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Multiobjective optimization for empty and foam-filled square columns under oblique impact loading

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ABSTRACT

This paper aims at optimizing the crashworthiness of empty and foam-filled thin-walled square columns under oblique impact loading, for variations in the load angle, geometry and material parameters of the column. Another focus is to reveal the relative merits of the optimized configurations for both types of columns under such loads. Dynamic finite element analysis (FEA) techniques validated by theoretical solutions and experimental data in the literature are used to simulate the crash responses of such devices subjected to different impact angles. Based on the FEA results, the Kriging metamodels are constructed for the two columns to predict the crashworthiness criteria of specific energy absorption (SEA) and peak crushing force (PCF) under oblique impact loading, which are set as design objectives in the following multiobjective optimization design (MOD) process. The Pareto fronts are identified for the MOD problems of the two types of columns under both single angle impact and the cases involving multiple impact angles, using the multiobjective particle swarm optimization (MOPSO) algorithm. It is found that the optimal designs are generally different under different load angles for either empty or foam-filled column. Results also indicate that more robust designs against oblique impact could be achieved by including multiple load angles in the MOD process. Compared to the empty column, the optimal foam-filled column may have better crashworthiness under pure axial loading, but the optimal empty column has more room to enhance the crashworthiness under oblique impact.

1. Introduction

With the more stringent safety regulations the world automotive industry is facing nowadays, considerable activities have been conducted on the vehicle structure crashworthiness design, as it can directly affect its passive safety performances. In this regard, thin-walled metallic columns are the most conventional and cost-effective energy-absorbing devices and have been widely used in the vehicle design and manufacture. For instance, the crash box of an automobile body in white (BIW) is usually made of thin-walled metallic columns to absorb the crash energy during an impact event. Over the past several decades, extensive efforts [1–7] have been exerted to investigate the crashing behavior and energy absorption characteristics of the thin-walled columns through experimental, theoretical and numerical methods. Meanwhile, due to the serious energy and environmental problems mankind is facing today, the desire for weight reduction of vehicle body structure has to be balanced by the need for crashworthiness in modern automotive industry. As such, design requirements for the crashworthiness devices of a vehicle body should cover both energy absorption capacity and lightweight of such structures.

To improve energy absorption of the thin-walled columns without increasing volume and too much weight, cellular materials such as honeycombs and metal foams are often used as fillers for such structures. Hanssen et al. conducted extensive experimental tests of square [8] and circular [9] columns with aluminum foam filler subjected to static and dynamic loads. Based on the experiments, design formulas for prediction of average force, maximum force and effective crushing distance were suggested. Ahmad and Thambiratnam [10] highlighted the advantages of using foam-filled conical tubes as energy absorbers by showing that the crush and energy absorption performances of conical tubes are significantly enhanced by foam filling. An optimization study for mass minimization of foam-filled square aluminum columns by Hanssen et al. [11] found that optimum foam-filled columns show smaller cross section dimensions in addition to less weight compared to the traditionally designed non-filled columns. With the further study of this subject, Santosa and Wierzbicki [12] revealed that superior

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specific energy absorption (SEA, absorbed energy per unit mass) can be obtained by filling the column with moderate or high strength aluminum foam, while thickening the column wall gives the best SEA with a lower constraint on the total weight of the structure. Nariman-zadeh et al. [13] used multiobjective genetic algorithms (GA) to search for the Pareto solutions of two objectives, namely energy absorption maximization and weight minimization for square aluminum columns both with and without aluminum foam filler. They found that non-filled columns are preferred over foam-filled ones when the desired energy absorption is no more than 4.8 kJ. Hou et al. [14] also indicated that foam-filler could even reduce the energy absorption capacity of unit structural mass under certain circumstances.

To seek the optimal configurations of foam or cellular material filled thin-walled columns with further improved crashworthiness performances, increasing attention has been drawn in recent years on the application of optimization techniques in designing such structures. For example, Zarei and Kröger employed multiobjective optimization to maximize the energy absorption and minimize the weight of honeycomb [15] and foam-filled [16,17] aluminum tubes under either axial or bending load. Yin et al. [18] optimized honeycomb-filled single and bitubular polygonal tubes to achieve maximum SEA and minimum peak crushing force (PCF). Hou et al. [14] and Zhang et al. [19] used multiobjective optimization methods to design aluminum foam-filled monotubal and bitubal thin-walled square columns, respectively. Acar et al. [20] conducted multiobjective crashworthiness optimization of tapered circular thin-walled tubes with axisymmetric indentations for maximum crush force efficiency (CFE, the ratio of the mean crushing force to the PCF) and maximum SEA. Sun et al. [21] first used the particle swarm optimization (PSO) in honeycomb crashworthiness design based on a two-stage multi-fidelity method for surrogate models. The multiobjective particle swarm optimization (MOPSO) algorithm was also adopted by Sun et al. [22] to seek optimal crashworthiness designs for the functionally graded foam (FGF) structures.

