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Original Research Article

Imperfection sensitivity analysis of steel columns at ultimate limit state

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ABSTRACT

The present paper applies Sobol's variance-based global sensitivity analysis (SSA) to quantify the contribution of input imperfections to the load-carrying capacity (LCC) of an IPN 200 steel compressed member. LCC is evaluated using the geometrically and materially non-linear finite element solution with regard to the effects of initial random imperfections including residual stresses. Comparison of results of SSA for (i) buckling about the minor principal axis, (ii) buckling about the major principal axis and (iii) lateral–torsional buckling due to bending moment is performed on the non-dimensional slenderness interval of 0–2. SSA for (i) and (ii) is performed for steel grade (a) S235 and (b) S355, SSA for (iii) is performed only for steel grade S235. SSA found similarities in results (ia) and (ib), (iia) and (iib) and identified significant differences between results (ia) and (iiia), (iia) and (iiia), where sensitivity to the initial axial curvature is more than two times higher in (ia) than in (iiia). The relationships between the effects of initial imperfections on LCC and the design criteria of reliability of Eurocode 3 are discussed.

1. Introduction

Initial geometric and material imperfections including residual stresses influence the reliability of load bearing steel members, which are subjected to compression or strong axial bending and compression associated with other action effects [1]. In probabilistic modelling, initial imperfections are treated as random variables, see e.g. [2,3]. The basis of probabilistic modelling is the stochastic computational model, whose inputs are random imperfections and output is a random variable, which is crucial for the assessment of adverse phenomena [4,5].

Adverse effects inherent in structural design are usually associated with the attainment of any of the limit states [6,7] established in standards [8,9], during which the structure or a part of the structure no longer satisfies requirements, see e.g. [10–12]. Probabilistic structural design is a decision problem [13,14] added to probabilistic structural analysis [15], in which the probabilities of the limit states primarily serve as indicators of safety and reliability [16].

In terms of safety and reliability of steel load bearing structures, the most important variable is the load-carrying capacity (LCC), which can be studied using statistical analysis, e.g. [17], probabilistic analysis, e.g. [18] and sensitivity analysis, e.g. [19–21]. Sensitivity analysis (SA) is a measure of the

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importance of input variables [15] and can help researchers understand "how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" [22].

The technique of SA is as old as that of differential calculus [15]. Various SA approaches are currently being applied in various sub-fields of the civil engineering field [23–25], see also reviews about SA [26–28]. Extensive development of SA and its applications occurred after Sobol's publication of the method based on the decomposition of the output variance [29,30]. Sobol sensitivity analysis (SSA) is referred to as global, because it can quantify the influence of input variables on the model output over the entire range of the distribution and provide the interaction effects between different input variables [31]. Examples of the increasing number of applications of SSA in engineering can be found in [32–37]. Recently there has been a development of new methods of SA based on SSA, for example, the so-called Goal Oriented SA [38] or SA for the measure of the effects of input variables on the structural failure [39].

The aim of the present paper is the SSA [29–31] of the effects of random imperfections on the random LCC of a compressed member with IPN 200 section. LCC is evaluated using the geometric and material non-linear finite element (FE) analysis. Experimental research provides important information on the random variability of initial imperfections of steel members like the yield strength [40–46], geometric deviations in dimensions of the cross-section [41,45], residual stress [47,48], member out-of-straightness [49] and frame out-of-plumb imperfections [50].

In stochastic models, the random realizations of input initial imperfections are simulated using the Monte Carlo method or some form of stratified sampling like Latin Hypercube Sampling (LHS) [51,52]. The realizations of output LCC are then obtained as runs of the non-linear FE model, see e.g. [53,54]. The disadvantage of non-linear FE models is the high computational burden of each run. Therefore, SSA is evaluated in the present article using an approach that approximates the dependence between initial imperfections and LCC using a polynomial metamodel, which is often referred to as a polynomial surrogate model or emulator or approximation model, see e.g. [55–57]. The developed surrogate model replaces the computational expensive full model based on FEM. This approach makes it possible to use a high number of samples of the LHS method and repeat SSA using the step-by-step method for a range of slenderness (lengths) of compressed member IPN 200.

The present study and [54] partially overlap with regard to the non-linear FE model and its random imperfections, however, new results of SSA of LCC of an imperfect compressed member made form steel grades S235 and S355 are presented in the present article. The obtained results are compared with [54]. In order to compare the results of both stability problems, the same IPN 200 section is considered.

It should be noted that the IPN-section is not a representative rolled section for columns, which are more often made from hot-rolled H-sections instead of I-sections. However, the results of SSA pertaining to flexural buckling (FB) can partially be generalized to other narrow flange section members subjected to compression. This is discussed in the conclusion of the present article. In contrast, SSA showed that compressed members (columns) fail due to different combinations of imperfections than beams in bending. I members subjected to combined compression and bending are not studied in the present paper.

2. Finite element model

The computational model is a column pinned at both ends, which is loaded centrically at one end, see Fig. 1a. The column consists of a double symmetrical rolled European steel cross-section IPN 200. The geometry of the member was slightly simplified and idealized by removing the fillets on the inner sides of the flanges and at the flange-to-web connections in order to maintain regularity of the mesh. Their influence is negligible acc. to [58]. The original and idealized cross-sections are shown in Fig. 1b and c.

The computational model was created using the software Ansys APDL [59]. The SOLID185 element was used for the model. It is a 8-node homogeneous structural solid element that is suitable for 3D modelling of solid structures. It has large deflection and large strain capabilities, plasticity, hyperelasticity, stress stiffening and creep. The enhanced strain formulation was considered. This formulation prevents shear

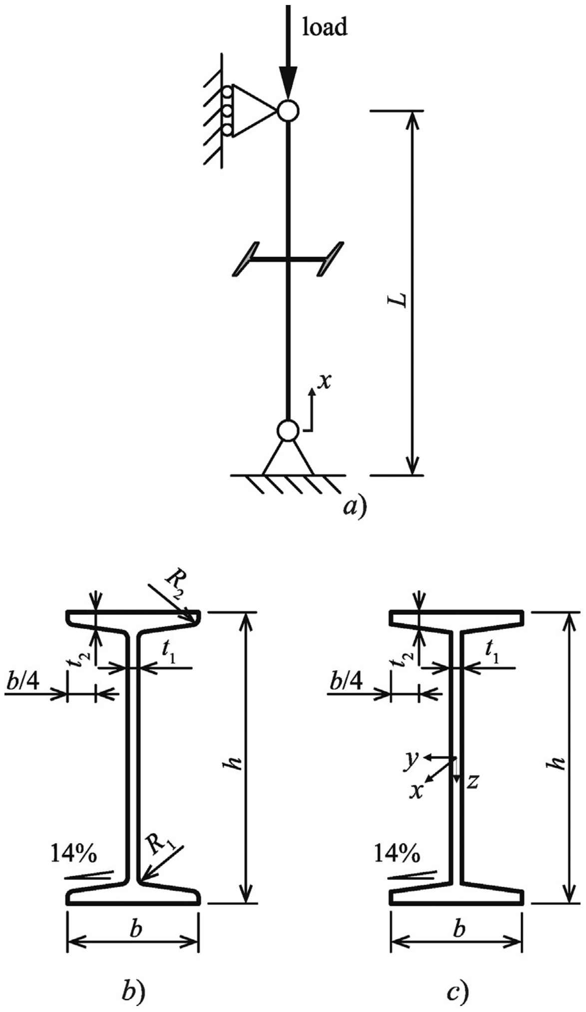

Fig. 1 – (a) Scheme of the compressed member, (b) real cross-section, (c) idealized cross-section.