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Nondeterministic optimization of tapered sandwich column for crashworthiness

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ABSTRACT

Foam-filled thin-walled structures signify a class of a promising energy absorber for improving the crashworthiness and safety of vehicles. Although the conventional deterministic optimization has been extensively applied to crashworthiness design of foam-filled thin-walled structures, the optimal solution could become infeasible when uncertainties of design variables and noise factors present in real world. To address this issue, a reliability based design optimization (RBDO) is adopted to consider the uncertainties of design variables and noise factors in crashworthiness optimization for the foam-filled bitubal tapered structure in this paper. Moreover, to comprehensively investigate the differences between deterministic and reliability based design optimization, single objective and multiple objective RBDO are established by integrating Kriging approximation with Monte Carlo Simulation (MCS). Since the optimal results of deterministic design usually converge at the constraint boundary, the solutions of RBDO often need to compromise some objective performance to satisfy the predetermined reliability levels. Furthermore, a comparative study on different Pareto fronts yielded from the deterministic optimization and RBDO under different reliability levels is conducted here. Besides, a grey relational analysis is carried out to determine the most satisfactory solution from the Pareto-set. The results demonstrate that the optimized foam-filled bitubal tapered columns are capable to considerably improve capacity of energy absorption with an increased reliability, potentially being a structural configuration for energy absorber.

1. Introduction

Thin-walled structures have been widely used as energy absorbers in automotive and aeronautical engineering to protect passengers/goods from severe injury/damage attributable to their excellent energy absorption capacity and lightweight [1]. The early studies on energy absorbers have largely focused on theoretical analysis and experimental tests. In this regard, Alexander [2] firstly derived an approximate expression to formulate mean axial crushing force of circular tubes in 1960s. Later, Wierzbicki and Abramowicz [3] proposed the close-form formulas to calculate the axial crush response of aluminum thin-walled columns under both static and dynamic loading conditions. The analytical solutions were then validated experimentally by Abramowicz and Jones [4,5] and Langseth and Hopperstad [6], respectively.

With rapid development of computational power and increased complexity of structural configurations, numerical methods, represented by nonlinear finite element analysis (FEA), has become a more dominant approach to design analysis of structural crashworthiness recently [7]. For example, crashworthiness designs of multi-corner and multi-cell thin-walled columns with different cross-sectional configurations were performed by using the numerical methods [8–10]. For example, experimental [11] and numerical methods were combined for studying the tapered tubes where one or more sides are inclined to the longitudinal axis under axial or oblique loads [12,13]. Compared with straight tubes, taper tubes have been considered preferable as they can provide a desired constant mean load-deflection response and are more capable of withstanding oblique impact loads as effectively as axial loads. Further, taper tubes are less likely to fail by global buckling [14], directly leading to the improvement of crashworthiness. Therefore, it is of considerable significance to perform the crashworthiness study of tapered tubal structures.

Recent attention has also been paid to such cellular materials as metallic foams filled in thin-walled structures to increase energy absorption without too much weight penalty. For example, Hanssen et al. [15] developed the close-form formulas to predict the responses of aluminum foam filled in aluminum columns under both quasi-static and

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dynamic loading. Reyes et al. [16] and Borvik [17] investigated the crashworthiness behavior of foam-filled tubes by experimental test and numerical simulation. Mamalis et al. [18] exhibited that the presence of foam filler can increase the mean crushing load and therefore energy absorbing capacity of thin-walled structures. It was shown that the mean crushing loads of foam-filled tubes are even higher than the sum of the crushing loads of foam alone and tubes alone attributable to their interaction [19,20]. In addition, crashworthiness of composite structures with different foam type were explored extensively. Wu et al. [21] investigated the crashworthiness of foam-filled lattice composite panels under quasi-static compression by using theoretical and experimental studies. Zheng [22] and Yan et al. [23] investigated energy absorptions of polyurethane-foam filled composite tubes under different impacting loads. Hesham et al. [24] performed the mechanical evaluation of different polyurethane foam-cores. Wang et al. [25] and Do et al. [26] studied the bending and fatigue behaviors of foam-filled composite panels. Wang et al. [27] investigated the compressive behavior of novel luffa-filled tubes. Ghamarian et al. [28] experimental and numerical studies showed that foam-filled thin-walled structures are preferred to use thicker tube walls for absorbing more crashing energy. It is however difficult to devise an ideal energy absorption structure through trial and error process down to the complex nature of interactive deformation presented in foam-filled thin-wall structures. For this reason, design optimization has been widely used by combining with approximate modeling techniques [29,30] to improve the efficiency of design process [31–34]. For example, Zarei et al. [35] investigated the maximum energy absorption and minimum weight of foam-filled aluminum tubes using the response surface method (RSM) and multicriteria optimization. Sun et al. [36–39] studied how to optimize crashworthiness of thin-walled column with functionally-graded foam density. Recently, new interest has been drawn to the tapered tubes filled with foams which combine the advantages of foam-filled and tapered structures for its superior balance of crashing stability and energy absorption capacity [40]. However, comparing with foam-filled straight tubes, the investigation into foam-filled taped tubes, especially foam-filled bitubal tapered structure, is scarce in spite of its conceivable potential.

