles for zone 2 in the section 3.2 will be used, i.e. the HEA 180 profile for grade S355 and HEA 160 for grade S500. The differences between the protected and unprotected situation as well as for 3 or 4 sides exposed to fire will be highlighted. This example corresponds to a fire load $N_{Ed,fire}$ of 160 kN. The example will be developed for these two profiles in order to compare the costs of the two profiles and to verify that this example is in a zone of no interest.

1. **Section factor with the correction factor taking into account the shadow effect $k_{sh}A_m/V$:**

   For an element exposed on its 4 sides the equation is as follows:

   $$k_{sh}A_m/V = 0.9[A_m/V]_{box} = 0.9\frac{(2b+2h)}{A}$$

   For the HEA 160 profile:

   $$k_{sh}A_m/V = 0.9[A_m/V]_{box} = 0.9\frac{(160+152)*2}{3880} \times 10^3 = 144.7423m^{-1}$$

   For the HEA 180 profile:

   $$k_{sh}A_m/V = 0.9[A_m/V]_{box} = 0.9\frac{(180+171)*2}{4530} \times 10^3 = 139.47m^{-1}$$

   When the element is exposed on 3 sides, the difference will occur in this step as shown in the following equation:

   $$k_{sh}A_m/V = 0.9[A_m/V]_{box} = 0.9\frac{(b+2h)}{A}$$

   This equation gives a value of 107.63 m^{-1} for the HEA 160 profile and 103.71 m^{-1} for the HEA 180 profile. In the further development, only the element exposed on its 4 faces will be considered.

2. **Temperature of the steel at 30 min $\theta_{a,30min}$:**

   As a recall, this project focuses on the fire resistance at 30 minutes. Therefore, it is necessary to determine the steel temperature at 30 minutes.

   - For an unprotected element, the determination of this temperature was carried out as explained in the section 2.3.3 according to the Eurocode [19]. Since this computation requires a high number of iterations, nomograms will be used to compare the results by hand with the developed code results. The nomogram is taken from a technical note from Info Steel [6] and is a graphical method for determining the fire resistance of steel structures.

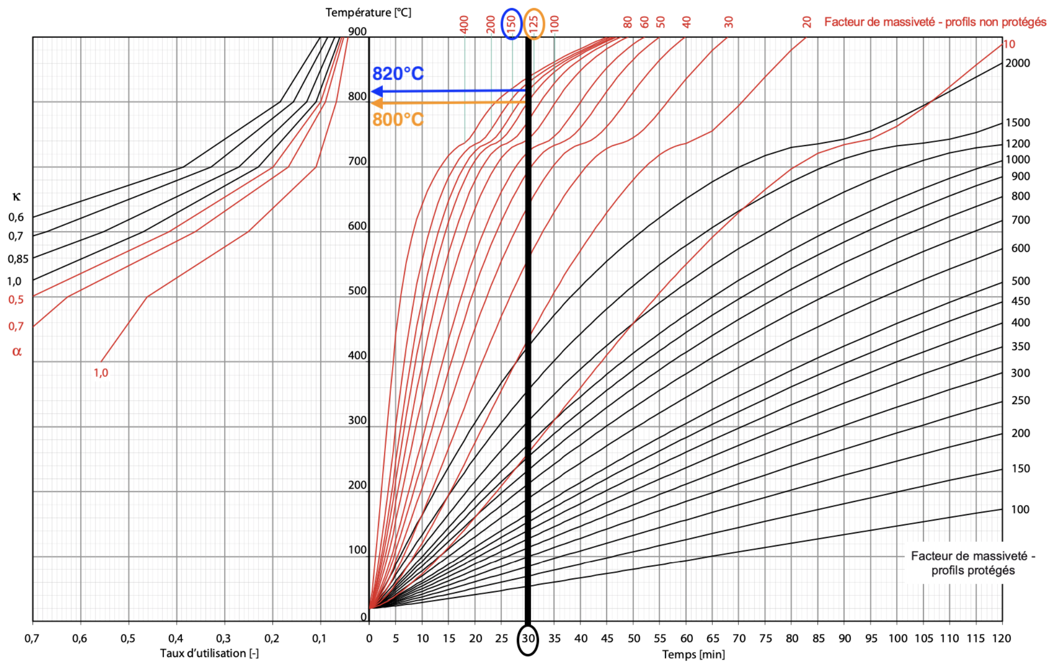


Figure B.1: Nomogram

For this graphical method, the values obtained in the previous step must be used. These are contained between $150m^{-1}$ and $125m^{-1}$, so these two curves will be used. As shown in Figure B.1, the temperature of the steel will therefore be between 800 °C and 820 °C. The numerical values of the steel temperatures provided by the code are:

$$\theta_{a,30min,HEA160} = 811.3°\text{C}$$

$$\theta_{a,30min,HEA180} = 808.1°\text{C}$$

The results obtained in this work are therefore consistent with the graphical method based on the Eurocode.

- When the element is protected, the section factor will not be computed. As explained in the section 2.4.2, the protection will impose a steel temperature at 30 minutes depending on the situation considered: 500 °C for the 4 exposed faces and 570 °C for 3 exposed faces. In this example the temperature of the steel at 30 minutes will be:

$$\theta_{a,30min} = 500°\text{C}$$

3. **Yield strength reduction factor** $k_{y,30min}$**:**

To obtain the yield strength reduction factor for an unprotected or protected element, the values of Table 5.3 of Eurocode prEN 1993-1-2 [21] must be used and a linear interpolation according to the 30 minutes steel temperature $\theta_{a,30min}$ obtained in the previous step must be performed. The following computation can therefore be done by hand:

$$k_{y,30min,HEA160} = k_{y,800°\text{C}} + (k_{y,900°\text{C}} - k_{y,800°\text{C}}) \times \frac{(\theta_{a,30min,HEA160} - 800)}{(900 - 800)}$$
$$= 0.11 + (0.06 - 0.11) \times \frac{(811.3 - 800)}{(900 - 800)} = 0.1044$$

The hand values are as follows:

$$k_{y,30min,HEA160} = 0.1044$$

$$k_{y,30min,HEA180} = 0.1059$$

4. **Design tension resistance of the cross-section N_{Rd} for normal temperature design:**

The design tension resistance can be computed based on the Eurocode [11]:

$$N_{Rd} = \frac{A \times f_y}{\gamma_{M,0}}$$

- A: the cross-section of the element.
- f_y: the steel yield strength.
- $\gamma_{M,0} = 1$.

