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Multiobjective optimization and sensitivity analysis of honeycomb sandwich cylindrical columns under axial crushing loads

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ABSTRACT

This paper firstly investigates the energy absorption characteristics of honeycomb sandwich cylindrical columns such as square, triangle, kagome and diamond core under axial crushing loads by nonlinear finite element analysis. The interaction effects between the honeycomb and column walls greatly improve the energy absorption efficiency. The response surface method with cubic basis functions is employed to formulate specific energy absorption and peak crushing force which reduces considerably the computational cost of crush simulations by finite element method. Both the single objective and multiobjective optimizations are performed for columns under axial crushing load with design variables inner, outer and core thickness. Models are optimized by multiobjective particle swarm optimization algorithm to achieve maximum specific energy absorption capacity and minimum peak crushing force. Furthermore, local and global sensitivity analyses are performed to assess the effect of design variable values on the specific energy absorption and peak crushing force functions in design domain.

1. Introduction

Constantly use of thin-walled column section beams is increasing in civil engineering, automotive engineering, shipbuilding and other industries because of their high strength–weight ratio, low price and exceptional energy absorption capability during crashworthiness analysis. Their purpose is to absorb the initial kinetic energy during the impact, to keep the force levels adequately low and to pass damage to the car system. Different criteria are being used to asses crashworthiness, including the deformation shapes of the car structure, the acceleration experienced by the vehicle during an impact, and the possibility of hurt predicted by human body models. Injury probability is defined using criteria, which are mechanical parameters that correlate with injury risk. When designing an energy absorber for a structure like a car, different factors such as the energy absorption per unit mass, the maximum crushing force, etc., can be used to evaluate its performance. Reduction of mass and increasing safety are usually desired in the design of the energy absorbing elements of a car. Therefore, higher specific energy absorption (SEA) is often considered as an important factor in this context.

A chief contest remains how to seek an optimal sectional structure for the energy absorption components such that the highest crashworthiness effecting may be achieved. An optimization problem contains high nonlinearities of material and shape, which have not been effectively addressed except some empirical closed form solutions or surrogate model techniques were adopted [1,2]. Abramowicz and Jones [3–5] made static and dynamic experiments on square and circular steel cylinders and compared the outcomes with conceptual computation.

The Response Surface Method (RSM) gains widespread acceptance as various computational crushing model techniques are recognized, and its applications in crashworthiness design have been greatly investigated by a number of researchers, e.g. Lee et al. [6], Chiandussi et al. [7], Avalle et al. [8], and Kim [9]. Lanzi et al. [10] applied radial basis functions (RBF) to the optimal shape design of composite absorbers. Fang et al. [11] also used RBF to achieve crashworthiness optimization using a vehicle model. Kodiyalam et al. [12] studied multidisciplinary design of vehicles based on approximation models by the Kriging method.

Multiobjective optimization, as a more practical design methodology, directs at addressing a number of design principles, which has become an attractive research topic in crashworthiness design lately [13,14]. In contrast to the single objective formulation, a multiobjective structure normally generates a group of solutions in a Pareto sense. As such, a more insight of the optimal design space may be provided to allow creation of a better design result [15,16].

Acar et al. [17] performed multiobjective crashworthiness optimization of tapered circular thin-walled tubes with axisymmetric indentations for maximum crush force efficiency (CFE), which is the ratio of the mean crushing force to the peak crushing force (PCF)

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and maximum SEA. Sun et al. [18] first used the particle swarm optimization (PSO) in honeycomb crashworthiness design based on a two-stage multi-fidelity method for surrogate models. The multi-objective particle swarm optimization (MOPSO) algorithm was also adopted by Sun et al. [19] to seek optimal crashworthiness designs for the functionally graded foam (FGF) structures. Multicriteria design is formulated as both the constrained single objective and multiobjective optimization problems for thin-walled aluminum structures, where cross sectional sizes of single, double, triple and quadruple-cell columns are taken [20]. Yin et al. [21] analyzed foam-filled multi-cell thin-walled structure (FMTS) to achieve the most excellent crashworthiness characteristics. A robust design methodology was performed to investigate the effects of parametric uncertainties of foam-filled thin-walled structures on the design optimization [22]. Their approach is well-suited to overcome the less-meaningful or even unacceptable results of conventional deterministic optimization approaches when considering the perturbations of design variables and noises of system parameters. Yin et al. [23] investigated the energy absorption characteristics of honeycomb-filled single and bi-tubular polygonal tubes (HSBPT). They adopted multiobjective optimization algorithm to achieve maximum SEA capacity and minimum PCF. Energy absorption properties of metal square honeycombs and the size optimization were performed by Li et al. [24]. The preprocessing software Patran was used to build FE models, and the explicit solver LSDYNA was employed to perform the crashworthiness analyses.

