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Investigation on structure optimization of crashworthiness of fiber reinforced polymers materials

Shuyong Duan, Yourui Tao, Xu Han *, Xujing Yang, Shujuan Hou, Zhangping Hu

State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, China

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ABSTRACT

Composite materials, in most cases fiber reinforced polymers, are nowadays used in the aerospace and transportation, in which high specific energy absorption (*SEA*) and strength are critical issues. Aimed at the improvement of *SEA* and the peak impact load (*P*), the structure optimization of composite tape sinusoidal specimen and corresponding experiments are investigated in this paper. Firstly, the finite element model of composite tape sinusoidal specimen is constructed and is validated by experiments. Then, both the single-objective and multi-objective optimizations are performed for composite tape sinusoidal specimen under axial impact loading. At last, the optimal results are validated by experiments. The optimal results show that the *SAE* increases 67.8% (from 51.3666 kJ/kg to 88.887 kJ/kg) and the *P* decreases 42.9% (from 34.9936 kN to 20.178 kN). This work lays a foundation for structural design of crashworthiness using fiber reinforced polymers materials.

1. Introduction

In the last decade, lightweight energy-absorption structures in automotive vehicles and airframes are increasingly used to meet the crashworthiness requirements with a minimum weight increase [1]. Generally, the lightweight design can be addressed from three aspects of applications of novel materials, structural optimization and advanced processing technology. So the most recent advices suggest to use composite materials in designing high performances energy absorption structures because of their advantages of lightweight, high strength/weight and stiffness/weight, good corrosion resistant and anti-fatigue performance, good vibration attenuation effect, thermostable performance, good damage-safety, design flexibility and easy manufacturing [2]. Indeed, structures made of reinforced fiber composite materials show excellent potentials as energy absorbing systems. In contrast to metallic structures such as steels and aluminium alloys, which absorb energy through plastic deformations, the energy absorption capabilities of composites results from brittle micro-fractures [3,4].

Now a lot of research regarding the composite material structure design has been doing, e.g. as one class of typical composites, carbon fiber reinforced plastic (CFRP), gains increasing popularity in numerous advanced applications for crashworthiness over the last decade [5–7]. In this respect Mamalis et al. [8] conducted a systematical experimental study on crashworthiness for thin-walled CFRP tubes, and found the strong effects of layout and strain rate of fiber reinforcing layers, fiber volume content and thickness of tube wall. Feraboli [9,10] discussed crush energy absorption of composite channel section specimens and LS-DYNA MAT54 modeling of the axial crushing of a composite tape sinusoidal specimen. More recently, Obradovic et al. [11] explored energy absorption characteristics of different CFRP structures using experimental and numerical approaches and confirmed the major role played as per failure criteria. Some other people's research effort has been also devoted to impact energy absorption of the "conventional" tubes with circular, square, channel section or cross-section tapered [12–14].

Nevertheless, experimental tests are both expensive and time consuming, in order to reduce cost and lead-time absorption composite devices, the use of detailed finite element analyses (FEA) looks very attractive. In particular, typical features of the problem such as the changes in boundary conditions caused by the contacts between different parts during crashes, the non-linear behavior of materials, the side effects (related to high deformation rate and meaningful deformations) and complex failure mechanisms of composite material require the use of explicit non-linear finite element codes. Several works has been carried out in this within showing how detailed FEA can be proficiently used to analysis composite absorbers and, eventually, be used as design tool. Specific and reliable damage laws [15–17] able to investigate the collapse and the damage modalities of composite materials have been proposed and validated.

As a matter of fact, the use of non-linear FEA to directly evaluate the objective and the constraint values during an optimization run would be unaffordable from a computational point of view. To

* Corresponding author.
E-mail address: hanxu@hnu.edu.cn (X. Han).

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overcome these difficulties, the optimization method is here based on a global approximation strategy, where the crash capabilities of the specimen are approximated by a system of response surfaces (RS) model built by means of minimum number of non-linear FEA. The RS are finally coupled with NSGA-II to carry out both constrained single- and multi-objective optimizations.

This paper aims to explore the influences of the thickness and radius on crashworthiness of composite tape sinusoidal specimen, in which *SEA* and *P* will be considered as criteria in the single-objective and multi-objective optimization method. The paper aims at maximizing the *SAE* and minimizing the *P* for composite tape sinusoidal specimen taken into account in an explicit finite element (FE) framework. A quadratic RS is constructed to precisely establish the relationship between the objective functions of the *SEA* as well as *P* and the geometrical design variables of the sectional configurations considered. In this paper, multicriteria design is formulated as both the constrained single-objective and multiple-objective optimization problems. The comparative studies will show how a compromise can be made for an optimal design.