Based on this equation, the following two resistances N_{Rd} are obtained:

$$N_{Rd,HEA160} = 3880 \times 500 = 1940000N = 1940kN$$

$$N_{Rd,HEA180} = 4530 \times 355 = 1608150N = 1608.15kN$$

5. **Design resistance $N_{fi,30min,Rd}$ of a tension member with a uniform temperature:**

According to the prEN1993-1-2:2021(E) [21], the design resistance $N_{fi,\theta_{A,30min},Rd}$ under fire condition should be determined based on the following equation:

$$N_{fi,30min,Rd} = k_{y,30min} \times N_{Rd} \times [\gamma_{M,0}/\gamma_{M,fi}]$$

Where

- $k_{y,30min}$: reduction factor for the yield strength of steel at temperature $\theta_{a,30min}$ reached at 30 minutes.
- N_{Rd}: design tension resistance of the cross-section for a normal temperature design.
- $\gamma_{M,0} = 1$ and $\gamma_{M,fi} = 1$.

The two fire resistances $N_{fi,30min,Rd}$ can be computed by hand as follows:

$$N_{fi,30min,Rd,HEA160} = 0.1044 \times 1940 = 202.5360kN$$

$$N_{fi,30min,Rd,HEA180} = 0.1059 \times 1608.15 = 170.3031kN$$

The numerical values based on the code are as follows:

$$N_{fi,30min,Rd,HEA160} = 202.429kN$$

$$N_{fi,30min,Rd,HEA180} = 170.024kN$$

The fire resistances of the considered profiles are therefore higher than the applied fire load of 160 kN. The hand computed values are almost equivalent to the numerical values and the difference is due to the rounding introduced by the hand computation. The hand computation allows to validate the developments made in the code.

6. **Cost computation:**

- In the unprotected case, the cost can be computed as followed:

$$Cost_{\text{grade,unprotected}} = G \times L \times c_{grade}$$

Where:

  - G is the mass per unit length of the considered profile (kg/m)
  - L is the length of the considered member (mm)
  - c_{grade} is the price per kilogram of the considered grade (€/kg) composed of the relative cost of the considered grade $\frac{c_{grade}}{c_{S355}}$ (Table 2.2) and the steel price per kilogram for S355 grade $c_{S355} = 1.2$€/kg.

The unprotected costs of the situation under consideration can therefore be computed:

$$Cost_{\text{S355,unprotected, HEA 180}} = 35.5 \times 3.5 \times 1 \times 1.2 = 149.1\text{€}$$

$$Cost_{\text{S500,unprotected, HEA 160}} = 30.4 \times 3.5 \times 1.187 \times 1.2 = 151.56\text{€}$$

- If the profile was protected, another equation is used to determine the cost and is the following:

$$Cost_{\text{grade,protected}} = G \times L \times c_{grade} + \text{WFT} \times A_L \times L \times c_{\text{WTF}} \times \text{Amplification factor}$$

Where:

  - WFT is the wet film thickness (mm) and corresponds to $\text{WFT} = \frac{\text{DFT}}{0.65}$ with DFT the dry film thickness (mm) given by the Table 2.4 for 4 faces exposed element.
  - A_L is the painted surface per unit length (mm^2/mm)
  - L is the length of the considered member (mm) of 3500mm.
  - c_{WFT} is the price per mm^3 of coating in liquid state (€/mm^3) and is 507 € for 25L which gives 2.028×10^{-5} €/mm^3.
  - Amplification factor = 10.

In order to facilitate understanding of the protected cost computation, this will be carried out for the HEA 160 profile with grade S500 and the HEA 180 profile with grade S355.

$$\begin{aligned} Cost_{\text{S355,protected, HEA 180}} &= 35.5 \times 3.5 \times 1 \times 1.2 \\ &+ \frac{0.343}{0.65} \times 1.024 \times 10^3 \times 3500 \times 2.028 \times 10^{-5} \times 10 \\ &= 532.6453\text{€} \end{aligned}$$

$$\begin{aligned} Cost_{\text{S500,protected, HEA 160}} &= 30.4 \times 3.5 \times 1.187 \times 1.2 \\ &+ \frac{0.349}{0.65} \times 0.906 \times 10^3 \times 3500 \times 2.028 \times 10^{-5} \times 10 \\ &= 496.84\text{€} \end{aligned}$$

7. **Interest of HSS: cost comparison**

The economic interest condition for the HSS grade will therefore be :

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

In this example with unprotected element, the condition is the following:

$$\frac{Cost_{\text{S500,unprotected, HEA 160}}}{Cost_{\text{S355,unprotected, HEA 180}}} = \frac{151.56}{149.1} = 1.0165 \nless 1$$

Therefore, the condition of interest of HSS is not respected and this confirm the result detailed in the section 3.2.

B - 2 Compression member

For this example of a complete design in compression, the unprotected case study will consider a 3.5m length of the compressed element, 4 faces exposed to fire, the strong buckling axis and a pinned ends column. For the RS grade, the optimal HEA 300 profile will be considered while the optimal HEA 280 profile will be considered for the HSS grade (S500). This example corresponds to a fire load $N_{Ed,fire}$ of 393 kN.

1. **Class determination:**

According to the prEN1993-1-2:2021(E) [21], the cross-sections may be classified as for normal temperature design with a reduced value for ϵ_{fi} to consider the influence of the elevated temperature:

$$\epsilon_{fi} = 0.85\sqrt{\frac{235}{f_y}}$$

For the RS grade:

$$\epsilon_{fi,RS} = 0.85\sqrt{\frac{235}{355}} = 0.6916$$

For the HSS grade:

$$\epsilon_{fi,HSS} = 0.85\sqrt{\frac{235}{500}} = 0.5827$$

Where f_y is the yield strength at 20 °C. To be able to classify the cross-sections, Table 7.3 from the prEN1993-1-1:2020 [20] is used with f_y at 20 °C and $\epsilon = \epsilon_{fi}$. Based on this table, the following conditions can be used for the internal compression parts:

- Class 1: $d/t_w \leq 28\epsilon_{fi}$
- Class 2: $d/t_w \leq 34\epsilon_{fi}$
- Class 3: $d/t_w \leq 38\epsilon_{fi}$

Where d/t_w is the width to thickness ratio of the web.

For the RS grade: web of HEA 300

- Class 1: $24.4706 \nleq 19.3641$
- Class 2: $24.4706 \nleq 23.5135$
- Class 3: $24.4706 \leq 26.2798 \rightarrow$ Class 3

For the HSS grade: web of HEA 280

- Class 1: $24.5 \nleq 16.3165$
- Class 2: $24.5 \nleq 19.8128$
- Class 3: $24.5 \nleq 22.1438 \rightarrow$ Class 4

For the outstand flanges, the following conditions can be used:

- Class 1: $c/t_f \leq 9\epsilon_{fi}$
- Class 2: $c/t_f \leq 10\epsilon_{fi}$
- Class 3: $c/t_f \leq 14\epsilon_{fi}$

Where c/t_f is the width to thickness ratio of the flanges with $c = (b - t_w - 2 \times r)/2$.

