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Weight and cost optimization of welded high strength steel beams

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ABSTRACT

In this study, economical use of high strength steel in welded beams is considered. The purpose is to compare the performance of high strength steels of grades S500 and S700 with the reference grade S355, when employed in simply supported, geometrically double-symmetric I-beams under uniform transverse loading. The beams are optimized separately for weight and cost under the design rules of Eurocode 3. Bending and shear resistances are considered, but lateral torsional buckling is neglected. Hybrid beams, where the flanges and the web may be of different steel grades, are also treated. The cross-section can belong to any of the four classes of Eurocode, which means that both plastic and elastic design is considered. The cost function takes into account fabrication, transportation and erecting the beam on site. The results indicate that while significant weight reduction can be obtained by high strength steels, rather limited cost savings are achieved compared with S355. On the other hand, hybrid cross-sections display promising potential as the most economical solution.

1. Introduction

Developments in manufacturing processes and material technologies have led to increase in strength of available steels. From the point of view of the designer, it is substantial to know how to best utilize the higher strength in structures. Higher strength typically implies increased manufacturing costs, which must be considered, when economical designs are pursued. A common strategy for achieving economical solutions in beams is to assign different steel grades to the web and the flanges such that the web is made of weaker steel than the flanges. These *hybrid* cross-sections provide the designer a further means to find better solutions.

High strength steels (HSS), or high-performance steels, have been studied extensively since the latter part of the 20th century. A brief history of HSS in the US is given in [1]. A series of research programs in the US addressing the contemporary design code limitations regarding HSS was carried out in the 1990s, leading to updated design rules for the use of HSS in steel bridges [2]. In Japan, HSS has been used widely in bridges [3]. A comprehensive overview of the use of HSS around the world can be found in [4].

In [5], the use of HSS in hybrid plated girders is treated following the European design codes [6,7]. An important observation is that the Eurocodes have virtually no rules for hybrid cross-sections. However, based on a series of experiments, the authors conclude that the existing design rules of Eurocode 3 can be employed for hybrids with minor modifications. More specifically, the classification of the cross-section is carried out using the yield strength of the compression flange, and partial web plastification is taken into account when evaluating the bending and axial force resistances.

As both the dimensions of the cross-section and the steel grades of the plates can be varied, it is not straightforward to determine the most economical design simply based on experience and intuition. Mathematical optimization theory provides a powerful tool for finding efficient solutions for beams with HSS plates. The design task is formulated as an optimization problem, where the chosen objective function is minimized (or maximized) such that the design rules of applicable codes are satisfied. Often the objective function is the weight of the beam, but it is widely acknowledged that the most economical solution does not in general coincide with the minimum weight design. Therefore, a more detailed manufacturing cost function should also be considered.

Several researchers have studied the optimization of both homogeneous and hybrid I-beams. In [8], the optimum cross-sectional properties of I-beams are treated. With simplified expressions, it is shown that the bending resistance and stiffness are maximized using the maximum allowable web slenderness. General rules are derived for the ratio of the flange and web areas. It is concluded that for hybrid beams, more material should be allocated to the flanges than in homogeneous beams. This work has been extended in [9], where with similar simplifications it is

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shown that hybrid beams lead to 18–22% weight savings compared with homogeneous beams, following the AISC design rules.

In [10], the design of hybrid I-beams is formulated as an optimization problem according to the AISC specification. Geometric programming is employed to find the minimum weight numerically, and efficient convergence is reported. The same method is applied in [11] for optimization of composite hybrid I-girders following AASHTO specifications. Monosymmetric geometry is allowed for the beam. The optimization variables are divided into design variables (plate dimensions, spacing of stiffeners) and dependent variables (e.g. moment of inertia). The dependent variables simplify the expressions of the design constraints, but they induce equality constraints defining their relation to the design variables.

In [12], the optimum design of both homogeneous and hybrid I-beams is considered. It is shown that hybrids lead to 20–40% weight savings and 17–30% savings in the total cost. However, it is noted that if the deflection constraint is active, hybrid beams are uneconomical.

It can be concluded that while the optimum design of HSS and hybrid I-beams has been studied to some extent, there still remains a need to investigate the topic using present HSS grades and design rules, and this gives the motivation for the current study. The aim is to apply optimization to determine the magnitude of the savings in weight and in manufacturing cost that can be attained by HSS in welded I-beams under European design rules. Both homogeneous and hybrid cross-sections are treated. Simply supported uniformly loaded beams are optimized separately for weight and cost. The magnitude of the load, and the span of the beam are varied in order to study their influence on the optimum designs. In the present version of the Eurocode, steel grades above S460 are considered to be HSS. Consequently, in this study, the steel grade S355 functions as the reference, and the HSS grades are S500 and S700. All of these grades are commonly available from European manufacturers. The discrete design variables are the plate dimensions, and the constraints are derived from Eurocode 3. Bending and shear are taken into account, but lateral torsional buckling is neglected, assuming that the beam is provided with sufficient transversal support. Both elastic and plastic design is allowed, and all four cross-section classes of Eurocode 3 are included. For hybrid beams, partial web plastification is allowed in all classes. The cost function employed is suitable for welded assemblies such as the beams considered in this work, and it includes the cost of material, plate cutting, welding, sawing, and painting. The costs of transportation and erection are also included.

