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Crashing analysis and multiobjective optimization for thin-walled structures with functionally graded thickness

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ABSTRACT

Thin-walled structures have exhibited significant advantages in light weight and energy absorption and been widely applied in automotive, aerospace, transportation and defense industries. Unlike existing thin-walled structures with uniform thickness, this paper introduces functionally graded structures with changing wall thickness along the longitudinal direction in a certain gradient (namely, functionally graded thickness – FGT). Its crashing behaviors are the key topics of the present study. We examine the crashing characteristics of functionally graded thin-walled structures and evaluate the effect of different thickness gradient patterns on crashing behaviors. It is shown that the gradient exponent parameter n that controls the variation of thickness has significant effect on crashworthiness. To optimize crashworthiness of the FGT tubes, the Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to seek for an optimal gradient, where a surrogate modeling method, specifically response surface method (RSM), is adopted to formulate the specific energy absorption (SEA) and peak crashing force functions. The results yielded from the optimization indicate that the FGT tube is superior to its uniform thickness counterparts in overall crashing behaviors. Therefore, FGT thin-walled structures are recommended as a potential absorber of crashing energy.

1. Introduction

Over the past years, research interests in crashworthiness have resulted in a series of systematic investigations into crash responses of various thin-walled structures via analytical, experimental and numerical approaches [1–8]. Two significant aspects, namely weight and crashworthiness, have drawn primary attention in these studies. As an effective structure, thin-walled components have showed significant advantages over other solid elements and are capable of carrying substantial loads with desired deformation, which could be appreciably higher than the corresponding ultimate or bulking loads [9,10]. In reality, thin-walled structural members play a critical role on enhancing the capability of energy absorption in impact engineering.

The automobile body in white (BIW) is mainly composed of thin-walled structural parts, which are made by stamping or forming process of traditional metal sheets with uniform thickness [11–19]. It is of great interests in investigating the crashworthiness of thin-walled structures for improving the vehicle safety and light weight. In this regard, Zhang et al. [12] evaluated the energy absorption characteristics of regular polygonal and rhombic columns under quasi-static axial compression. Song et al. [13] introduced origami patterns into thin-walled structures and minimized the initial peak force and subsequent fluctuations. Tang et al. [20] presented a cylindrical multi-cell column to improve energy absorption. Najafi and Rais-Rohani [21] proposed a sequentially coupled nonlinear finite element analysis (FEA) technique to investigate the effects of sheet-forming process and design parameters on energy absorption of thin-walled tubes made of magnesium alloy. Acar et al. [22] studied the crashing performances of tapered tubes using multiobjective optimization. Although such thin-walled structures have been extensively used as energy absorbers for their high energy absorption capacity, light weight and low cost [23], all these thin walled structures were based upon the uniform material and/or the same wall thickness. The inherent shortcoming resides on that such structures may not exert their maximum capacities in crashworthiness, and furthermore, a uniform wall thickness does not necessarily make best use of material for meeting the requirements of vehicular light weight [24–26]. So there is an urgent need to develop new structural configuration with different material and/or thickness combinations for maximizing crashworthiness and material usage.

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According to Yang et al. [27], a metal sheet with varying thickness could be a more desirable structure because it not only uses material more efficiently, but also increases design flexibility considerably. It has been demonstrated that with an optimal choice of different materials grades (e.g. via tailored welded blanks (TWB), or hybrid blanks) and/or thicknesses (e.g. via tailor rolling blanks), crashing performance of the combined components can be improved to a higher extent. Indeed, design of specific thin-walled components with desired materials/thicknesses in a more efficient manner could represent new potential for further reducing weight and enhancing performance of the products. Of these components with variable material/thickness, the TWB structures, which consists of laser-welded sheet metals of different thicknesses and materials, provide a flexible combination of component materials and thicknesses, which has been adopted in vehicular floor component [28], B-pillar [29], front-end structure [30], and door inner panels etc. [31,32]. The main shortcoming of those blanks lies in that it consists of discrete thickness sections and may lead to stress concentration in the interfaces. To overcome such defects of TWB, a relatively new rolling process, named tailor rolled blank (TRB), has been developed. In the newly developed TRB process, the rolling gap can be varied, which leads to a continuous thickness variation in the workpiece. Applications of such a rolling process allow reducing more weight compared with traditional stamping or forming processes. As such, varying sheet thickness can better meet more and more demanding design requirements, thereby enhancing utilization of material and/or thickness comparing with traditional stamping uniform sheets.