For the RS grade: flanges of HEA 300

- Class 1: $8.4821 \nleq 6.2242$
- Class 2: $8.4821 \nleq 6.9157$
- Class 3: $8.4821 \leq 9.6820 \rightarrow$ Class 3

For the HSS grade: flanges of HEA 280

- Class 1: $8.6154 \nleq 5.2446$
- Class 2: $8.6154 \nleq 5.8273$
- Class 3: $8.6154 \nleq 8.1582 \rightarrow$ Class 4

The class of the cross-section will correspond to the worst class between the flanges and the web of the element. Therefore, the cross-section of the HEA 300 for RS grade is Class 3 and the area is not modified ($\beta = 1$).

For the HEA 280 with an HSS grade, the above conditions are not respected. Therefore, this cross-section is Class 4 (prEN1993-1-5 [22]) and an effective area A_{eff} will be used to consider the plate buckling behavior by using effective widths. In this case, there are no longitudinal stiffeners. The effective area of the compression zone of a plate with the gross cross-sectional area A_c should be obtained from:

$$A_{c,eff} = \rho \times A_c$$

Where ρ is the reduction factor for plate buckling. To take into account the fire situation in the effective cross-section computation procedure, the prEN1993-1-2 [21] proposes a modified ρ factor which can be computed as follows for the profile HEA 280 with an HSS grade:

- Internal compression elements: web

$$\rho = \frac{(\overline{\lambda}_p + 0.9 - \frac{0.26}{\epsilon})^{1.5} - 0.055(3 + \psi)}{(\overline{\lambda}_p + 0.9 - \frac{0.26}{\epsilon})^3} \leq 1$$

$$\rho = 0.67 \leq 1 \rightarrow OK$$

- Outstand compression elements: flanges

$$\rho = \frac{(\overline{\lambda}_p + 1.1 - \frac{0.52}{\epsilon})^{1.2} - 0.188}{(\overline{\lambda}_p + 1.1 - \frac{0.52}{\epsilon})^{2.4}} \leq 1$$

$$\rho = 0.8 \leq 1 \rightarrow OK$$

Where:

- $\epsilon = \sqrt{235/f_y} = \sqrt{235/500} = 0.68$
- $\overline{b}$ is the appropriate width corresponding to d = 196 mm for the web and c = 112 mm for the flanges.

- t is the thickness of the plate corresponding to $t_{web} = 8$ mm for the web and $t_{flange} = 13$ mm for the flanges.
- ψ is the stress ratio given in Table 6.1 for internal elements and Table 6.2 for outstand elements of the prEN1993-1-5 [22]. Since the profile is subjected to pure compression, the value of ψ for the web and flanges is unitary to consider a uniform stress distribution.
- k_σ is the buckling factor corresponding to the stress ratio ψ. For long plates k_σ is given in Table 6.1 for internal elements and Table 6.2 for outstand elements of the prEN1993-1-5 [22]. For stress ratio $\psi = 1$, k_σ is equal to 4 for the web and to 0.43 for the flanges.
- $\overline{\lambda}_p = \frac{\bar{b}/t}{28.4 \times \epsilon \sqrt{k_\sigma}}$ which is $\overline{\lambda}_p = 0.629$ for the web and $\overline{\lambda}_p = 0.675$ for the flanges.

Having determined the reduction factor for plate buckling, it is possible to compute the effective area of the different compression elements based on their effective widths:

- Internal compression elements:

$$b_{eff} = \rho \times d = 130.59mm$$

- Outstand compression elements:

$$c_{eff} = \rho \times c = 89.59mm$$

The effective area for the profile HEA 280 with an HSS grade can be computed as such:

$$A_{eff} = A - (d - d_{eff}) \times t_w - 4 \times (c - c_{eff}) \times t_f = 8041.57mm^2$$

Once the effective area of the cross-section is determined, the penalization coefficient can be defined as follows:

$$\beta = A_{eff}/A$$

This coefficient is equal to 1 for Class 1,2 and 3. Therefore, this penalization coefficient is equal to 1 for the profile HEA 300 with a RS grade and is equal to 0.826 for the profile HEA 280 with an HSS grade (A=9730).

2. **Section factor with the correction factor taking into account the shadow effect $k_{sh}A_m/V$:**

This step is the same as in the tension element case detailed in section B - 1.

For the HEA 280 profile exposed on its 4 sides:

$$k_{sh}A_m/V = 0.9[A_m/V]_{box} = 0.9\frac{(270 + 280) * 2}{9730} \times 10^3 = 101.7472m^{-1}$$

For the HEA 300 profile exposed on its 4 sides:

$$k_{sh}A_m/V = 0.9[A_m/V]_{box} = 0.9\frac{(290 + 300) * 2}{11250} \times 10^3 = 94.4m^{-1}$$

3. **Temperature of the steel at 30 min $\theta_{a,30min}$:**

In this step, the procedure is the same as in the tension element case detailed in section B - 1.

- For an unprotected element, the numerical values of the steel temperatures provided by the code are:

$$\theta_{a,30min,HEA280} = 769.55°\text{C}$$

$$\theta_{a,30min,HEA300} = 759.36°\text{C}$$

For the graphical method using nomogram, the values obtained in the previous step are contained between $100m^{-1}$ and $80m^{-1}$, so these two curves will be used. The temperature of the steel will therefore be between 770 °C and 740 °C. The results obtained in this work are therefore consistent with the graphical method based on the Eurocode.

- When the element is protected, the section factor will not be computed. As explained in the section 2.4.2, the protection will impose a steel temperature at 30 minutes of 500 °C for the 4 exposed faces.

4. **Yield strength reduction factor $k_{y,30min}$ and Young Modulus reduction factor $k_{E,30min}$:**

In this step, the procedure is the same as in the tension element case detailed in section B - 1 but the computation of the Young Modulus reduction factor is required.

To obtain the yield strength reduction factor and the Young Modulus reduction factor for an unprotected or protected element, the values of Table 5.3 of Eurocode prEN 1993-1-2 [21] must be used and a linear interpolation according to the 30 minutes steel temperature $\theta_{a,30min}$ obtained in the previous step must be performed. The values are as follows:

$$k_{y,30min,HEA280} = 0.1465$$

$$k_{E,30min,HEA280} = 0.1022$$

$$k_{y,30min,HEA300} = 0.1588$$

$$k_{E,30min,HEA300} = 0.1063$$

5. **Reduction factor for flexural buckling in the fire design situation χ_{fi}:**

In order to determine the reduction factor for flexural buckling in the fire design situation χ_{fi}, the following steps need to be followed:

(a) The elastic critical force for the relevant buckling mode can be computed based on the following equation:

$$N_{cr} = \frac{\pi^2 \times E \times I}{(K \times L)^2}$$

Where

- E is the Young modulus of steel and is 210 000 MPa.
- I is the inertia around the the considered buckling axis. In this example, the strong axis is considered and therefore the inertia of the strong axis y-y. For the profile HEA 280, the inertia is $I_y = 13670 \times 10^4 mm^4$ and for the profile HEA 300, the inertia is $I_y = 18260 \times 10^4 mm^4$.

