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An efficient coupled numerical method for reliability-based design optimization of steel frames

Linh A. Le [a,b], T. Bui-Vinh [c], V. Ho-Huu [a,b], T. Nguyen-Thoi [a,b,*]

[a] Division of Computational Mathematics and Engineering, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
[b] Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
[c] University of Social Sciences and Humanities, VNU-HCM, Ho Chi Minh City, Viet Nam

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ABSTRACT

The paper proposes an efficient coupled numerical method for reliability-based design optimization (RBDO) of steel frames. In this RBDO problem, the objective function is to minimize the weight of the whole steel frame. Design variables are cross sectional areas of beams and columns which are considered as discrete variables and chosen from the sets of wide-flange shape steel sections provided by the American Institute of Steel Construction (AISC). Random variables relate to the material properties and applied loads. Probabilistic constraints of ultimate load limits and serviceability limits are defined following the specifications for structural steel buildings by AISC. For analyzing the behavior of steel frames, the finite element method for frame structures is utilized. For searching the optimal solution of RBDO problems, an efficient coupled numerical method by combining the Single-Loop Deterministic Method (SLDM) and the Improved Differential Evolution (IDE) is proposed to give the method called SLDM-IDE. In the SLDM-IDE, all of the probabilistic constraints are converted to the approximate deterministic constraints. This helps transform the RBDO problem into an approximate deterministic optimization problem which can be solved by standard optimization algorithms. This helps reduce significantly the computational cost for solving the original RBDO problem. Three numerical examples are conducted, and obtained results are compared with those of previous publications to demonstrate the robustness and efficiency of the proposed approach.

1. Introduction

During last decades, many new materials and structures have been developed to cater the unceasing need about the accommodations of people, especially in big cities. However, regardless of the diversity of materials and structures, steel frame structures still play a greatly important role in structural engineering. This is because the steel frame structures possess various advantageous properties such as the high strength and easiness of shaping which allow engineers to build high and cost-efficient structures.

In the field of engineering, it is important to design structures that satisfy pre-defined objectives but with a cost as low as possible. Optimization methods have been developed to serve this purpose by archiving a good balance between the expense and safety of the structures. Proposing and solving optimization problems not only help reduce the structural cost significantly but also ensure to satisfy the ultimate strength and serviceability limits. The optimization of steel frame structures hence has been receiving a great attention during the past decades. Some of remarkable studies could be listed out here such as Pezeshk et al. [1] who employed Genetic Algorithm (GA) to design a geometrical nonlinear steel-framed structures; Camp et al. [2] who utilized the Ant Colony Optimization (ACO) in association with penalty constraint handling technique to obtain the optimal design of steel frames with discrete design variables or Hasancebi et al. [3] who recently presented the Bat Inspired algorithm (BI) for optimization of 3D steel frames. Other optimization algorithms including Harmony Search algorithm (HS) [4–6], Improved Ant Colony (IAC) [7,8], Big Bang Big Crunch algorithm (BBBC) [9,10] have been also employed for design optimization of the steel frames. In these optimizations, the constraints are usually chosen based on practically accepted standards such as Specification for Structural Steel Buildings (ANSI/AISC - 1994), (ANSI/AISC - 2010) or British Standard (BS5950 – 1990).

However so far, these above-mentioned deterministic optimization problems have not yet taken into account the uncertainties of variables which might be the results of natural causes (i.e. climate change, rainfall, flood, earthquake) or man-made causes (i.e. calculation errors, modeling errors, manufacturing errors). Whereas these uncertainties can make the design become susceptible to any change of structures'

* Corresponding author at: Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Viet Nam.
E-mail addresses: leanhlinh@tdt.edu.vn (L.A. Le), hohuuvinh@tdt.edu.vn (V. Ho-Huu), nguyenthoitrung@tdt.edu.vn (T. Nguyen-Thoi).

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conditions and put the building in the danger of failure. Over the past twenty years, a novel concept of design named reliability-based design optimization (RBDO) has been developed to address this problem by considering additionally the variations of uncertainties via their distributions and probability densities in the optimization process. As a result, the structures would be designed not only with a cost as low as possible but also with a certain level of safety. Theories and methods for analyzing the structural reliability have been developed substantially in the last few years, and they are actually useful tools for rationally evaluating the safety of complex structures [11]. Related to steel frames, some efforts for solving the RBDO in the past few years can be referred such as the study by Manolis et al. [12] who used the Monte Carlo simulation method incorporating the Latin hypercube sampling technique to handle probabilistic constraints of 2D steel frames under seismic loadings, or the work by Ghasemi et al. [13] who used the Genetic Algorithm to solve the probabilistic design for I-shaped cross section steel frames, or the study by Mohsenali et al. [14] who employed the software OpenSees in association with Genetic Algorithm to solve the reliability-based optimization problem for frames with discrete design variables. It can be seen from the literature that the research on the RBDO for steel frame structures is still somewhat limited.

During the process of solving the RBDO problems, the probabilistic constraints have to be checked from time to time to ensure that they are satisfied before yielding to the optimal design. This will consume a very large proportion of the computational cost and hence requires a lot of efforts to increase the solvers' efficiency, especially when these constraints are related to analyses of the structures' behavior through numerical simulations. Among current approaches, the Single-Loop Deterministic Method (SLDM) proposed by Li et al. [15] is a promising approach for solving RBDO problems. While other approaches such as double loop method [16,17] or decoupled double loop method [18–21] execute the reliability assessment many times during the optimization process, the SLDM separates the probabilistic constraints from the optimization process and handles them independently. The SLDM solves RBDO problems through two following steps: (1) converting the probabilistic constraints to approximate deterministic constraints and hence the RBDO problems are converted to approximate deterministic optimization problems; and (2) solving the obtained deterministic optimization problems by the standard optimization algorithms. This hence helps reduce the computational cost significantly.