2. Design methodology

2.1. Definition of crashworthiness optimization problem

The structural impact problem is one class of geometry and material nonlinear problems. Crashworthiness defined as the resistance of a vehicle to protect its occupants from serious injury or death in accidents [18]. Therefore, it counts as an essential parameter for vehicles and aircrafts design and due to its importance, it has been a topic of researches for engineers and scientists for years [19]. In abroad range of automotive and aerospace applications collapsible impact energy absorbers as structure elements made of fiber reinforced composite materials are used [20,21]. The crashworthiness capacity can be evaluated from the following several levels:

- Initial crush load can be got directly from the force–displacement response.
- Average crush load can be obtained by averaging the crush load values over the crush displacements through the post-crush region.
- Maximum load commonly defines as peak crushing force, *P*
- The post-crush displacement, δ, which is total displacement of crushed specimen, can also be obtained in the force–displacement curve.
- Absorbed crash energy E_{total} which is referred to the area under the force–displacement curve [22].

$$E_{total} = \int_{v} A(\varepsilon) dV \tag{1}$$

where $A(\varepsilon)$ represents the total strain energy density of the structure concerned.

- Specific absorbed energy (*SAE*) is defined as the absorbed crash energy per unit of the crushed specimen mass [22].

$$SEA(x) = \frac{E_{total}}{m} \tag{2}$$

where *m* is the total mass of the crushed specimen mass.

On the one hand, the *P* is sometimes considered one of the critical design objectives to prevent the occupants' body from severe biomechanical injury [23,24]. On the other hand, the crushing force is time-dependent, whose peak may occur at different time steps in different designs. This makes the exploitation of traditional FE-driven sensitivity analysis techniques very challenging. Nevertheless, in a FE-based RS model framework, the true *P* can be approximated in terms of various basis functions and their combinations, numerically. To account for these two different design criteria, the optimization problem can be formulated in the following forms:

(1) The single-objective optimization design with a major concern in the energy absorption capacity of structure as:

$$\begin{cases} \text{Max} & F(x) = SEA(x) \\ \text{S.t.} & X_a^L \leqslant x_1 \leqslant X_a^U \\ & X_a^L \leqslant x_2 \leqslant X_a^U \end{cases} \tag{3}$$

and in the *P* as

$$\begin{cases} \text{Min} & F(x) = P(x) \\ \text{S.t.} & X_a^L \leqslant x_1 \leqslant X_a^U \\ & X_a^L \leqslant x_2 \leqslant X_a^U \end{cases} \tag{4}$$

respectively, where X_a^L, X_b^L, X_a^U, X_b^U are given as the constraints of *P* and *SEA*, respectively. $X_a^L = (x_{a1}^L, x_{a2}^L, \ldots, x_{ak}^L)$, $X_b^L = (x_{b1}^L, x_{b2}^L, \ldots, x_{bk}^L)$ and, $X_a^U = (x_{a1}^U, x_{a2}^U, \ldots, x_{ak}^U)$, $X_b^U = (x_{b1}^U, x_{b2}^U, \ldots, x_{bk}^U)$ and for the lower and upper bounds of these *k* design variables, respectively.

(2) Definition of multi-objective optimization.

In many realistic problems, several goals must be simultaneously satisfied to obtain an optimal solution. However, sometimes these multiple objectives, which must be simultaneously satisfied, conflict. The multi-objective optimization method is the common approach to solve this type of problem. multi-objective optimization, in general, can be mathematically formulated as follows [18]:

$$\begin{cases} \text{Min} & \varphi_r(x), & r = 1, \ldots, l \\ \text{Max} & \phi_s(x), & s = l+1, \ldots, k \\ \text{S.t.} & g_u(x) \leqslant 0, u & = 1, \ldots, U \\ & h_v(x) = 0, & x = 1, \ldots, V \\ & X^L \leqslant x \leqslant X^U, & x \in R^n \end{cases} \tag{5}$$

where *l* and $(k - l)$ are the numbers of minimization $\varphi_r(x)$ and maximization $\phi_s(x)$ of objective functions, respectively. Vector $x = (x_1, x_2, \ldots, x_n)$ denotes these *n* design variables, $X^L = (x_1^L, x_2^L, \ldots, x_n^L)$ and $X^U = (x_1^U, x_2^U, \ldots, x_n^U)$ are their lower and upper bounds. $g_u \leqslant 0$ and $h_v(x) = 0$ stand for *U* inequality and *V* equality constraints respectively.

In this paper NSGA-II is used as a kind of multi-objective optimization method. And the Pareto-sets can be obtained. Although the Pareto-set can provide designer with a large number of design solutions for their decision-make in the beginning of design stage, decision must be made for the most satisfactory solution (termed as "knee point") from Pareto-set finally. Conventionally, the most satisfactory solution is often decided by the weight method which aggregates many objectives into a single cost function in terms of weighted average to emphasize their relative importance. However, it can be difficult to assign proper weight to each objective. In this paper, we present the normalization to determine Knee Point improves the accuracy of Minimum Distance, mathematically given as below, which allows us determining a most satisfactory solution from Pareto-set,

$$\min D = \sqrt{\left(\sum_{\tau=1}^{n} \left(\frac{f_{c\tau}}{\min(f_\tau(x))} - 1 \right)^2 \right)} \tag{6}$$

where *n* is the number of the objective components, $f_{c\tau}$ is the τth objective value in the *c*th Pareto solution, *D* is the distance from knee point to an "utopia point" For details about the NSGA-II approach, refer to Ref. [25].