- K is the buckling length coefficient which depends on the support conditions. In this example, K is taken equal to 1 because the element has pinned ends.
- L is the length of the element which correspond to 3.5m.

The two following values can be obtained:

$$N_{cr,HEA280} = \frac{\pi^2 \times 210000 \times 13670 \times 10^4}{(1 \times 3500)^2} = 232813N$$

$$N_{cr,HEA300} = \frac{\pi^2 \times 210000 \times 18260 \times 10^4}{(1 \times 3500)^2} = 309482N$$

(b) The relative slenderness at ambiant temperature can be computed based on the classification of the cross-section:

- For Class 1,2 or 3 cross-sections:

$$\overline{\lambda} = \sqrt{\frac{A \times f_y}{N_{cr}}}$$

As established in the classification of the cross-sections, the HEA 300 profile with grade RS is class 3 and its reduced slenderness can be computed as such:

$$\overline{\lambda} = \sqrt{\frac{11250 \times 355}{30894682}} = 0.3595$$

- For Class 4 cross-sections:

$$\overline{\lambda} = \sqrt{\frac{A_{eff} \times f_y}{N_{cr}}}$$

The profile HEA 280 with HSS grade is class 4 and therefore it can be computed as follows:

$$\overline{\lambda} = \sqrt{\frac{0.826 \times 9730 \times 500}{23128713}} = 0.4168$$

(c) The relative slenderness $\overline{\lambda}_\theta$ for the temperature θ_a is taking into account the degradation of the mechanical properties caused by the fire condition and is given by:

$$\overline{\lambda}_\theta = \overline{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

For the profile HEA 280, the relative slenderness is computed as follows:

$$\overline{\lambda}_\theta = 0.4168\sqrt{\frac{0.1465}{0.1022}} = 0.4990$$

For the profile HEA 300, the value is:

$$\overline{\lambda}_\theta = 0.3595\sqrt{\frac{0.1588}{0.1063}} = 0.4394$$

(d) In the fire condition, a specific buckling curve is used and so the imperfection factor can be determined as follows:

$$\alpha = 0.65\sqrt{235/f_y}$$

For the profile HEA 280 with HSS grade this gives:

$$\alpha = 0.65\sqrt{235/500} = 0.4456$$

For the profile HEA 300 with RS grade this gives:

$$\alpha = 0.65\sqrt{235/355} = 0.5289$$

(e) computation of ϕ_θ:

$$\phi_\theta = 0.5(1 + \alpha\overline{\lambda}_\theta + \overline{\lambda}_\theta^2)$$

For the profile HEA 280 with HSS grade:

$$\phi_\theta = 0.5(1 + 0.4456 \times 0.4990 + 0.4990^2) = 0.7357$$

For the profile HEA 300 with RS grade:

$$\phi_\theta = 0.5(1 + 0.5289 \times 0.4394 + 0.4394^2) = 0.7128$$

(f) The value of the reduction factor for flexural buckling in the fire design situation χ_{fi} can be determined according to:

$$\chi_{fi} = \frac{1}{\phi_\theta + \sqrt{\phi_\theta^2 - \overline{\lambda}_\theta^2}}$$

For the profile HEA 280 with HSS grade:

$$\chi_{fi} = \frac{1}{0.7357 + \sqrt{0.7357^2 - 0.499^2}} = 0.78$$

For the profile HEA 300 with RS grade:

$$\chi_{fi} = \frac{1}{0.7127 + \sqrt{0.7128^2 - 0.4394^2}} = 0.785$$

6. **Design resistance $N_{fi,30min,Rd}$ of a tension member with a uniform temperature:**

The design buckling resistance $N_{b,fi,\theta,Rd}$ at time t of a compression member with a uniform temperature θ_a should be determined based on the following equations [21]:

- For Class 1,2 or 3 cross-sections

$$N_{b,fi,\theta,Rd} = \chi_{fi} \times A \times k_{y,\theta} \times f_y/\gamma_{M,fi}$$

For the profile HEA 300 with RS grade which is a Class 3, this resistance can be obtained with hand computation as follows:

$$N_{b,fi,\theta,Rd} = 0.785 \times 11250 \times 0.1588 \times 355 = 497853N = 498kN$$

The numerical value coming from the code is 497 721.5 N.

- For Class 4 cross-sections

$$N_{b,fi,\theta,Rd} = \chi_{fi} \times A_{eff} \times k_{y,\theta} \times f_y/\gamma_{M,fi}$$

For the profile HEA 280 with HSS grade which is a Class 4, this resistance can be obtained with hand computation as follows:

$$N_{b,fi,\theta,Rd} = 0.78 \times 0.826 \times 97390 \times 0.1465 \times 500 = 459193N = 559kN.$$

The numerical value coming from the code is 461 576 N.

In the case of compression, not only the applied fire load is taken into account, but also the self-weight of the profile. The fire load considered is 393 kN and the self-weight to add to the load is 2.674 kN for the HEA 280 profile and 3.09 kN for the HEA 300 profile. The fire resistances of the considered profiles are therefore higher than the applied fire load combined with the self-weight of the profiles.

7. **Cost computation:**

   This step will be the same as the one carried out in the tension example in section B - 1. The case of the protected cost will not be covered as it has already been covered. Only the unprotected cost will be detailed.

8. In the unprotected case, the cost can be computed as followed:

$$Cost_{\text{grade,unprotected}} = G \times L \times c_{grade}$$

   Where:

   - G is the mass per unit length of the considered profile (kg/m)
   - L is the length of the considered member (mm)
   - c_{grade} is the price per kilogram of the considered grade (€/kg) composed of the relative cost of the considered grade $\frac{c_{grade}}{c_{S355}}$ (Table 2.2) and the steel price per kilogram for S355 grade $c_{S355} = 1.2$€/kg.

