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Design optimisation of welded I-beams made of high strength steels

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Abstract

Nowadays, hot rolled steel sections are used in practice. The cross-sectional dimensions are therefore fixed and catalogued by the steel manufacturers. However, when the span of the members and/or the applied load becomes significant, such hot rolled steel sections can no longer meet the ultimate and/or service design criteria and the use of a built-up welded I-beam should be considered. They are typically made of three steel plates welded together to form a monolithic I-beam. By varying the dimensions of these plates, an infinite amount of cross-section geometries can be defined. But face to this high variability of solutions, the designers encounter difficulties in identifying the most appropriate combination of geometrical and mechanical properties for the constitutive plates.

To study and optimise these profiles, a MATLAB® routine has been developed at the University of Liege. It allows, for different load cases, to find suitable cross-sectional dimensions that minimise the weight and/or the total cost of the element. This routine follows the current recommendations prescribed in prEN1993-1-5 and evaluates the possibility of using transverse stiffeners along the web to further reduce the weight and cost of the element. The so-developed routine is presented in the present paper. Also, the advantage of considering the use of high strength steels for such structural members is discussed to propose recommendations to the designers for the selection of the most appropriate steel grade.

Keywords

Welded I-beams, Transverse stiffeners, High-strength steels, Weight optimization

1 Introduction

Many studies exist regarding the use of high-strength steels for built-up welded I-sections. Miki [1] indicates that the most economical and efficient designs are based on optimized design and material use. In this context, high-strength steels enable to realize significant weight savings. Johansson [2] expresses that hybrid girders are more economical than homogeneous girders and some design recommendations are given to develop such girders. The benefit of such sections is also confirmed by design guides and European research reports for high-strength steels ([3]–[5]). Mela [6] realized weight and cost optimizations of welded high-strength steel beams. It was shown that the most economical solution does not coincide with the minimum weight design but is closed and weight savings of up to 34% can be contemplated. This study was focused on members with no risk of lateral-torsional buckling and illustrated the high dependency of the optimised solution on the load and span of the beam.

To sum up, the literature review states that homogeneous, and hybrid high-strength beams made of high-strength steel may lead to significant weight and cost savings. The dependency on the load and span amplitudes have also been illustrated. However, none of these works gives practical advice for designers to help them in designing and selecting the most relevant steel grade. In the framework of a PhD thesis, the University of Liège is investigating the economic benefit of using high-strength steels in steel structures [7] and, in this context, investigations have been initiated to determine when it makes sense to consider high-strength steels for built-up welded I-sections through optimal design procedures.

In particular, a MATLAB [8] routine was developed to optimize the design of welded I-beams [9]. Depending on the dimensions of the obtained cross-section, the possibility of using transverse stiffeners is considered and a procedure has been developed to ensure their optimal positioning. Indeed, in many cases, the web of the optimised section presents large slenderness, and therefore the risk of shear buckling is high. There are two ways to reduce this risk, either by increasing the web thickness or by using transverse stiffeners. The two ways have been contemplated in order to identify the most appropriate one in terms of weight and cost savings. The routine was developed based on the rules prescribed by the upcoming version of standard prEN1993-1-5 [10].

This paper reports on the conducted investigations aiming at identifying the benefit in considering high-strength grades for homogeneous welded I-beams. In particular, the following sections briefly present the adopted methodology, the optimised solutions obtained considering a standard grade and the impact of using high-yield strengths on the optimised solution. The influence of the span and load amplitudes on results are also addressed in a parametric study. Finally, a criterion is established to help the designers in their grade choices.

