Engineering Structures 134 (2017) 37–47

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Global sensitivity analysis of lateral-torsional buckling resistance based on finite element simulations

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ARTICLE INFO

Article history:
Received 10 August 2016
Revised 22 November 2016
Accepted 19 December 2016

Keywords:
Sensitivity analysis
Stability
Reliability
Lateral-torsional buckling
Steel
Beam
Imperfections
Out-of-straightness
Residual stress
FE modelling

ABSTRACT

The article examines a hot-rolled steel I-beam subjected to lateral-torsional buckling (LTB) due to bending moment. The paper describes a non-linear finite element (FE) model and numerical approximation and simulation methods used for the global sensitivity analysis of the static resistance of a beam under major axis bending. The presented geometrically and materially non-linear FE model based on solid elements models in detail the LTB and the effects of initial imperfections on the ultimate limit state of a steel beam. Simulation runs of random imperfections are generated using the Latin Hypercube Sampling (LHS) method. Polynomial approximation of the model output helped minimise the number of runs of the non-linear finite element model. The approximation polynomial then facilitated the evaluation of sensitivity indices using a high number of simulation runs. The relationships between the slenderness and the first and second-order sensitivity indices are plotted in graphs. The graphs show the results of global sensitivity analyses of stochastic effects of initial imperfections and residual stress on the resistance of the investigated steel beam.

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1. Introduction

Lateral-torsional buckling (LTB) is a typical failure mode of unbraced I-beams subjected to bending about the major principal axis that both twist and deflect laterally. Lateral-torsional buckling resistance (LTB-R) including the effects of imperfections, residual stresses and plasticity effects may exhibit broad stochastic scattering due to the random influence of these effects [1]. Detrimental imperfections like initial curvature of the axis and residual stress may dramatically reduce the LTB-R. High sensitivity of LTB-R to the stochastic variability of initial imperfections increases the probability of failure of beams. Due to these reasons, it is important to study the effects of these inevitable initial imperfections and residual stresses on the LTB-R, which is the goal of the presented article.

The research of thin-walled beams has evolved from the classic Vlasov theory [2] to advanced non-linear finite element (FE) models; see e.g. [3–8]. In literature, the imperfect I-beam subjected to uniform bending moment is the only case for which the elastic closed-form analytical solution of lateral-torsional buckling resistance (LTB-E) exists [9]. The development of numerical methods, such as FE methods, has lead to the continuous investigation of the available closed form solutions present in standard literature [9–13] and codes [14–16]. It has been clearly shown that such formulae are often conservative and in certain cases wrong [17].

The efficient use of computational models requires an understanding of key relationships between inputs and outputs. Analytical, especially numerical models of LTB failure modes are unfortunately often so complex that they prevent the understanding of the response of the model output to changes in model inputs based on intuition.

The dependence of model output on model inputs can be studied using stochastic sensitivity analysis (SA). The diversity of problems that are solved using mathematical modelling has recently lead to the development of several highly successful methods of sensitivity analysis [18–21]. Advanced methods of stochastic global sensitivity analysis are usually highly numerically demanding, especially in cases where it is necessary to evaluate the sensitivity indices using the Monte Carlo numerical simulation method. The computer time needed for the evaluation of one realization (one run) of the output random variable increases with increasing complexity of the computational model. Furthermore, the more complex the sensitivity analysis, the more realizations (numerical simulations) are needed to obtain statistically correct output.

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http://dx.doi.org/10.1016/j.engstruct.2016.12.032
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In engineering fields, scientists try to keep up to date with the current trends of modern research aimed at global sensitivity analysis (GSA) of model outputs [22]. GSA is necessary in situations where a priori information on the nature of the model is unavailable (model-free setting) or the model is considered to be non-additive [23]. In contrast, local SA (LSA) puts emphasis on the local (point) impact of the input factors on the model output [20]. LSA, which is also known as differential SA, belongs to the class of the one-factor-at-a-time methods. LSA has apparent advantages [21]. It is very straightforward compared to GSA, thus, making it easy to apply and interpret. In the case of a linear model, all information needed for SA is obtained from the first-order derivatives [24]. In the case of a non-linear but additive model, i.e. no interactions are present among factors, then derivatives of higher and cross order suffice to understand the model [24]. LSA cannot be used to describe higher-order interaction effects among factors. The outputs of non-linear and non-monotonous computational models such as LTB-R should be studied with GSA. One of the most effective methods of stochastic GSA is Sobol's sensitivity analysis SSA [25,26], which is based on the total decomposition of the variance of the output variable into terms with increasing dimensions.

