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Original Research Article

Sensitivity and reliability analyses of lateral-torsional buckling resistance of steel beams

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ABSTRACT

The presented paper deals with an analysis of the effects of random imperfections on the load carrying capacity of a steel beam, which is subjected to the effects of lateral-torsional buckling arising from equal and opposite end bending moments. The load carrying capacity of a hot-rolled steel beam was analyzed in the analytical form. Histograms obtained from experimental research were available for most imperfections. Realizations of the input imperfections were computed using the Latin Hypercube Sampling method. Global sensitivity analysis was used to identify those imperfections, whose variability has a dominant effect on the load carrying capacity. Sensitivity analysis identified three continuous intervals of beam slenderness in which the load carrying capacity is sensitive to different types of imperfections. Reliability of design according to the EUROCODE 3 standard was verified by performing the statistical analysis of the ultimate limit state.

1. Introduction

I-beams are usually made of structural steel and are used in construction and civil engineering [1]. An I-shaped section is a very efficient form for carrying both bending and shear loads in the plane of the web, but has low carrying capacity in the plane associated with bending about its minor principal axis, and is furthermore inefficient in carrying torsion [1]. I-beams can thus be effectively used for carrying bending about their major principal axis. The load carrying capacity of an I-beam decreases with its increasing length (slenderness) due to lateral-torsional buckling (LTB).

The LTB behaviour of I-beams is very sensitive to imperfections [2,3]. The methods for modelling imperfections can be classified as deterministic or random [4]. Random uncertainty of imperfections can be taken into account in stochastic models using random variables or random fields [5,6]. The thesis [5] studies very similar subject matter as the presented paper, i.e. the effects of random imperfections on the stability of steel structures. The thesis [5] presents on a series of slender I-beams the simulation of buckling variability combining advanced methods of nonlinear structural shell finite elements and modern stochastic process theory. The greater the complexity of the stochastic model, the more information on input random imperfections is needed. At

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present, in the case of frame structures, we can encounter problems focused on the modelling of initial geometric imperfection using linear combinations of eigenmodes [7]. Works aimed at the global sensitivity analysis of the influence of imperfections on limit states of structures occur rarely, although imperfections may drastically reduce the theoretical ultimate strength of perfect members.

The presented paper deals with the statistical and global sensitivity analyses of the LTB reliability of a simply supported hot-rolled steel European IPE 220 beam with initial random imperfections. The beam IPE 220 has an I-shaped cross-section, see Fig. 1 and [8–10]. Attainment of the limit state (in general, occurrence of failure) cannot, due to technical and economic reasons, be eliminated completely. Structures are therefore designed so that the probability of failure is minimal while the structure is still cost-effective. There are two types of structural limit states. One is pertinent to the load carrying capacity (ultimate limit state), and the other to serviceability (serviceability limit state). In the context of stability problems of steel structures, the load carrying capacity is generally more important than the structural serviceability, because it is related to ensuring the structure safety against collapse.

The load carrying capacity is generally a random variable that is dependent on input random material and geometric imperfections. The load carrying capacity is most frequently studied experimentally in a laboratory, while its random properties are studied using numerical, stochastic models and with the aid of computers. The reliability required for steel structures is obtained through design according to EN 1990 [11] and EN 1993 (EUROCODE 3) [12]. According to [11], the design load carrying capacity can be obtained as the lower quantile of the random load carrying capacity, see, e.g. [13,14,8]. EUROCODE 3 lists the rule for evaluation of the design buckling resistance moment using characteristic values of material properties, nominal values of geometric characteristics, and partial safety factors. The design reliability according to [12] may be verified using the general principles for structural design of civil engineering works given in [11].

The derivation of the close-form formula for the elastic load carrying capacity of an imperfect IPE-beam loaded in bending is performed in this article. The analysis stems from the works of [15] and [16,17]. Imperfections are considered as random variables according to the results of experimental research [9,25]. The influence of random imperfections on the ultimate limit state of slender beams is studied using global sensitivity analysis (SA) [18] analogously as, e.g. in [19]. The imperfections, which have the greatest effect on reliability and should thus be addressed in experiments with the aim of the most precise determination of their random variability, were determined applying SA. The reliability of design according to [12] was verified using statistical analysis of the ultimate limit state. Non-dimensional beam slenderness $\bar{\lambda}_{LT}$ evaluated according to [12], enabling a more general comparison of results, was considered as the analysis parameter.

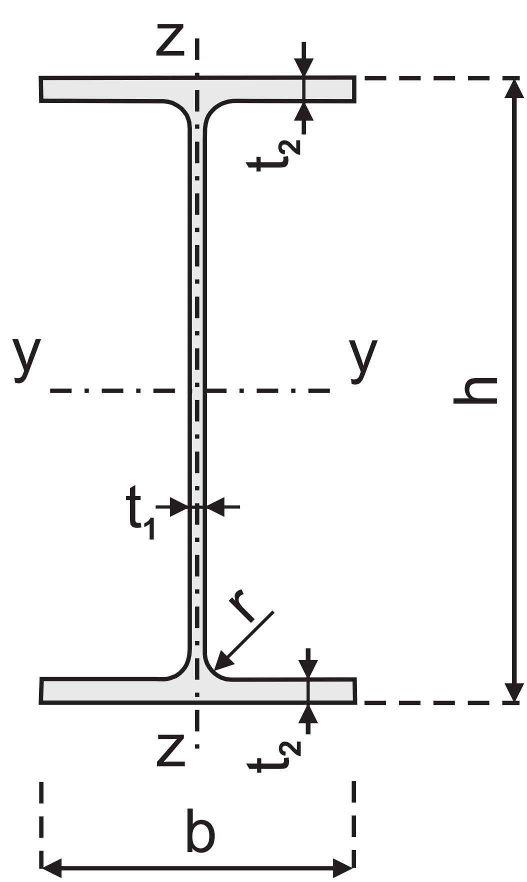

Fig. 1 – IPE cross-section.

2. Lateral-torsional buckling of straight beams

The first available theoretical work on LTB of solid rectangular beams was published by Michell [20] and Prandtl [21]. Their work was extended by Timoshenko [22,23] to include the effect of warping torsion in IPE-beams.

For an idealized perfectly straight elastic IPE-beam, there are no out-of-plane x-z deformations until the applied bending moment M reaches the critical value M_{cr} and the beam buckles by deflecting laterally and twisting, see Fig. 2. This case represents a simple configuration, and buckling analysis leads to a close-form solution [24].

The deflection υ and twist angle φ of the buckled shape can be obtained from two differential equations:

$$EI_z \frac{\partial^2 \upsilon}{\partial x^2} + M_{cr}\varphi = 0 \tag{1}$$

$$EI_\omega \frac{\partial^3 \varphi}{\partial x^3} - GI_t \frac{\partial \varphi}{\partial x} + M_{cr} \frac{\partial \upsilon}{\partial x} = 0 \tag{2}$$

where E is Young's modulus of elasticity, G is shear modulus, I_z is the second moment of area about axis z, I_ω is warping section constant, and I_t is torsion constant. The solution of Eqs. (1) and (2) satisfying the boundary conditions at the supports

$$(\upsilon)_0 = (\upsilon)_L = 0, \quad \left(\frac{\partial^2 \upsilon}{\partial x^2}\right)_0 = \left(\frac{\partial^2 \upsilon}{\partial x^2}\right)_L = 0, \quad (\varphi)_0 = (\varphi)_L = 0, \quad \left(\frac{\partial^2 \varphi}{\partial x^2}\right)_0 = \left(\frac{\partial^2 \varphi}{\partial x^2}\right)_L = 0 \tag{3}$$