2 Methodology

2.1 General structure

A bi-supported beam subjected to a uniformly distributed load is considered as study case. Such a beam must meet several criteria. The first is to respect the Serviceability Limit State (SLS) conditions, i.e., to limit the maximum deflection at midspan. By maximizing the lever arm between flanges, a high moment of inertia is guaranteed with flanges of small sections. Then, Ultimate Limit State (ULS) conditions must be checked, and, amongst other possible failure modes, the bending resistance of the element should be guaranteed. This resistance is also maximized if the lever arm between flanges is large. In the proposed routine, these two design criteria impose a relation between the area of the flanges and the height of the web, and as shown hereafter, lead to optimal cross-sections characterized by high webs for both ULS and SLS conditions. The geometry of the flanges, i.e., their width b_f and their thickness t_f are fixed to have at least Class 3 flanges.

The web thickness has little impact on inertia and bending strength, thus the web thickness (t_w) should be as small as possible to optimize the overall weight leading to slender beam webs. However, the beam web should also comply with ULS criteria which impose minimum values for the web thickness. The first one is associated with a possible instability mode called flange-induced buckling in which the compressed flange buckles into the web if the latter is not sufficiently rigid. According to the Eurocode recommendations for this failure mode, the web slenderness must be limited to a maximum value which, in some cases, governs the web design. The second one corresponds to the check of the shear resistance. In the presence of a slender web, there is a risk of shear buckling. In this case, two contributions to the shear resistance are considered: a contribution from the web and a contribution from the flanges. This second contribution is generally negligible compared to the first one. The contribution of the web depends on its thickness, its height and the length of the shear panels. As mentioned above, the height of the web is fixed by the deflection and bending resistance criteria. Therefore, if the shear resistance is insufficient, there are two possibilities. Either the thickness of the web is increased, or transverse stiffeners are added to reduce the length of the shear panels. The developed routine considers both possibilities and identifies the one leading to the smaller weight or smaller cost according to the selected optimisation function.

The general structure of the MATLAB routine is represented in Figure 1. The routine is working as follows:

- A span L and an applied load are fixed;
- A vector with possible h_w varying until $L/10$ (to be able to apply the beam theory) is fixed;
- For each value of h_w, the required value of b_f and t_f (and so A_f) are determined to comply with the deflection and bending resistance criteria; the couple b_f - t_f is defined to have a cross-section at the boundary between Class 3 and Class 4;
- The required value of t_w is computed to ensure the shear resistance and to avoid the flange-induced buckling – the possibility of using stiffeners is considered;
- The so-obtained results for each value of h_w, are reported in a matrix.

The optimised solution for the considered span, load and web height is the one corresponding to the lowest weight or the lowest cost according to the selected optimisation function.