In this article, SSA is used to map the influence of random input imperfections on the ultimate (inelastic) lateral-torsional buckling resistance (ultimate load carrying capacity) denoted as LTB-R. The term imperfection refers collectively here to both geometrical (initial axial twist and curvature, tolerance of dimensions of the cross section) and material (yield strength, residual stress, Young's modulus) imperfection [27]. The stochastic LTB-R was evaluated by Monte Carlo runs using Latin hypercube sampling (LHS) [28,29] on I-beam samples, which are randomly generated and subsequently analysed using the commercially available geometrically and materially non-linear FE program ANSYS [30].

A highly detailed model based on non-linear FE method allows detailed modelling of the effects of all imperfections on LTB-R. End-fork boundary conditions and uniform bending moment loading were considered, see Fig. 1. An elastic solution in the closed form [9], which was applied for the evaluation of LTB-E (lateral-torsional buckling resistance including the effects of imperfections, without residual stress and based on elastic and first yield analysis) [31,32], also exists for this type of boundary condition and loading. SSA was evaluated for LTB-R and LTB-E and the obtained results were compared. Due to the high complexity of the repeated calculations of LTB-R, SSA of the FE model was not performed, but rather the SSA of the polynomial approximation of the FE model.

2. FE model

Numerical simulations were performed using the Ansys software [30] as a process of running geometrically and materially non-linear model with regard to imperfections, such as initial geometric imperfections and residual stresses. The FE research was performed on a model of European hot-rolled steel I200 beam, which is statically loaded on both ends by bending moment M, see Fig. 1.

Due to potential problems that could occur whilst generating the FE mesh, the cross-sectional geometry of I200 was slightly simplified and fillets in the flange-to-web connection and at the ends of the flanges were neglected. The cross-sectional geometry of I200 is considered as biaxially symmetrical. The I200 cross-section is thus defined by five dimensions h, b, t_1, t_2 and α, see Fig. 2. According to [33], the effect of the fillet was found to be negligible in LTB problems.

Commercially available software ANSYS was used for the FE analysis. Homogeneous structural solid element SOLID185 was used for the model. It is an 8-node element having three degrees of freedom at each node: translations in the nodal x, y, and z directions. It is suitable for 3D modelling of solid structures. It has plasticity, hyper-elasticity, large deflection and large strain capabilities, stress stiffening and creep. The enhanced strain formulation, which prevents shear locking in bending-dominated problems and volumetric locking in nearly incompressible cases, was considered. The element introduces nine internal degrees of freedom to handle shear locking, and four internal degrees of freedom to handle volumetric locking. All internal degrees of freedom are introduced automatically at the element level and condensed out during the solution phase of the analysis [30]. SOLID185 allows for prism, tetrahedral, and pyramid degenerations when used in irregular regions. However, this was not the case, and only hexahedron elements were created [30].

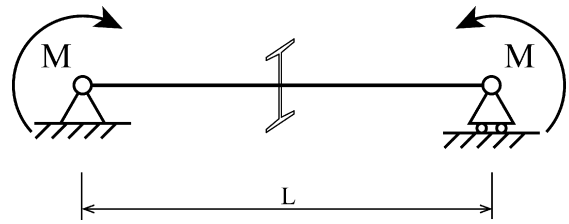

Fig. 1. Simply supported I-beam subjected to uniform bending moment.

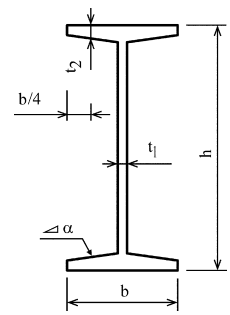

Fig. 2. The geometry of beam I200.

Even though it is customary to model LTB problems using shell elements instead of solid elements, certain undesirable effects, such as small material overlap in the flange-to-web connection, occur in shell models. The beam is thus a little bit more rigid and has a higher load-carrying capacity [3,34]. Another disadvantage of shell elements is the problematic modelling of the varying thickness of parts of the cross-section. In this case the flange thickness t_2. These undesirable effects were eliminated using solid elements SOLID185, however, at the cost of increasing demands on CPU time.

2.1. Mesh, boundary conditions and loads

Generally, the results obtained from the FE model are more accurate the finer the FE mesh. This, however, leads to an increase in the computational time. It is thus necessary to find a balance between the computational time and the desired accuracy. The mesh density was tested and the optimal setting of 20 elements over the entire height of the web, 10 elements over the entire width of the flanges and two elements over the web and flange thickness was chosen, see Fig. 3. It was tested that two elements over the thickness are sufficient and the final value of resistance is not influenced by the number of elements even in the plastic behaviour. The x–axis corresponds to the longitudinal axis of the beam; axes y and z lie in the plane of the cross-section. The origin of the coordinate system is placed in the centre of gravity of the cross-section. This also corresponds to the shear centre in a doubly

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