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An efficient approach for design optimization of structures involving fuzzy variables

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Abstract

We propose a new approach for solving design optimization problems of structures involving fuzzy variables. First, the possibilistic safety model of structures with fuzzy variables is investigated. A possibilistic safety index (PSI) is presented to compare different designs. This paper then presents the PSI-based design optimization (PSIBDO) model for structures with fuzzy variables. The optimization problem is a triple-loop nested problem, and the computational cost is high. To reduce the computation time, a technique called target performance-based design approach (TPBDA) is proposed to overcome difficulties encountered by the PSIBDO. With the proposed TPBDA, the triple-loop nested problem is reduced to a double-loop one, and the computational time is considerably reduced. Several examples are given to demonstrate the efficiency of the proposed approach.

Keywords: Optimization; Fuzzy variables; Possibilistic safety; Possibilistic safety index

1. Introduction

Optimization techniques for structural optimal design have been widely used in practice, generally consisting of deterministic optimization and non-deterministic optimization methods. The former aims to search for the optimum solution under given constraints without considering uncertainties. However, in many engineering structures, structural performances exhibit variations due to the presence of uncertainties, such as the fluctuation of external loads, the variation of material properties, etc. Deterministic optimization approaches are unable to handle such uncertainties, and thus the so-called optimum solution obtained may lie in the infeasible region when uncertainties are present. Thus, realistic design approaches must be able to deal with the uncertain nature of structures [1]. Several non-deterministic design optimization approaches considering structural uncertainties have been reported in the literature, including reliability-based design optimization (RBDO) [2,3] and structural robust design optimization [4–6]. The former focuses on searching the optimum solution under prescribed reliability constraints, while the latter aims to minimize the variation of the objective function. This paper focuses on RBDO.

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RBDO under the probabilistic framework has attracted much attention, both in research and practice [7–13]. Under this framework, estimating the failure probability requires precise information on the statistical distribution of random variables. However, data on the random variables are usually rare due to practical limitations. In addition, the failure probability is usually very sensitive to the distribution of the random variable, and small errors in the distribution may result in a misleading result of the failure probability [14]. Instead of requiring the precise information on the uncertainties, bounds on the uncertainties are relatively easier to obtain for many practical structures. Based on the convex set model theory, Ben-Haim and Elishakoff [15–17] first proposed a non-probabilistic framework using an ellipsoid set to cope with this situation. Utilizing interval analysis, Guo [18] presented another non-probabilistic framework with an interval set. Recently, Kang [19] developed a novel non-probabilistic framework based on the multi-ellipsoid convex set model, which can provide a unified description for the ellipsoid set and the interval set.

Dealing with uncertainties in human behavior is difficult within the probabilistic framework [20]. Fuzzy set has been adopted to deal with uncertainties in human behavior and expert judgment [21–38]. Cai et al. [21–26] were among the first to introduce the possibility and fuzzy-state assumptions to replace the probability and binary-state assumptions. With these new assumptions, profust (probability and fuzzy-state assumptions) reliability theory, posbist (possibility and binary-state assumptions) reliability theory, and posfust (possibility and fuzzy-state assumptions) reliability theory were established. Many researchers have further expanded research along these directions. Utkin et al. [27] investigated reliability analysis of a general system. Cheng et al. [28] conducted fuzzy system reliability analysis using confidence intervals. Furuta [29] summarized fuzzy logic and its application to reliability analysis. Cooman et al. [30] used the binary-state theory to model possibilistic uncertainty. Cremona [31] constructed a possibilistic alternative to the probabilistic one. Sawyer [32] used the fuzzy set theory to describe mechanical and structural systems, and developed a strength-based safety index to describe the safety of structures, which can address the problems with discrete data. Marco [33] introduced fuzzy numbers to structural reliability analysis and extended it to stability analysis. Mourelatos [34] performed reliability estimation and design with incomplete data based on the possibility theory. Dodagoudar [35] conducted reliability analysis for a slope using the fuzzy set theory. Li et al. [36] presented a practical approach for reliability analysis of mechanical structures, which is based on the fuzzy stress-random strength interference model and the fuzzy linear regression method. For the same problem in Ref. [36], Jiang et al. [37] developed a numerical algorithm for fuzzy reliability analysis. Based on the non-probabilistic framework for interval sets in Ref. [18], Guo et al. [38] constructed a possibilistic safety model for fuzzy variables similar to the probabilistic framework. They employed the concept of failure possibility to describe the safety of structures. Compared with the probabilistic framework, it is easier to implement the theory used in Ref. [38] without requiring calculation simplifications. In summary, fuzzy variables have been widely applied to structural analysis considering uncertainties in human behavior and expert experience in order to circumvent the difficulties involved in the probabilistic framework.

In addition, many researchers have focused on design optimization of structures with the fuzzy uncertainties [39–43]. Möller et al. [39,40] and Behravesh et al. [41] investigated the design optimization problem of structures with fuzzy variables included in the constraints. Marano et al. [42] presented a fuzzy-based robust structural optimization approach. Utkin et al. [43] developed an approach for reliability optimization of the systems involving fuzzy uncertainties.

In this paper, we first construct a possibilistic safety model for structures with fuzzy variables and then propose a possibilistic safety index (PSI) to compare different designs. The PSI-based design optimization (PSIBDO) of structures with fuzzy variables included in the constraints is investigated, which is a triple-loop nested problem. The inner loop focuses on evaluating the PSI, while the outer loop aims to minimize the objective function. Evaluating the PSI is a double-loop nested problem. Thus, the corresponding computational burden is heavy, and the numerical stability usually cannot be guaranteed. To overcome these difficulties in PSIBDO, a method called target performance-based design approach (TPBDA) is proposed to solve the design optimization problem. The basic idea of TPBDA is motivated by the performance measure approach (PMA) [7] and the concerned performance-based approach (CPA) [19]. PMA is employed to solve RBDO involving random variables, while CPA is applied to RBDO dealing with uncertain-but-bounded variables. The only difference between PSIBDO and TPBDA is that the constraint on PSI is replaced by the constraint on the target performance. It is easier to compute the target performance than PSI. With equivalent transformation of the constraints, the original PSIBDO is transformed into TPBDA. Additionally, design sensitivity analysis for the target performance can be easily performed, and the numerical stability can then be improved.

This paper is organized as follows. In Section 2, the possibilistic safety model of structures with fuzzy variables is introduced. PSIBDO is given in Section 3. Section 4 provides TPBDA and sensitivity analysis for the target perfor-