In the other front of developing the algorithms for solving optimization problems, Differential Evolution (DE) proposed by Storn et al. [22] has been emerged as a very efficient global method. It has been recently improved to different versions and applied in many engineering problems including truss structures optimization [23–26], composite plates optimization [27,28], damage detection [29–32], pattern recognition [33]. Good results from these researches show the efficiency and applicableness of the DE in many engineering applications. Nevertheless, the extension of these methods for optimization designs of steel frame structures, especially in relation to probabilistic constraints has not yet been executed.

Based on the above-mentioned considerations, this paper proposes a novel coupled numerical method for solving RBDO problems of steel frames with discrete variables by combining the Single-Loop Deterministic Method (SLDM) [15] and an Improved Differential Evolution (IDE) [34] to give a so-called SLDM-IDE. The IDE is an improved version of the DE in which two improvements including a roulette wheel selection and elitist selection are employed. These improvements aim to enhance the efficiency for the conventional DE. In these RBDO problems, the objective function is to minimize the weight of the whole steel frame. Design variables are cross sectional areas of beams and columns which are assumed as discrete variables. Random variables are the elastic modulus, yield strength of the steel and applied loads. Constraints of ultimate load and serviceability limits of the problems are defined based on the Specifications for Structural Steel Buildings by the American Institute of Steel Construction (AISC).

2. Formulation of the RBDO problem of steel frames

In general, the mathematical form of a RBDO problem of steel frames is formulated as

$$\begin{aligned}&\text{Minimize } W(\mathbf{A}) = \sum_{i=1}^{n} A_i \rho_i L_i \\ &\text{Design Variables: DV} = \{A_i\} \\ &\text{Constraints} \;:\; \begin{cases} \text{Prob}\left\{C_k^{\sigma} \le 0\right\} \ge r_k = \Phi(\beta_k) & k = 1,\ldots,nc \\ \text{Prob}\left\{C_r^{\delta} \le 0\right\} \ge r_r = \Phi(\beta_r) & r = 1,\ldots,ns \\ A_i \in \mathbf{G} \quad i = 1,\ldots,n \end{cases}\end{aligned} \tag{1}$$

where $W(\mathbf{A})$ is the objective function which is the weight of the whole frame; n is the number of structural components in the frame; ρ_i and L_i are respectively the weight density and length of ith structural component; A_i is the cross sectional area of ith component, which is chosen from discrete module set $\mathbf{G}$ of thin wing steel (W) provided by AISC; r_k and r_r are the desired probability of the kth and rth constraints; β_k and β_r are the target reliability indexes of each constraint; $\Phi(.)$ is the standard cumulative function of the normal distribution; ns, nc are the number of stories and number of components in the frame; C_k^{σ} and C_r^{δ} are constraints related to ultimate load and serviceability limits defined following the AISC-LRFD 2010 [35]. For ultimate loading limits, the constraints are calculated from components under bending and axial forces as

$$C_k^{\sigma} = \begin{cases} \dfrac{P_r}{P_c} + \dfrac{8}{9}\left(\dfrac{M_{rx}}{M_{cx}} + \dfrac{M_{ry}}{M_{cy}}\right) - 1 & \text{if} \quad \dfrac{P_r}{P_c} \ge 0.2 \\ \dfrac{P_r}{2P_c} + \left(\dfrac{M_{rx}}{M_{cx}} + \dfrac{M_{ry}}{M_{cy}}\right) - 1 & \text{if} \quad \dfrac{P_r}{P_c} < 0.2 \end{cases} \tag{2}$$

where P_r is the required axial strength computed as in Appendix 8, Section 8.2 of the AISC-LRFD 2010 [35]; $P_c = \phi P_n$ is the design axial strength in which $\phi = 0.9$ is the tensile/compression resistance factor and P_n is the nominal compression strength computed as in chapter E, Section E3 of the AISC standard; M_r is the required flexural strength computed as in Appendix 8, Section 8.2 of the AISC; $M_c = \phi_b M_n$ is the design flexural strength in which $\phi_b = 0.9$ is the resistance factor for flexural, and M_n is the nominal flexural strength calculated as in the chapter F, Section F2 of the standard; x and y are respectively the subscript symbols of strong and weak axis bending.

The serviceability limits on the other hand is computed through the storey drift at the column end of ith storey as

$$C_r^{\delta} = \frac{|\delta_r|}{|\delta_r^u|} - 1 \tag{3}$$

where δ_r is the horizontal displacement of the rth storey; $\delta_r^u = H_r/300$ is the allowable displacement of a storey calculated from the height of that storey H_r.

3. The SLDM-IDE for solving RBDO problems of steel frames

3.1. The Single-Loop Deterministic Method for handling probabilistic constraints

In the Single-Loop Deterministic Method (SLDM) for solving RBDO problems of steel frames, the probabilistic constraints in Eq. (1) can be rewritten in the general form as:

$$\text{Probabilistic constraints:} \quad \text{Prob}\{g_i(\mathbf{u}) \le 0\} \ge r_i^t = \Phi(\beta_i^t), \quad i = 1, 2, \ldots, nc + ns \tag{4}$$

where $g_i(\mathbf{u})$ is the limit state function comprising of the ultimate loading limits C_k^{σ} and the serviceability limits C_r^{δ}; $\mathbf{u}$ is the vector of random variables including Young's modulus, yield strength and applied loads.