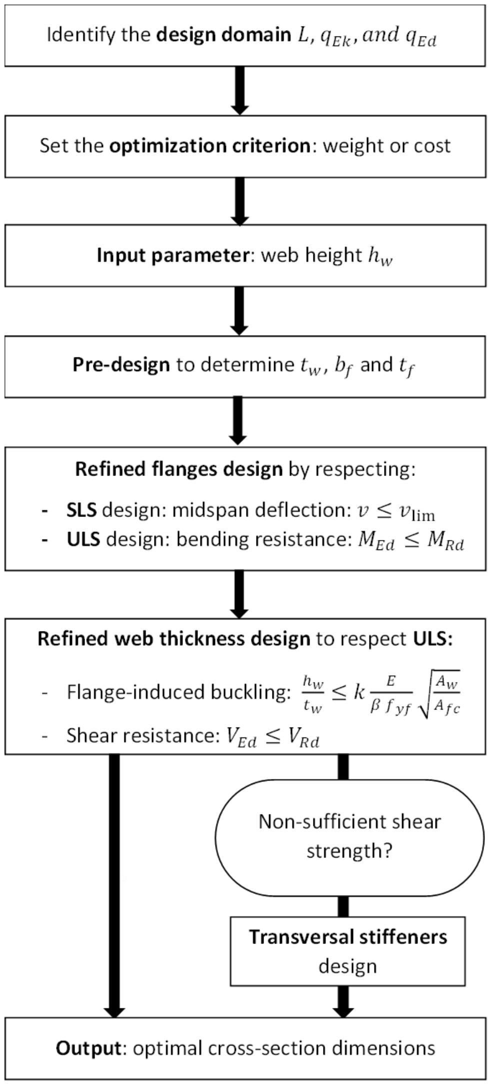

Figure 1: General structure of design optimizations

2.2 Assumptions and load cases

To illustrate the use of the proposed routine, a simply supported beam with a 25m span subjected to a uniformly distributed ultimate design load of 80kN/m (q_{Ed}) is considered as study case. For SLS verifications, it is assumed that the characteristic load q_{Ek} is equal to the design load divided by a mean safety coefficient of 1.4; so, the characteristic load is equal to 57.1 kN/m. The deflection limit $v_{\lim}$ for SLS checks is considered equal to L/250.

The optimisation process using the routine has been applied for different steel grades varying from S355 to S690, S690 which is the maximum yield strength covered by Eurocode design recommendations. S355 is considered as the reference steel grade while grades ranging from S460 to S690 are considered as high strength steels. In the framework of this publication, the gains resulting from the use of S460 or S550 instead of S355 are discussed. Within the present study, only homogeneous welded I-section beams are considered; the implementation of the optimisation of hybrid cross-sections is under implementation at the time of writing this paper. In addition, cross-sectional dimensions remain unchanged along the length (i.e., the moment of inertia is constant).

2.3 Weight and cost optimizations

As mentioned previously, the developed routine can target an optimisation of the weight or the cost of the member.

For the minimisation of the member weight as optimisation function, the weight of the member can be subdivided into three components: the web, the flanges, and the transverse stiffeners. Since the weight of the stiffeners is almost negligible in comparison to the two other components, the optimization of the member is reduced to the optimization of the cross-section.

For the minimisation of the cost, the total cost is mainly influenced by the material and the welding costs. The welding cost being non-negligible in comparison to the material cost makes the benefit of using transverse stiffeners null; also, it has been demonstrated in [9] that the consideration of the flange-induced buckling is, in most of the cases, governing the definition of the required minimum thickness for the web which is such that there is no need for transverse stiffeners. Accordingly, the solution without transverse stiffeners is generally the most cost-effective solution and so, the relation between the minimum cost and h_w is really close to the one obtained through weight optimization. This feature was besides observed in previous research [6]. Therefore, although welding costs influence the results in a cost optimisation, it has been decided to focus on weight optimisation in the scope of this research. Further results regarding the impact of web to flange welds in a cost optimisation will be detailed in a future paper.

3 Results

In the present section, results obtained with the developed routine are presented. In a first step, a criterion to identify the transition from solutions governed by SLS criteria to solutions governed by ULS criteria is first established. Then, the results from the optimisation process applied to the study case considering S355 steel grade are detailed. Finally, comparisons between results obtained for different steel grades for cases with and without risk of lateral torsional buckling are discussed.

3.1 Transition height criterion establishment

As long as flanges are designed to limit the deflection at midspan, the yield strength has no impact on the flanges' dimension because SLS checks are independent of the yield strength. In this case, there is therefore no benefit in using high-strength steels. High-strength steels can only be of interest when the flanges are designed to respect ULS conditions. The web height corresponding to this transition between designs governed by SLS and ULS conditions can be approximated through the expression reported in Eq. (1) (in a case where lateral-torsional buckling is prevented and for Class 3 cross-sections).

$$I_{y,SLS} = \frac{5.q_{SLS}.L^4}{384.E.f_{lim}}$$

$$I_{y,ULS} = \frac{M_{Ed}.\frac{h}{2}}{f_y} = \frac{q_{ULS}.L^2.\frac{h}{2}}{8.f_y}$$

$$\frac{5.q_{SLS}.L^4}{384.E.f_{lim}} = \frac{q_{ULS}.L^2.\frac{h}{2}}{8.f_y} \rightarrow h_w^* = h = \frac{5}{24}.\frac{q_{SLS}}{q_{ULS}}.\frac{L^2.f_y}{E.f_{lim}} \qquad \text{Eq. (1)}$$

where $I_{y,\ SLS}$ is the required inertia to satisfy the SLS while $I_{y,\ ULS}$ is the required inertia to satisfy the ULS.