There have been some reports on TRB in sheet metal forming. For example, Zhang et al. [33] investigated the effects of transition zone length, blank thickness variation, friction coefficient and die clearance on the springback of TRB component. Meyer et al. [34] used TRB to increase the maximum drawing depth compared to the blanks with constant thickness. Urban et al. developed a design tool by combining numerical simulation and optimization algorithm to improve the formability of TRB [35]. To the author's best knowledge, however, very limited studies on crashworthiness design of thin-walled TRB structures have been performed to date.

To make use of TRB thin-walled structures with functionally graded thicknesses (FGT) for impact engineering, it is essential to understand the energy absorption characteristics in comparison with those well-studied uniform thickness (UT) thin-walled structures. More importantly, it is of particular importance to seeking the best possible thickness gradient for crashing performance with different measures. Thus the objective of this paper resides in quantifying and improving crashing behaviors of thin-walled structures with functionally graded wall thickness. For this reason, two critical issues need to be addressed in this paper: (1) a direct problem that quantifies the crashing characteristic of functionally graded thin-walled structures with variable wall thickness and evaluates the effects of the different thickness pattern on both specific energy absorption (SEA) and peak impact forces; (2) an inverse problem that seeks optimal gradient for maximizing the specific absorption energy (SAE) and minimizing peak crashing force (F_{max}).

As for the functionally graded thickness structure, the thickness of thin-walled varies throughout the depth in an ascending or descending gradient. It is expected that the gradient exponential parameter (n) has a significant effect on crashworthiness. To represent such complex crashworthiness objective functions with respect to gradient parameter, which has not been explored in literature before, a surrogate model technique, namely specifically response surface method (RSM), will be attempted here. To maximize the energy absorption and minimize the peak crashing force, the multiobjective optimizations for the FGT structures are formulated and the Non-dominated Sorting Genetic Algorithm (NSGA-II) is applied for its proven effectiveness in crashworthiness design [36,37].

2. High-strength steel column structures with functionally graded wall thickness

2.1. Geometrical description and material properties

Dynamic axial crushing simulation was performed in the square tubes which were made of high-strength steel grade DP800 [38]. The dynamic procedure was conducted at velocities of 5 m/s, 10 m/s and 15 m/s, respectively, with an impacting mass of 600 kg in order to assess the crash behaviors measured in the impact force and energy absorption. Fig. 1 illustrates the geometry of thin-walled square structure in the dynamic tests. These specimens have a nominal square core cross-section with rounded corners and the average dimensions of 60 mm × 60 mm. The strain-rate dependent properties of DP800 are considered herein and the true-stress versus true-plastic strain curves at different strain rates (0.000903/s, 1.029/s, 278/s and 444/s, respectively) are plotted in Fig. 2. To characterize the material behavior, an empirical constitutive equation for the effective yield stress as a function $\bar{\sigma}$ of the effective plastic strain is fit to the following formulae [39]:

$$\bar{\sigma}(\bar{\varepsilon}) = \left(\sigma_0 + \sum_{i=1}^{2} Q_i(1-\exp(-C_i\bar{\varepsilon}))\right)\left(1+\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0}\right)^q \tag{1}$$

where σ_0 is the initial yield stress, and Q_i and C_i denote strain hardening coefficients, q represents a material constant and $\dot{\varepsilon}_0$ is a user-defined reference strain rate. The relevant material properties are summarized in Table 1. It is assumed that the material properties remain the same regardless of variation in sheet thickness.

2.2. Structural crashworthiness criteria

The design optimization aims to generate a controllable crashing pattern for maximizing energy absorption and minimizing the peak forces during collapse [7]. There are several key indicators to evaluate crashworthiness of a structure, e.g. energy absorption (*EA*), specific energy absorption (*SEA*), average crash force (F_{avg}), and crash force efficiency (*CFE*), as given in Eqs. (2)–(5) respectively (Fig. 3), are widely used in the measurement.

As a key indicator, the energy absorption (*EA*) of a structure measures the capacity of absorbing impact energy, which can be determined mathematically as,

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

where $F(\delta)$ is the instantaneous crashing force with a function of the displacement δ.

The specific energy absorption (SEA) assesses the absorbed energy per unit mass of a structure as,

$$SEA = \frac{EA}{m} \tag{3}$$

where m is the total mass of the structure. In this case, a higher value indicates a higher energy absorption efficiency of material.

The average crashing force F_{avg} for a given deformation also indicates the capacity of energy-absorption of a structure, which is calculated as *EA* divided by the compressive displacement δ as [35],