The other critical issue is that these abovementioned studies on foam-filled structures have largely restricted on deterministic analysis and design, in which all the design variables and parameters are assumed to be certain. However, real-life problems inevitably involve some degree of uncertainties, such as material properties, geometries, manufacturing precision and operational conditions, whose nature is largely nondeterministic. It must be pointed out here that in general, a deterministic optimization tends to push a design toward one or more active constraints, thus leaving very little or no room in accommodating errors from modeling, simulation and/or manufacturing uncertainties/imperfections [41–43]. For this reason, the nondeterministic problems in reality solved by deterministic optimization methods could become less meaningful or even unacceptable. To address the issue, some reliability-based design optimization (RBDO) methods [44,45] have been proposed and applied in crashworthiness design. In this regard, Acar and Solanki [46] performed a so-called system reliability based design optimization (SRBDO) of vehicle for crashworthiness; and they analyzed the effects of reliability allocation on different failure modes. Youn et al. [47] performed RBDO for a full vehicle structure by using performance measurement and hybrid mean value method. Rais-Rohani et al. [48] conducted RBDO for the side rails of vehicle by using advanced mean value plus method.

Besides, engineering designs are often imposed as multicriteria and/or multiobjective problems. In this area, Khakhali et al. [49] performed a multiobjective reliability design of the S-shaped hollow box based on the polynomial neural network models and Monte Carlo simulation (MCS) technique. Sinha [50] adopted an approximate moment approach and reliability index for critical responses to perform multiobjective crashworthiness reliability optimization. Harish et al. [51] presented a fuzzy multiobjective reliability optimization based on Particle Swarm Optimization (PSO). To address different design strategies, comparative studies on reliable and robust designs were also conducted. For example, Gu et al. [52] compared multiobjective reliable and robust optimizations for crashworthiness design of vehicle structures. Vijay et al. [53] performed a comparative study on different formulations of reliability based robust design optimization. Fang et al. [54] performed the robust crashworthiness design of foam-filled bitubal circular tube with uncertainty. Despite these progress made, the reliability design of foam filled structures remains an open question, especially in a multiobjective optimization context. Few reports have been available to take into account the effects of noise factors, such as impacting velocity and impacting angle, on the crashworthiness reliability design of foam-filled structures.

This paper aims to explore the differences between deterministic and reliability based design optimization (RBDO) for foam-filled bitubal taper tubes, in which the single objective and multiobjective RBDO are formulated by integrating Kriging modeling technique with Monte Carlo Simulation (MCS). Since the results yielded from the multiobjective RBDO are generally presented in a form of Pareto optimum, a grey relational analysis is thus adopted to define the most satisfactory solution from multiple solutions in the Pareto set. The results showed that the reliability of the optimum is significantly improved and the fluctuation effect of noise factors (e.g. impacting velocity and impacting angle) have been eliminated. The rest of the paper is organized as follows, Section 2 presents the numerical model of foam-filled bitubal tapered structure, Section 3 describes the single and multiobjective deterministic and reliable optimization methods, Section 4 depicts the grey relational analysis, Section 5 presents the results and discussion, and finally, Section 6 draws some conclusions.

2. Numerical analysis of foam-filled bitubal tapered structure

2.1. Finite element (FE) model and validation

The geometric configuration of a novel bitubal tapered tube with a square cross-section and filled with foam is shown in Fig. 1a. The length

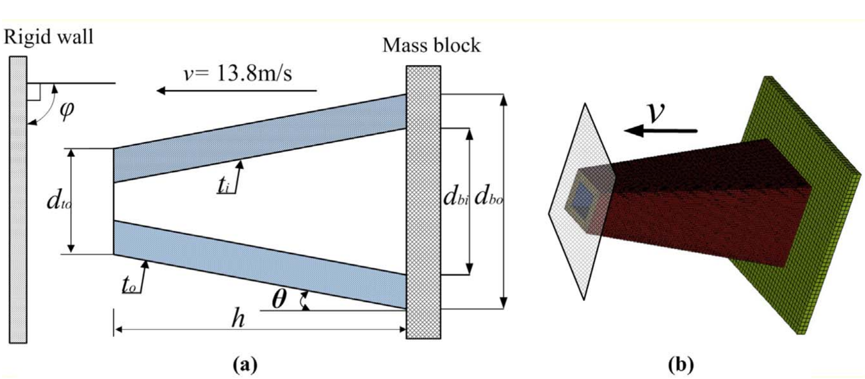

Fig. 1. Schematic of impact by the foam-filled bitubal tapered tube: (a) geometric configuration; (b) FE model for impact simulation.