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Crashworthiness optimization of automotive parts with tailor rolled blank

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ABSTRACT

Tailor rolled blank (TRB) as an advanced manufacturing process developed recently has broad application prospects in automotive and aerospace industries for its significant advantages in better load-carrying ability and lighter mass. TRB is a typical custom product, whose performance is closely related to its thickness variation, thus how to obtain the optimal thickness variation of a TRB part becomes a challenging task, especially for crashworthiness design. To address this issue, an optimization method based on the variation of wall thickness is presented to maximize the energy absorption capacity of TRB parts. Firstly, finite element (FE) models of two typical automotive parts, TRB top-hat column and TRB bumper beam, are established and validated through crushing experiments. Then a heuristic optimization method is proposed based on the general assumption that more mass enables to absorb more energy. The elemental energy density is used to optimize structural thickness distribution of geometrical and material nonlinear structures. Numerical results demonstrate the capability and effectiveness of the proposed optimization method for achieving the best thickness layout of automotive TRB parts for crashworthiness.

1. Introduction

Since thin walled structures have the advantages of light weight, low price, high strength and stiffness, high reliability, excellent loading-carrying efficiency and energy absorption capacity, they have been widely used as energy absorbers in crashworthiness applications such as automobile, train and aeronautical industries to protect passenger from severe injuries or fatalities [1]. To better understand the energy absorption mechanism and improve the design quality of energy absorbers, exhaustive studies have been conducted by using analytical, experimental and numerical approaches for thin-walled structures with various sections [2–5], different cell numbers [6–10], different tapered angles [11,12] under single/multiple loading cases [13,14]. Generally speaking, all crashworthiness structures are expected to absorb maximum kinetic energy with minimum mass. In order to achieve this goal, the optimization technique is the best choice. In this regard, Bi et al. [15] adopted the response surface methodology to optimize the crashworthiness of foam-filled thin-walled structures. Liu [16] optimized the crashworthiness of straight and curved octagonal section columns. In which, maximizing the specific energy absorption (*SEA*) is set as the optimization objective and the side length of cross-sections and wall thickness are selected as design variables, and maximum crushing force is set as the design constraint. Zhang et al. [17] improved the bending resistance and crashworthiness of the beam through optimizing the shape of the arc-like rib. All these thin walled structures mentioned above are based on the uniform material and/or the uniform wall thickness. In fact, energy absorbers often experience very complex loading, which implies that different regions of the structures should have different roles to maximize usage of materials [18]. On the other hand, since the design optimization methodologies are widely adopted, the capacity of such conventional materials and structures could have been pushed to its limits unless some new manufacturing process or configurations can be introduced.

Under such circumstances, some advanced manufacturing processes, e.g. tailor welded blank (TWB) and tailor rolled blank (TRB), have been developed and widely applied in automotive industry. Compared with TWB, TRB varies the blank thickness continuously through adjusting the roll gap (see Fig. 1), which leads to better formability and greater weight reduction [19]. The advantages of TRB are as follows [20]: (1) production cost of TRB does not depend on the number of thickness transitions; (2) any thickness transition can be chosen within the process limits; (3) there are no stress peaks across the transition due to the smooth thickness variation; (4) TRBs compared with TWBs have better forming characteristics because of the elimination of welding seams and corresponding heat-affected zones in TWBs. Due to the advantages of TRB, some studies have been conducted

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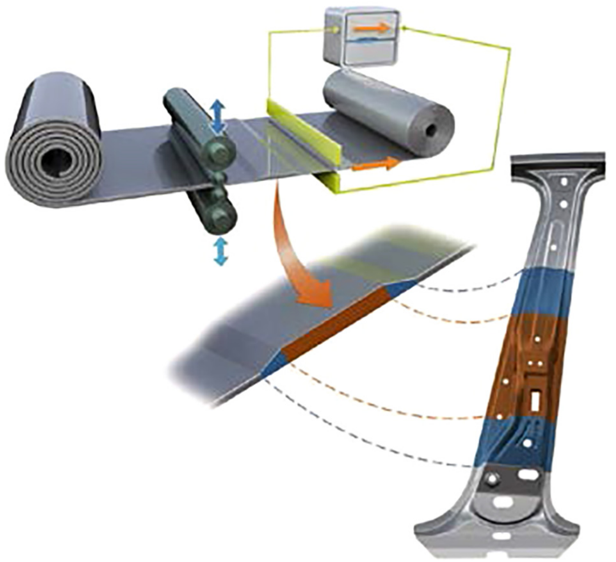

Fig. 1. The schematic of rolling process for TRB [20].

[21–24]. For example, Yang et al. [25] pointed out that the sheet with varying thickness could be more promising structure in the area of crashworthiness. Sun et al. [1] developed TRB thin-walled tubes with varying wall thickness along the longitudinal direction in certain gradient, which showed that the TRB tube is superior to its uniform thickness counterparts in overall crashing behaviors. Besides of variable thickness in axial direction, Zhang et al. [26] introduced variable thickness in cross-section of square tubes, which can increase up to 30–35% energy absorption than the traditional uniform thickness square tube under axial loading. Lately, Sun et al. [27] first investigated the crashworthiness of TRB tubes under dynamic bending load. The aforementioned investigations have shown that the TRB structures have excellent crashworthiness characteristics.