The preconception to increase the plastic deformation zones of the thin-walled columns through the buckling of different honeycomb sandwich lattices is based on the fact that more tube walls will be included to fold locally. This interaction strengthening effect between honeycomb core and tubes is used to improve the crush resistant force and increase the energy absorption. The use of lightweight materials as honeycomb cores affects the bending mode of thin-walled hollow cylinder, shortens bending lengths and increases number of lobes. Furthermore, the interaction effects due to the multi-axial compression of the filling cores increase the energy absorption of the filling thin-walled columns. However, in the compressed foam-filled tubes, a considerable amount of material does not participate in the plastic deformation which in turn reduces the energy absorption efficiency of the column [25,26].

Therefore, in this paper, the crashworthiness of some types of honeycomb sandwich bi-tubal circular columns under axial crushing loads is investigated. The present study aims at maximizing the SEA and minimizing the PCF for thin-walled aluminum sandwich cylindrical structures by comparing the performance of different honeycomb cores shaped as square, triangle, Kagome and diamond in an explicit finite element framework. Both the single objective and multiobjective optimizations are performed for columns under axial crushing load with design variables inner, outer and core thickness. Models are optimized by multiobjective particle swarm optimization algorithm to achieve maximum specific energy absorption capacity and minimum peak crushing force. Furthermore, a local and global sensitivity analysis is performed to assess the effect of design variable values on the SEA and PCF functions in design domain.

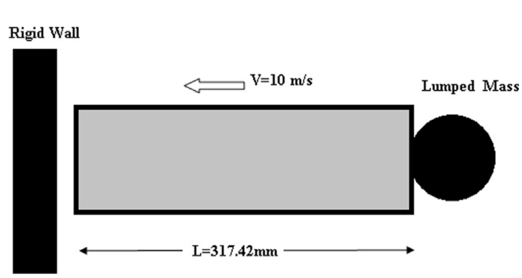

Fig. 1. The impact model with lumped Mass.

2. Theory

2.1. Crashworthiness

The study on the crashworthiness of thin-walled structures and optimization of their performance is usually started from the definition of the crashworthiness indicator. The force displacement curves of a typical thin-walled structure, as demonstrated in Fig. 1, can measure the impact characteristics to a certain extent. The absorbed energy E is equivalent to the mechanical work done by the impact force $F(x)$ during the crush distance d and therefore, is calculated as

$$E(d) = \int_0^d F(x)\,dx \tag{1}$$

The average force magnitude F_{avg} for a given deformation can be calculated as

$$F_{avg} = E(d)/d \tag{2}$$

To define specifically the energy absorption capabilities of different materials and weights, the specific energy absorbed per unit mass M is defined by

$$SEA = \frac{E}{M} \tag{3}$$

Obviously, a higher SEA value indicates a higher energy absorption capability.

As it is basically very difficult to measure the crashworthiness in terms of a unique physical quantity or mathematical formula, the crashworthiness optimization is consequently served to seek a best possible design of structure for a desirable crashing performance. Before to proceed to the main part of the article, some preliminary material are briefly discussed in the next sections to establish the required background.

2.2. Multiobjective optimization

Multiobjective optimization, which is also known as multicriteria optimization or vector optimization, is generally defined as finding a vector of design parameters satisfying constraints to give satisfactory values to all objective functions. In such problems, there are a number of objective or cost functions (a vector of objectives) to be optimized (minimized or maximized) simultaneously. These objectives may conflict with each other so that improving one of them will deteriorate another. As a result, no single optimal solution can be found as the best with respect to all of the objective functions. In such case, a set of optimal solutions, known as Pareto optimal solutions or Pareto front is to be found for multiobjective optimization problems. These optimal solutions are non-dominated to each other and could not lead to the improvement of all objectives simultaneously but are superior to the rest of solutions in the search space. In general, multiobjective optimization can be mathematically expressed as

$$\begin{cases} \text{Min . } \boldsymbol{F}(\boldsymbol{x}) = [f_1(\boldsymbol{x}), \ldots, f_2(\boldsymbol{x})]^T \\ \text{s.t. } \boldsymbol{x}_L \le \boldsymbol{x} \le \boldsymbol{x}_U \\ h_v(\boldsymbol{x}) = 0,\ v = 1, \ldots, p \\ g_u(\boldsymbol{x}) \ge 0, u = 1, \ldots, q \end{cases} \tag{4}$$

where $\boldsymbol{x}$ denotes the vector of design variables, n is the number of objective functions, $f_n(x)$ is the nth objective function, $\boldsymbol{x}_L$ and $\boldsymbol{x}_U$ denote the lower bounds and the upper bounds of design variables, respectively, p and q are the numbers of equality constraints h_v and inequality constraints g_u, respectively.