All these abovementioned studies have been focused on the crushing behavior and energy absorption characteristics of thin-walled structures under either pure axial or lateral load. However, thin-walled columns working as energy-absorbing devices will rarely experience these two special loading conditions in the real-world, but rather a combination of axial and non-axial or oblique loads, especially during an actual vehicle crash event. According to requirements in the automotive industry, the bumper system should endure a load applied with a 30° load angle to the longitudinal axis [23]. Such loading conditions will cause the column to deform via a combination of both axial progressive and global bending modes. Compared to progressive collapse, the global bending deformation of a thin-walled column is generally unstable with an associated reduction in crash energy absorption. For this reason, some work has been carried out regarding oblique loading of thin-walled columns. Han and Park [24] have numerically investigated the oblique crush behavior of square thin-walled column made of mild steel and showed that there exists a critical load angle at which a transition takes place from the axial progressive collapse mode to the global bending mode, while the latter yields a significant reduction in the mean load. Reyes et al. performed extensive experimental and numerical analyses on the quasi-static oblique loading behavior of both empty [23,25] and foam-filled [26] square aluminum columns. The studies showed that the energy absorption drops drastically when a global bending mode is initiated instead of progressive collapse, and it decreases further with increasing load angle. In aware of this, thin-walled tapered energy absorbers have drawn some attention recently as they appear to have less chance to fail via global bending under oblique loads. Nagel and Thambiratnam [27–29] showed that tapered thin-walled rectangular tubes have more advantages than their straight counterparts in applications when oblique impact is inevitable. Ahmad et al. also [30] demonstrated the advantages of using foam-filled conical tubes in applications where oblique impact load is expected. Recently, Qi et al. [31] performed multiobjective optimization design (MOD) of a class of multi-cell tapered (MCT) square tubes for improved crashworthiness under oblique impact loading. Unlike the case for pure axial or lateral loading condition, there is little information available in literature about the application of optimization techniques in the crashworthiness design of empty or foam-filled columns under oblique loads, even though oblique impact are much more common in real crash events.

The aim of this study is to address the crashworthiness design issues for both empty and foam-filled thin-walled square columns under oblique impact loading by following the multiobjective optimization procedure. The SEA and PCF were considered as crashworthiness criteria in the design problems. The design variables included geometric and material parameters of the columns, namely the cross-sectional width, wall thickness, wall material yield stress, and the foam filler density. Another focus was the relative merits of the optimized empty and foam-filled columns under oblique loads, which has been raised by some pioneer researchers [26] and not yet been disclosed.

2. Materials and methods

2.1. Crashworthiness criteria under oblique loading

In general, there are several key characterization parameters to evaluate the crashworthiness of the energy-absorbing structures, i.e., mean crushing force (F_m), peak crushing force (PCF), energy absorption (EA) and specific energy absorption (SEA). The mean crushing force for a given structural deformation is defined as

$$F_m = \frac{1}{\delta}\int_0^{\delta} F(x)dx \tag{1}$$

where $F(x)$ is the instantaneous crushing load and δ is the structural deformation at a specific time when MCF is calculated. The PCF that can closely relate to the structure deceleration is often a critical criterion in crashworthiness design. For instance, PCF should be reduced or constrained under certain level in automotive crash safety design for preventing occupants and/or goods from severe injury or damage [32]. The *EA* is typically indicated by the total strain energy absorbed during the deformation of the structure, and can be theoretically determined from the crush force–displacement curve, as

$$EA(d) = \int_0^{d} F(x)dx \tag{2}$$

where d is the effective stroke length [1,33], which is taken as 0.5 l in this study, and l is the initial length of the energy-absorbing structure.

If structural weight is an important factor under consideration, a combined criterion called specific energy absorption (SEA) could be defined as the ratio of the absorbed energy to total mass of the structure M_t as

$$SEA = EA/M_t \tag{3}$$

Ideally, the energy absorbers should be designed for maximum crashworthiness performances under both axial and oblique loads