   The unprotected costs of the situation under consideration can therefore be computed:

$$Cost_{\text{S355,unprotected, HEA 300}} = 88.3 \times 3.5 \times 1 \times 1.2 = 370.86€$$

$$Cost_{\text{S500,unprotected, HEA 280}} = 76.4 \times 3.5 \times 1.187 \times 1.2 = 380.8846€$$

9. **Interest of HSS: cost comparison**

   The economic interest condition for the HSS grade will therefore be :

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

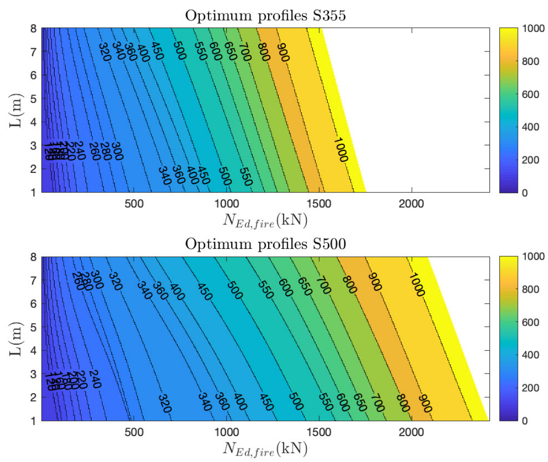
   In this example with unprotected element the condition can be expressed as follows:

$$\frac{Cost_{\text{S500,unprotected, HEA 280}}}{Cost_{\text{S355,unprotected, HEA 300}}} = \frac{380.8846}{370.86} = 1.0127 \not< 1$$

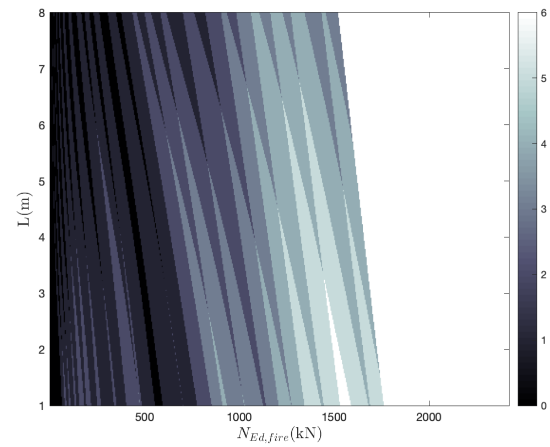
   Therefore, the condition of interest of HSS is not respected and this confirms the result detailed in the section 4.2.

C Unprotected compressed member

For an area to be considered as of no interest, it must not respect the condition 2.10 in the specific case of unprotected elements but which can also be translated by 2.8 to have a more general condition. In order to identify the zones of non-interest where the 2.10 condition is not respected, Figure C.1 should be used to obtain the optimal profiles of the RS design and the HSS design and then determine the number of profiles of difference between the two designs.



(a) Optimal profiles



(b) Profile gap between HSS and RS optimal designs

Figure C.1: Case study for unprotected compressed members for all length

Based on the number of gap profiles and the optimal profiles, Figure C.2 should be used, which expresses the 2.10 condition graphically. The blue curve represents areas of two profile gaps while the black curve represents areas of 1 profile gap. If the blue or black curve is below the pink curve relating to the relative cost of the HSS grade to the RS grade, then the HSS grade is of no economic interest and red areas of non-interest will appear.

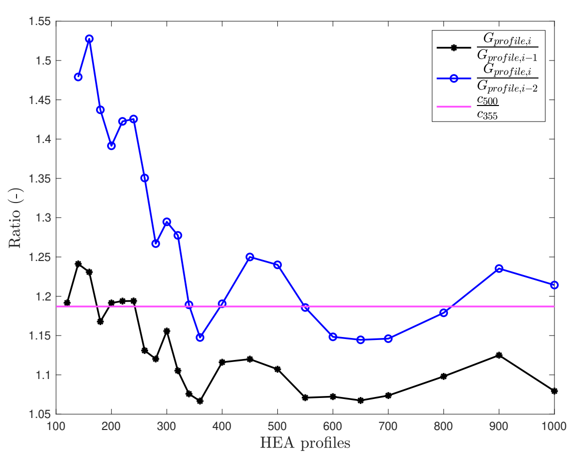
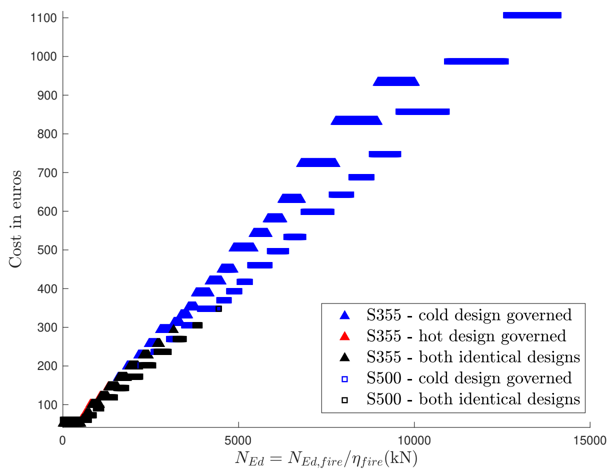


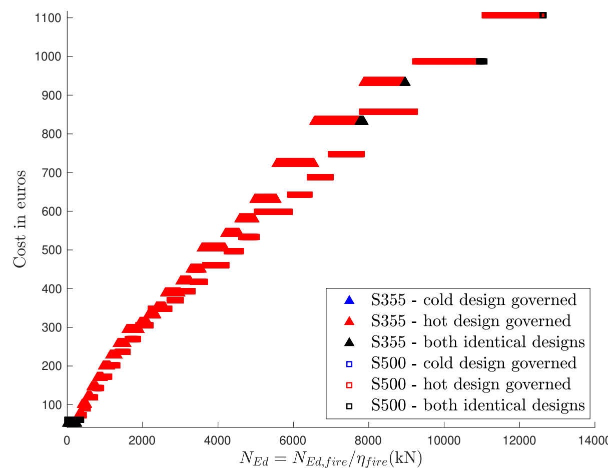
Figure C.2: Case study for unprotected compressed members: weight ratios and relative cost ratio