The above relationship assumes that the stress distribution is elastic. Indeed, when h_w increases, optimal sections are almost systematically of Class 3 or 4. However, in the case of a Class 4 cross-section, the inertia considered for SLS can be greater than the one for ULS. Indeed, by reducing SLS stresses, the penalty coefficient for a Class 4 cross-section is reduced. In this case, our interaction height is on the safe side because it is associated with a h_w greater than its real value. In case of a similar penalty coefficient for SLS and ULS conditions, the h_w value from which ULS conditions are governing will be the same as the one expressed in Eq. (1).

The flange thickness being (i) unknown at the beginning of the design process and (ii) negligible by contrast to the total height, "h_w^*" can be directly compared to "h_w". In addition, for Class 4 cross-sections, the neutral axis is lower than the symmetry axis (upper web part under compression stresses in pure positive bending moment). Therefore, comparing h_w to the transition height is on the safe side as it overestimates a bit the real transition point. The transition height h_w^* is represented in next figures as a key parameter to ease the interpretation of the results and determine whether there is a benefit in considering a high-strength steel grade.

3.2 Optimum design for S355

The optimum weight as a function of the web height using S355 is represented in Figure 2 assuming that the considered member cannot fail through lateral torsional instability. Two curves are reported in Figure 2: one corresponding to the optimised solutions complying with the SLS criterion alone ("SLS design" curve) and one corresponding to the solutions complying with the ULS criterion alone ("ULS design" curve). The optimal solutions, represented by the black dashed line, correspond to the solutions which allow complying with both SLS and ULS requirements.

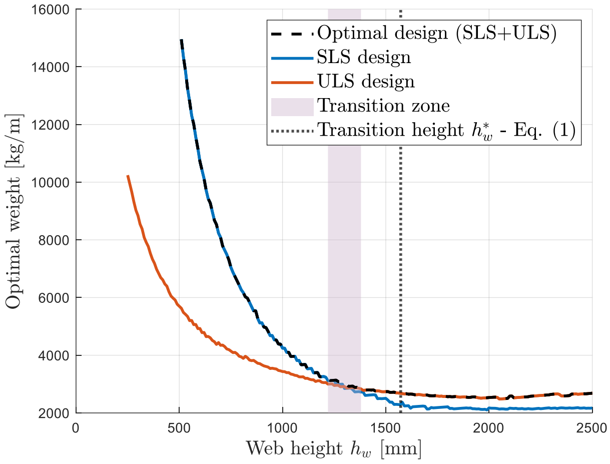

Figure 2: Optimal designs for the case study in S355

As can be seen in Figure 2, the optimal weight as a function of the web height can be divided into 3 zones: a zone where the optimum design is governed by the SLS design, a zone where the ULS design is governing and a transition zone in-between. As soon as the height of the web increases, optimal sections are almost always Class 4 ones, the stress distribution in the cross-section is therefore elastic. To increase the flexural resistance, flanges are becoming thinner and wider to maximize the area under maximum stress. On the contrary, for SLS conditions, flanges are becoming as thick as possible to increase the moment of inertia. Nonetheless, there exists a transition zone in which the optimum is neither the SLS design nor the ULS design as the obtained solution for both designs is not satisfying all the design criteria. To illustrate this phenomenon, the 3 optimal profiles for each design in the case where $h_w = 1220\mathrm{m}$ (transition zone) are reported in Table 1.