The performance of TRB parts are closely related to the thickness variation, thus it is critical to obtain the optimal thickness distribution under crashworthiness [23,28,29]. As an effective alternative as the design of conventional thin-walled structures, the engineering optimization methodology is inevitably used to design the TRB parts. In this regard, Chuang et al. [30] adopted a multidisciplinary design optimization methodology to obtain the optimal thickness profiles of underbody parts. Duan et al. [18] combined the support vector machine (SVR) surrogate models with artificial bee colony algorithm to obtain the optimal thickness distribution of front longitudinal beam inner. Although the optimization methodology promotes the development of TRB design to some extent, the design optimization mentioned above mainly focused on few parameters used to adjust the thickness variation, which greatly limited the performance of TRB parts. In other words, the material utilization is not exhaustively exploited, thus there is an urgent need to develop a novel design method to fine adjust thickness variation of TRB structures.

Topology optimization, as an efficient design approach of structures, can handle nonlinear large-scale combinatorial optimization models with multi-decision-making variables. In order to improve the performance of thin-walled structures, the design obtained from topology optimization can be further modified by the parameter optimization. In fact, much research has been done to improve the crashworthiness of thin-walled structures by topology optimization [31–34]. Fox example, Huang et al. [35] investigated topology optimization for the crashworthiness of continuum structures using the bi-directional evolutionary structural optimization (BESO) approach. Ortmann and Schumacher [36] developed a graph and heuristic based topology optimization technique for designing the cross-section profile of crashing structures. The modified hybrid cellular automaton (HCA) methods were also used for topology optimization of crashworthy structures [37–39]. Sun et al. [40–42] proposed the structural topology optimization method based on intelligent algorithm for the crashworthiness design of multi-cell tubes. This paper aims to establish an optimization approach for large deformation of energy-absorbing TRB structures where only allow to change the thickness of structures.

It is well known that B-pillar and bumper beam are the most significant deformable parts under vehicle side and frontal impact, respectively. Their crashworthiness and deformation modes can greatly influence the vehicle safety. In addition, the B-pillar and bumper beam are mainly subjected to some local lateral loads, which lead to that the material utilization of different regions has significant difference. Thus this kind of parts should be very suitable to be designed with TRB. To the authors' best knowledge, there have been very limited reports available on the crashworthiness design of B-pillar and bumper beam with TRB. Therefore, the paper aims to present a novel optimization method to design the simplified B-pillar (top-hat column) and bumper beam with TRB under the bending collapse loading conditions. Following this introduction, an optimization model for energy absorption is first developed in Section 2. Based on the proposed optimization method, the two TRB automotive parts are analyzed and discussed in Section 3. Finally, some conclusions are drawn in Section 4.

2. Design problem and optimization method

2.1. Design problem statement

The design is to improve the structural crashworthiness and energy absorption characteristics through gradually optimizing the thickness distribution in the design domain. When designing the energy absorption structures, certain constraints should be considered, such as force limitation and deformation limitation. Typically, a maximum allowable crushing distance is required to retain sufficient space for survival in automotive collision. To simulate the crush behavior of a structure, nonlinear finite element analysis is conducted by gradually increasing the displacements of impact points from 0 to the maximum allowable crushing distance U^* as shown in Fig. 2.

To obtain such an efficient energy absorption design that dissipates as much energy as possible during a maximum allowable crushing distance, the natural choice of the optimization objective is to maximize the total external work shown as the area enclosed by the curve in Fig. 2, which is equal to the total internal energy under quasi static conditions. Considering the mass constraint and displacement constraint, the optimization problem can be formulated using the elements thickness as the design variables,

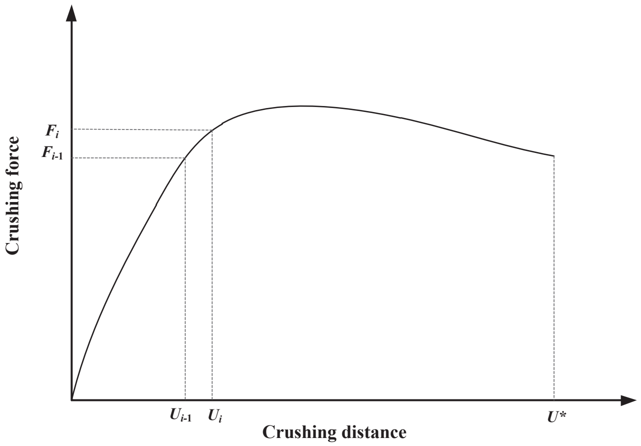

Fig. 2. Schematic diagram for the force-displacement relationship by gradually increasing the crushing distance.