D Ambient and elevated temperatures

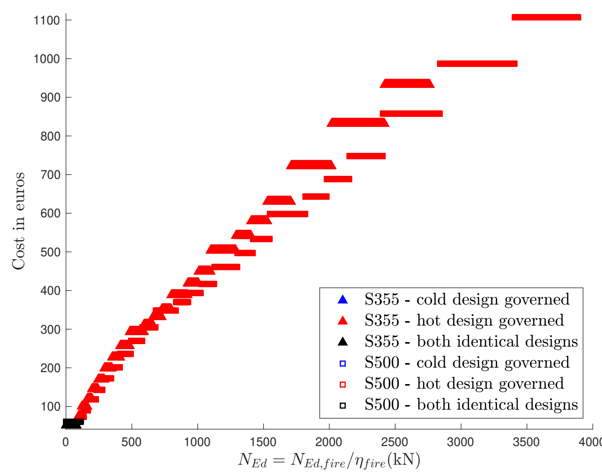
D - 1 Unprotected tensioned members



(a) η_{fire}=0.1

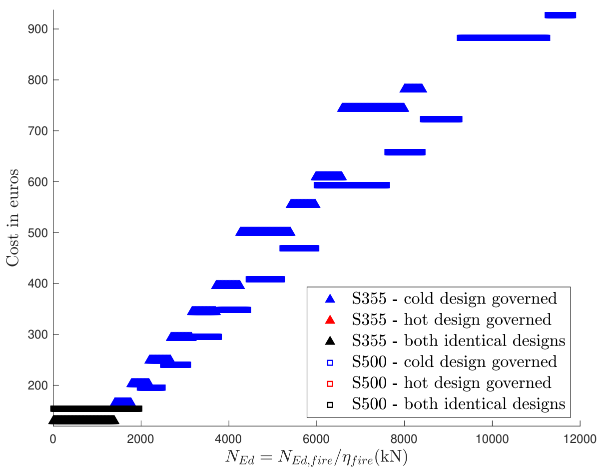


(b) η_{fire}=0.2

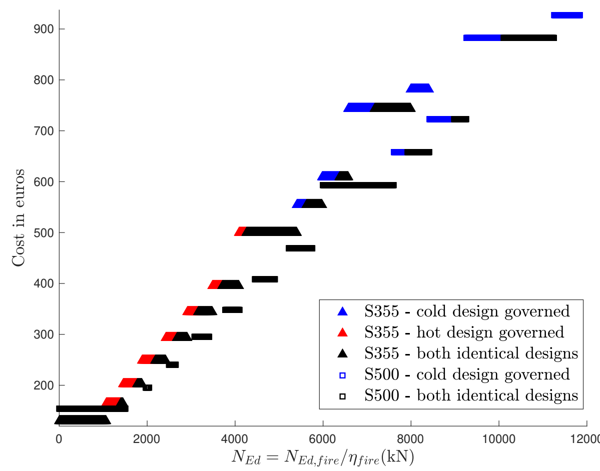


(c) η_{fire}=0.65

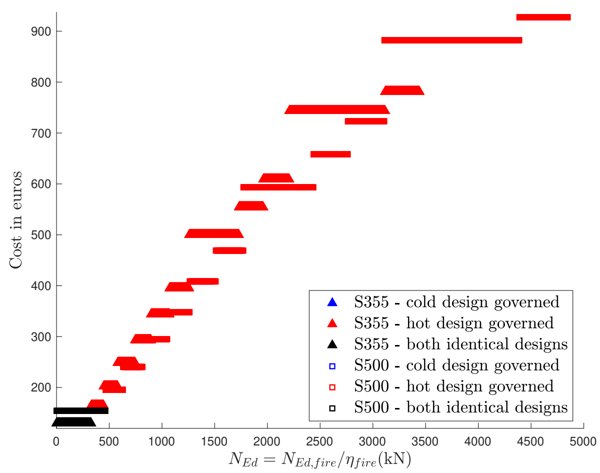
Figure D.1: Ambient and elevated temperatures for an unprotected tensioned member: HEAA product range



(a) η_{fire}=0.1

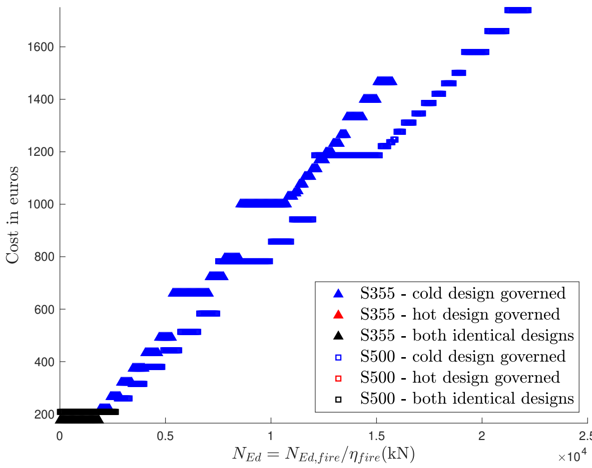


(b) η_{fire}=0.2

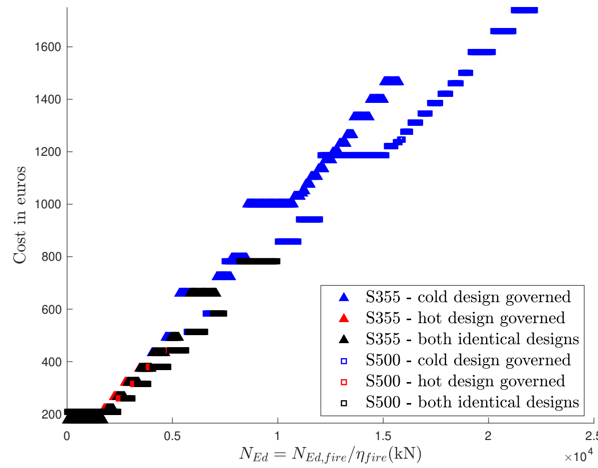


(c) η_{fire}=0.65

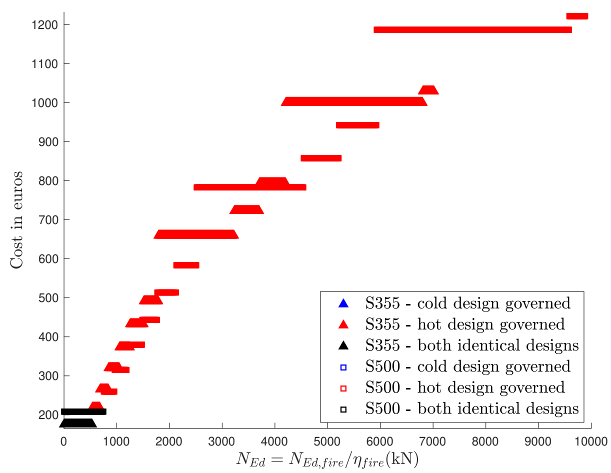
Figure D.2: Ambient and elevated temperatures for an unprotected tensioned member: HEC product range



(a) η_{fire}=0.1



(b) η_{fire}=0.2



(c) η_{fire}=0.65

Figure D.3: Ambient and elevated temperatures for an unprotected tensioned member: HEM product range