Table 1: Example of an optimum design in the transition zone

	SLS+ULS	**SLS**	**ULS**
I_y	$1.51x10^{10}mm^4$	$1.49x10^{10}mm^4$	$1.29x10^{10}mm^4$
M_{Rk}	$6.88x10^9mm^4$	$6.57x10^9mm^4$	$6.61x10^9mm^4$
A_f	$16800mm^2$	$16000mm^2$	$15200mm^2$
Cross-section			

In addition, the transition height h_w^* between SLS and ULS governing zones predicted using Eq. (1) is well on the safe side as h_w^* appears later than the transition zone. Eventually, one should determine the optimum design which corresponds to an optimum web height ($h_{w,opt}$) of 2050 mm for S355 as reported in Figure 2.

3.3 Results without lateral-torsional buckling

Knowing the transition height h_w^* between SLS and ULS conditions, cases in the zone governed by ULS conditions may present a weight gain if high-strength steel grades are used. The optimum weights as a function of the web height for S460 and S550 are shown in Figure 3.

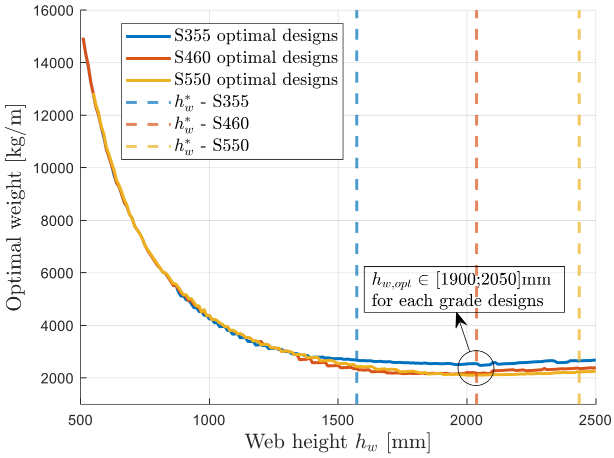

Figure 3: Results without lateral torsional buckling for 3 steel grades

As expected, Figure 3 illustrates that there is no benefit in using high-strength steels as long as SLS conditions govern the design. On the contrary, beyond the S355 transition height, there is always a weight gain associated with the use of a high-strength steel grade. However, the real benefit is depending on the corresponding weight saving. To quantify the benefit of using high-strength grades, the weight gains have been evaluated for web heights higher than the transition height h_w^* for S355 and below the limit of the beam theory $h_w = L/10$ (Figure 3).

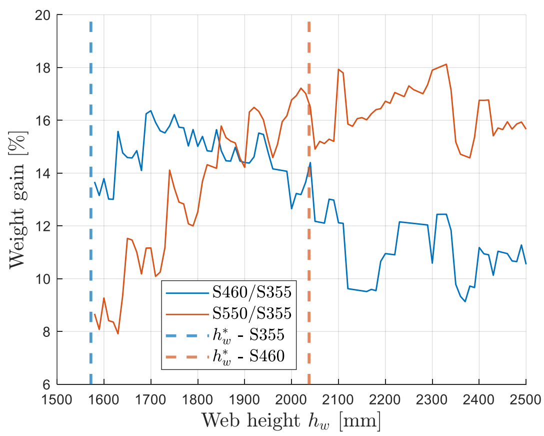

Figure 4: Weight gain induced by the use of high-strength steels for members prevented against lateral-torsional buckling

Figure 3 and Figure 4 illustrate that the approximate transition height effectively initiates a zone for which the use of a grade greater than S355 leads to weight savings. Similarly, beyond the second transition height corresponding to S460, there is a weight gain associated with the use of a higher grade than S460. This limit is therefore effective to determine for which web heights, there is a benefit in considering a higher grade.

The weight gains are thus only quantified for web heights beyond this limit value. However, the gain is difficult to quantify because it strongly depends on the load and the span of the element. These parameters are studied in section 4 through a sensitivity study.

Finally, the results indicate that no transverse stiffeners are useful for grades higher than S500. This observation can be explained by the flange-induced buckling criterion in which f_{yf} is in the denominator of the criterion ratio which significantly limits the web thickness reduction for such grades. This criterion is very conservative as previously discussed [11] but is taken in its current form as prescribed by the reference standard [10] as no alternative is proposed in the literature.