The paper is organized as follows. In Section 2, the problem formulation is presented, with details of the cost function and the constraints. The optimization method is described in Section 3, and the solutions are presented and discussed in Section 4. Finally, the results of the study are summarized in Section 5.

2. Problem formulation

Consider a simply supported beam under uniform transverse load, with geometrically double-symmetric I-profile as shown in Fig. 1. It is assumed that the beam functions as a joist that is supporting a concrete slab (or a similar structure). In the following, the general form of minimum weight and minimum cost problems are derived.

The design load in the ultimate limit state, q (N/mm), the span L (mm), and the steel grades of the plates are considered as fixed parameters, and varying the value of any of them produces a different optimization problem. Note that the yield strengths of the top flange, f_{yt} (MPa), and the bottom flange, f_{yb} (MPa), need not be equal, i.e. $f_{yt} \neq f_{yb}$ is allowed. Following [7], it is assumed that $f_{yw} \leqslant f_{yt} \leqslant 2f_{yw}$, and $f_{yw} \leqslant f_{yb} \leqslant 2f_{yw}$.

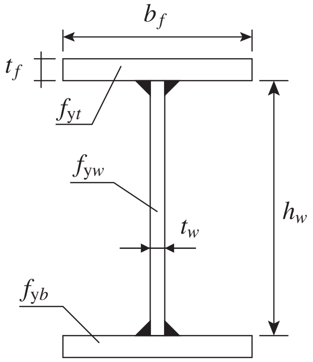

Fig. 1. Geometrically double-symmetric I-section.

Formulating an optimization problem requires identifying the objective function, design variables, and constraints. The design variables are the dimensions of the cross-section (see Fig. 1). They are collected into a vector, denoted by

$$\mathbf{x} = \{b_f \; t_f \; h_w \; t_w\} \quad [\text{mm}] \tag{1}$$

In this study, discrete values are allowed for the plate dimensions. Denote the set of possible values of the plate thicknesses, t_f, and t_w, by T. It is defined as

$$\begin{aligned} T = \{&5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 25, \\ &30, 35, 40, 50, 60, 80, 100\} \quad [\text{mm}] \end{aligned} \tag{2}$$

Similarly, the set of values of flange width and web height is denoted by B. Here, B contains integer values from 100 mm to 1000 mm in 10 mm intervals. That is $b_f, h_w \in B = \{100, 110, 120, \ldots, 990, 1000\}$. The discrete values of the design variables reflect the actual design situation, where availability of the plate dimensions and manufacturability considerations restrict the choice of plate dimensions.

2.1. Objective functions

In this study, both the weight and fabrication cost are chosen as objective functions. The weight is written as

$$W(\mathbf{x}) = \rho L(2A_f + A_w) = \rho L(2b_f t_f + h_w t_w) \quad [\text{kg}] \tag{3}$$

where $\rho = 7.850 \cdot 10^{-6}$ kg/mm^3 is the density of steel and L [mm] is the length of the beam. Furthermore, A_f and A_w [mm^2] are the areas of one flange and the web, respectively.

For the cost objective function, several alternatives can be found in the literature [13–16]. The manufacturing cost function used in the present study is based on a feature-based cost model that is well-suited for welded steel assemblies such as beams [17]. The manufacturing process is divided into cost centres, each containing a set of cost components such as labour, material, equipment, energy, and real estate. The main task is then to devise appropriate expressions for the cost components of every cost centre. These expressions depend on the specific technologies used, and they contain many parameters that must be obtained by measurement. Unless otherwise stated, the default values found in [17] are used for the parameters appearing in the cost function. The values of the unit costs are typical in Finland.

The cost function can be written as

$$\begin{aligned} C(\mathbf{x}) = {} & C_M(\mathbf{x}) + C_B(\mathbf{x}) + C_C(\mathbf{x}) + C_S(\mathbf{x}) + C_W(\mathbf{x}) + C_P(\mathbf{x}) \\ & + C_T(\mathbf{x}) + C_E(\mathbf{x}) \quad [\text{€}] \end{aligned} \tag{4}$$

Each term, C_k, in Eq. (4) is derived from the following general form:

$$C_k = (T_{Nk} + T_{Pk}) \frac{(c_{Lk} + c_{Eqk} + c_{Mk} + c_{REk} + c_{Sek})}{u_k} + T_{Pk}(c_{Ck} + c_{Enk}) + C_{Ck} \tag{5}$$