D - 2 Unprotected compressed members

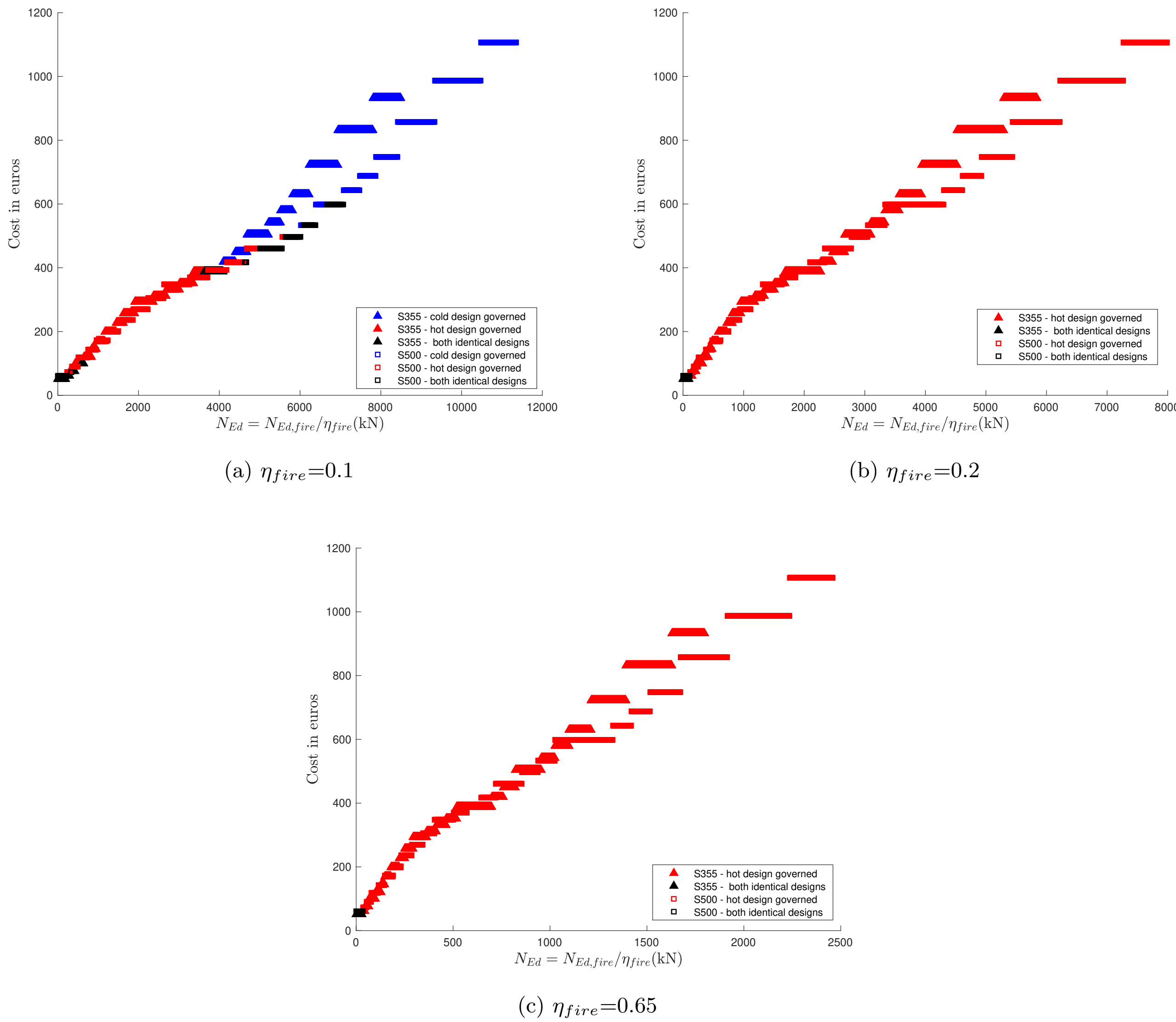
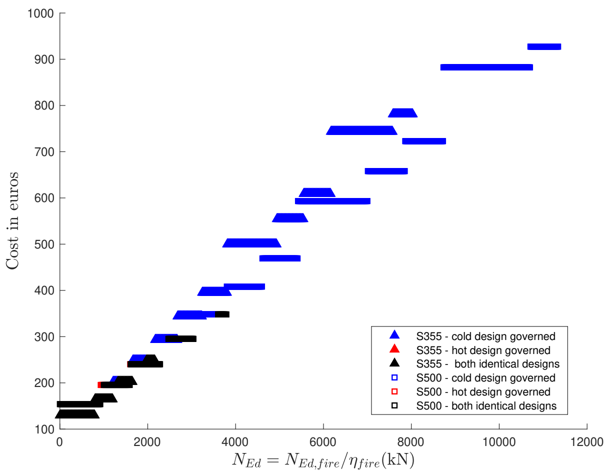
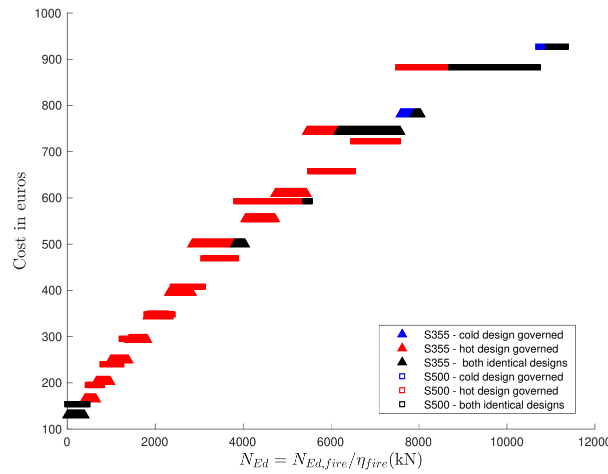


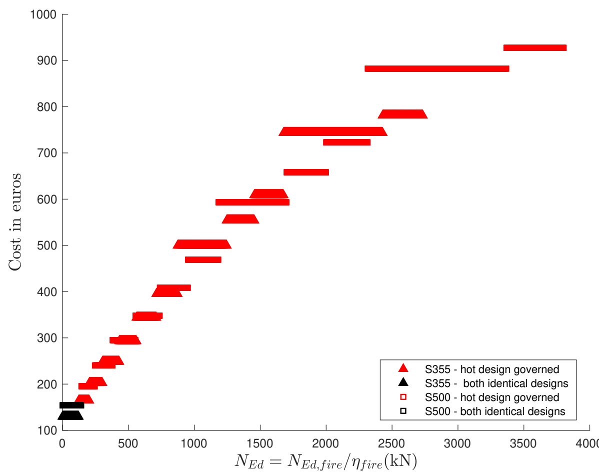
Figure D.4: Ambient and elevated temperatures for an unprotected compressed member: HEAA product range