3.4 Results with lateral-torsional buckling

In cases for which the lateral-torsional buckling is not prevented, there is no weight gain associated with the use of high-strength steels as an increase of the optimum weight with the increase of the steel grade is observed as reported in Figure 5. Indeed, ULS conditions become stricter when considering lateral-torsional buckling, in particular for what concerns the weak-axis inertia. So, the widths of the flanges must be sufficiently large whatever the yield strength to maximize this weak-axis inertia. As the flange's width is increasing, its thickness has also to be increased to remain Class 3 and to maintain the same level of bending resistance, leading to a weight increase. Consequently, the benefit in using high-strength steels in members for which lateral-torsional buckling may occur is highly limited.

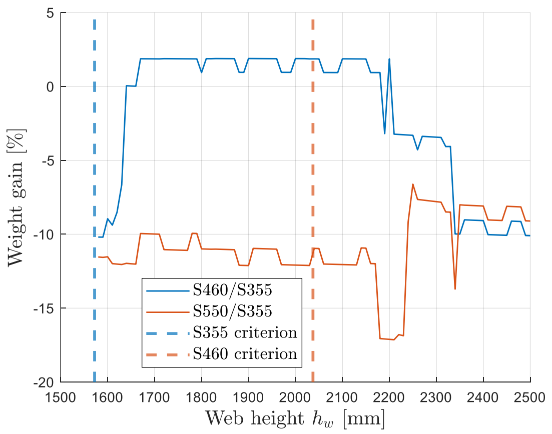

Figure 5: Weight gain induced by the use of high-strength steels for members not prevented against lateral-torsional buckling

4 Parametric study

In the parametric study summarised in this section, the influence of three parameters is investigated: the beam span, the value of the applied load and the value of the deflection limit criterion. The results of the parametric study are discussed considering the weight associated with the optimum web height for each steel grade. For the cases considered herein, it is assumed that lateral-torsional buckling is prevented.

4.1 Impact of the span

The weight ratio as a function of the yield strength and the span is represented in Figure 6.

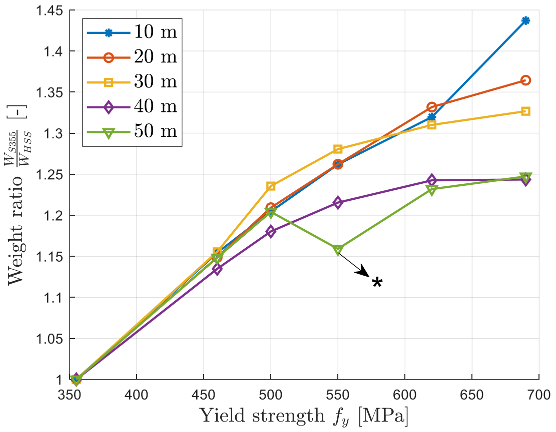

Figure 6: Impact of the span on results

Figure 6 illustrates that the higher the span length, the less the benefit in considering high-strength steels. Indeed, according to Eq. (1), the higher the span length, the higher the transition height; so, the height domain for which SLS conditions govern increases and thus the benefit in considering high-strength steels decreases with the span. However, as can be seen in Figure 6 and Figure 7, there are some fluctuations (marked by the "*" symbol) which can be attributed to the non-continuity of the geometrical properties (t_f and t_w) or to the flange-induced buckling criterion which limits the reduction of the web thickness. Anyway, this approach of considering the optimal design is conserved as it gives a good trend of the effect of each parameter on the results.

4.2 Impact of the loading amplitude

The weight ratio as a function of the yield strength and the load is represented in Figure 7.