(a) η_{fire}=0.1

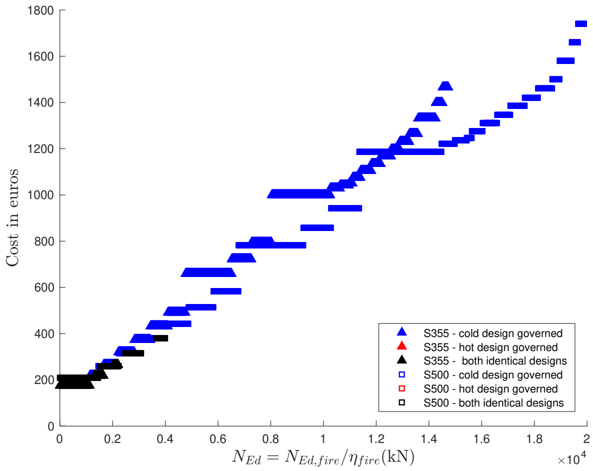


(b) η_{fire}=0.2

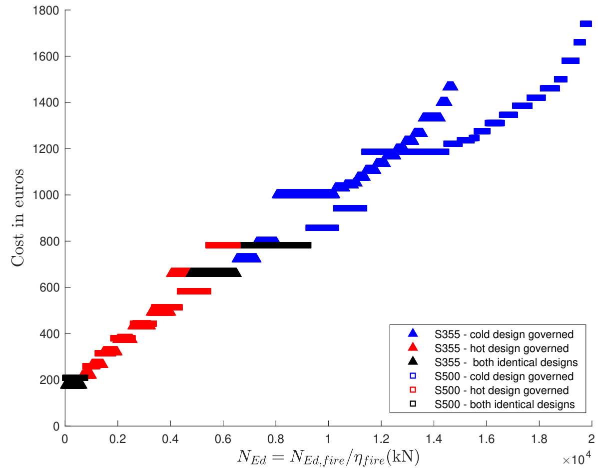


(c) η_{fire}=0.65

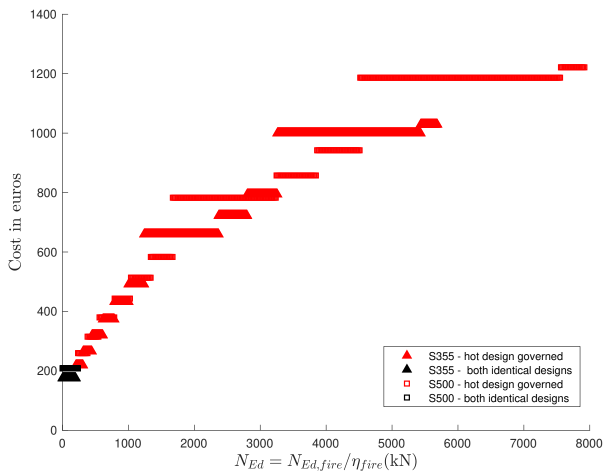
Figure D.5: Ambient and elevated temperatures for an unprotected compressed member: HEC product range



(a) η_{fire}=0.1



(b) η_{fire}=0.2



(c) η_{fire}=0.65

Figure D.6: Ambient and elevated temperatures for an unprotected compressed member: HEM product range

References

[1] Arcelormittal. https://sections.arcelormittal.com/products_and_solutions/products_range/EN?expand=520, accessed 29/05/2022.

[2] Boursorama. COURS EUR/USD SPOT:https://www.boursorama.com/bourse/devises/taux-de-change-euro-dollar-EUR-USD/, accessed 12/07/2022.

[3] Bouwenmetstaal. https://www.bouwenmetstaal.nl/themas/parametrisch-ontwerpen/smartconnection/cost-components/, accessed 12/07/2022.

[4] Gobert group: Promat-promapaint-sc4 blanc 25l peinture intumescente en phase aqueuse. https://gobert.groupegobert.com/produit/promat-promapaint-sc4-blanc-25l-cHJvbTEyMzE=, accessed 29/05/2022.

[5] Meps international ltd. https://mepsinternational.com/gb/en/products/world-steel-prices, accessed 12/07/2022.

[6] *Nomogrammes - Méthode graphique pour déterminer la résistance au feu des structures en acier.* Centre Information Acier (Infosteel), 2007.

[7] *Kosten im Stahlbau 2021.* Bauforumstahl, Düsseldorf, 2021.

[8] Arcelor mittal: Price-list sections, channels and merchant bars, Effective on 11th December 2017.

[9] Baddoo, N., and Chen, A. *High strength steel design and execution guide.* SCI Steel Construction Institute, 2020.

[10] Commission, E., for Research, D.-G., Innovation, Schillo, N., Kövesdi, B., Pétursson, E., Horváth, L., Manoleas, P., Schaffrath, S., Feldmann, M., Minkkinen, J., Seyr, A., Clarin, M., Tuominen, N., Virdi, K., Valkonen, I., Mela, K., Pavlovic, M., Somodi, B., Heinisuo, M., Veljkovic, M., Björk, T., Turán, P., Erkkilä, J., and Ongelin, P. *Rules on high strength steel (RUOSTE) : final report.* Publications Office, 2016.

[11] EN1993-1-1. *Eurocode 3 - Design of steel structures - Part 1-1: General rules and rules for building.* May 2005.

[12] EN1993-1-12. *Eurocode 3 - Design of steel structures - Part 1-12: Additional rules for the extension of EN 1993 up to steel grades S 700.* Febuary 2007.

[13] EN1993-1-2. *Eurocode 3 - Design of steel structures - Part 1-2: General rules -Structural fire design.* April 2005.

[14] Franck, B. *Economic benefit in using high performance materials for steel-concrete composite columns in the field of building structures.* Université de Liège, June 2020.

[15] Franssen, J.-M. *Fire safety engineering course.* Université de Liège, 2021.

[16] Li, G.-Q., and Wang, Y.-B. *Behavior and Design of High-Strength Constructional Steel.* Woodhead Publishing Series in Civil and Structural Engineering. Elsevier Science & Technology, San Diego, 2020.

[17] Maraveas, C., Fasoulakis, Z., and Tsavdaridis, K. D. Mechanical properties of high and very high strength steel at elevated temperatures and after cooling down.

[18] Neuenschwander, M., Scandella, C., Knobloch, M., and Fontana, M. Modeling elevated-temperature mechanical behavior of high and ultra-high strength steels in structural fire design. *Materials & design 136* (2017), 81–102.

[19] prEN1991 1-2. *Eurocode 1 - Actions on structures - Part 1-2: General actiond - Actions on structures exposed to fire*. September 2021.

[20] prEN1993 1-1. *Eurocode 3 - Design of steel structures - Part 1-1: General rules and rules for building*. September 2020.

[21] prEN1993 1-2. *Eurocode 3 - Design of steel structures - Part 1-2: General rules -Structural fire design*. November 2020.

[22] prEN1993 1-5. *Eurocode 3 - Design of steel structures - Part 1-5:Plated structural elements*. September 2020.

[23] Promat. *Peintures intumescentes PROMAPAINT®-SC4 et PROMAPAINT®-SC3 La nouvelle solution stabilité au feu " tout en esthétisme "*. Augustus 2018.

[24] Saufnay, L. *Intérêt des aciers laminés à haute limite d'élasticité dans le domaine de la construction métallique*. Université de Liège, June 2019.

[25] Seif, M., Luecke, W., Choe, L., Main, J., McColskey, J., Zhang, C., Weigand, J., Gross, J., and Sadek, F. Temperature-dependent material modeling for structural steels: Formulation and application, 2016-04-15 2016.

[26] Shakil, S., Lu, W., and Puttonen, J. Experimental studies on mechanical properties of s700 mc steel at elevated temperatures. *Fire safety journal 116* (2020), 103157–.

[27] Winful, D. A., Cashell, K. A., Afshan, S., Barnes, A. M., and Pargeter, R. J. 10.18: Material properties of high strength steel under fire conditions. *ce/papers 1*, 2-3 (2017), 2668–2677.