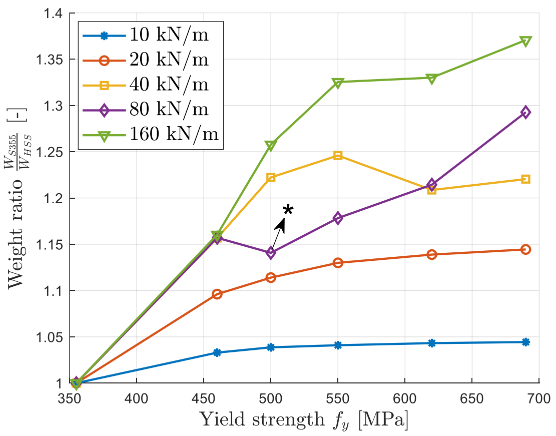

Figure 7: Impact of the loading amplitude on results

As can be seen in Figure 7, the higher the load, the higher the optimal web height to resist while the transition height remains unchanged (considering that q_{ULS}/q_{SLS}=1.4), thus the higher the advantage in using high-strength steels.

4.3 Impact of the deflection limitation

The impact of the deflection limit is shown in Figure 8.

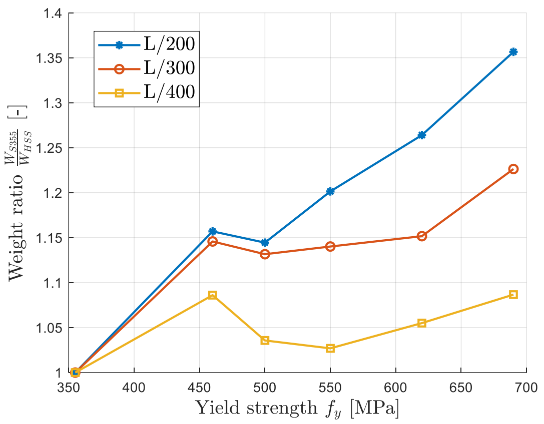

Figure 8: Impact of the deflection limit on results

As expected, the higher the deflection limit, the less the benefit in using high-strength steels. The height transition factor can also be expressed in its dimensionless form (starting from Eq. (1)) as:

$$\frac{h_w^*}{L} = \frac{5}{24} * \frac{1}{1.4} * \frac{f_y \gamma}{E} \quad \text{Eq. (2)}$$

In this form, the transition height becomes independent of the loading (considering that q_{ULS}/q_{SLS}=1.4) and γ coming from the deflection limit expressed as L/γ directly reflect the influence of the span and the selected deflection limit criterion on the results.

5 Discussions, conclusions, and perspectives

Within the present paper, first results from a study aiming at identifying the benefit in using high-strength steels (HSS) for homogeneous built-up welded I-beams have been presented. In a first step, the adopted methodology for the optimisation of the I-beams and its implementation in a routine has been described. Then, in a second step, a transition height above which the use of HSS could present a benefit has been first derived. Indeed, this transition height allows for identifying the zone where the design is governed by ULS and so, where the use of HSS could reduce the amount of the required material. Finally, the developed routine has been used to highlight the gain in terms of weight savings which could be expected by using HSS in study cases. In particular, through a parametric study, it has been highlighted that key parameters such as instabilities, the span, the level of applied load or the deflection limit can highly influence the gain which could be expected from the use of HSS. Indeed, in presence of lateral torsional buckling, it is shown that there is almost no benefit in using HSS while the gain in using HSS is increasing when the applied load is increasing or when the deflection limit / the span is decreasing. Also, given the welding costs and the strong influence of the current rule to check flange-induced buckling, it can be concluded that the use of transverse stiffeners is not relevant in most of the cases, and particularly, for grades higher than S500.

As perspectives, hybrid beams i.e., beams where the flanges and the web may be of different steel grades, should be investigated and their optimisation should be implemented in the developed routine. In addition, further investigations should be realised to evaluate the reliability of the flange-induced buckling criterion for high-strength steels as the latter is strongly influencing the required minimum thickness for the beam web. Finally, extensive parametric analyses should be performed to provide clear indications to practitioners to help them in the selection of optimum solutions for built-up welded sections.

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