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Sensitivity analysis and reliability based design optimization for high-strength steel tailor welded thin-walled structures under crashworthiness

Xueguan Song [a], Guangyong Sun [b,*], Qing Li [b]

[a] School of Mechanical Engineering, Dalian University of Technology, 116024, PR China
[b] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006, Australia

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ABSTRACT

Tailor welded blanks (TWB) have been widely applied in automobile industry. This paper firstly conducts experimental tests to investigate the crashworthiness of three different types of TWB hat-shaped structures. Their combinations provide three representative TWB configurations: namely the same material grade with different wall thicknesses; different grades with the same thickness, different material grades with different thicknesses, respectively. Secondly, the finite element (FE) models corresponding to each of the samples are established to perform crashworthiness analysis. It is exhibited that the FE simulations are in good agreement with the experimental tests. Thirdly, the surrogate models are constructed to approximate the crashworthiness responses of these TWB structures. Fourthly, a sensitivity analysis is conducted to explore the effects of the weld line location, wall thickness and material properties for each segment of TWB structures subject to crashing load. The results showed that the wall thickness is most sensitive to the crashworthiness of TWB structures. Finally, reliability based design optimization is carried out by taking into account the uncertainties in the TWB configuration. The results demonstrate that the optimized TWB tubes are capable to improve energy absorption as well as enhance the reliability, potentially being an ideal structure for crashworthiness.

1. Introduction

Government legislations, environmental concerns, safety regulations, and consumer demanding are all driving the vehicle manufacturers to continuously reduce the fuel consumption and emissions of vehicles. Some investigations showed that reducing the weight of the vehicles is one of the key approaches to improve fuel efficiency, since every 56.69 kg weight reduction would result in a gain of 0.09–0.21 km per liter fuel economy [1,2] and 10% reduction of vehicle weight results in 5–8% increase in fuel efficiency [3]. In general, the body-in-white (BIW) accounts for 40% of the vehicle weight, which is largely composed of thin-walled structural components. Thus, weight reduction of BIW or thin-walled structures offers a promising way to improve the fuel economy of vehicles. On the other hand, reducing the weight must not downgrade performances such as stiffness, crashworthiness, durability as well as noise, vibration, harshness (NVH) etc. Among these performances, the crashworthiness is the most critical. To date, the most typical approach in reducing automobile weight while meeting vehicle performance requirements is by using lighter/stronger materials, such as high strength steels (HSS), to replace conventional steel. In this regard, Kim et al. [4] studied some successful applications of aluminum vehicles produced by Audi and Jaguar, and reported that the technical possibility of reducing the weight by 11–25% through use of aluminum substitutions alone. The Ultralight Steel Auto Body (ULSAB) project achieved a BIW weight reduction of 68 kg (from 271 kg to 203 kg) through the application of HSS [4]. The door beam was replaced with ultra-high strength steel to realize full marks of crash test, with stiffness increase of 2.5 times, strength increase of 3.8 times, more lightweight of 9.32% than that of origin pipe [5].

Although the method of above mentioned material substitution can reduce vehicle weight effectively, the lighter/stronger materials are fairly expensive at present so that it may only be used for high-end luxury automobiles or some key components. Therefore, simple substitution of traditional steel with lighter/stronger materials can't meet the requirement of lightweight development. Besides the material substitution, redesigning the vehicle structures using optimization techniques is another effective method to achieve the lighter weight. In this regard, Christensen et al. [6] proposed to use topology optimization to minimize the BIW mass

* Corresponding author.
E-mail address: sgy800@126.com (G. Sun).

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of a hybrid electric vehicle subjected to multiple crash scenarios including high-speed front impact, offset deformable barrier, side impact, pole impact, high-speed rear impact and low-speed rear impact in addition to a roof crush scenario. Parrish et al. [7] optimized the design of a full-vehicle model. The results showed that the optimal solution maintained or improved its crashworthiness characteristics with up to 50% weight savings. Lee et al. [8] combined size, shape and topology optimization to design continuum structures for least weight and maximum stiffness. Zhu et al. [9] presented to use conservative surrogate models for lightweight design of vehicle structures with crashworthiness criteria. In order to further improve the optimization efficiency, many researchers recommended the surrogate model based design optimization to conduct the structural lightweighting design [10–16]. In summary, optimization techniques enable to promote automotive lightweight.

From the abovementioned description, it is easily found that the conventional lightweight techniques have largely focused on the structures and components with single material and thickness. In fact, a single automobile component often bears very complex loads, implying that different regions would have different local performances. In order to meet the performance requirements, a novel lightweight technology, named tailor welded blanks, has been developed and widely applied in vehicle industry. Tailor welded blanks are semi-finished parts which weld at least two different thicknesses/materials sheets together prior to the forming process [17], which can save materials to a better extent. In other words, one can use thicker or stronger materials in the critical regions and thinner or weaker/lighter materials in less critical regions to reduce the overall weight [18]. Due to greater flexibility and lightweight potential in structural design, researchers have been conducting some investigations into the crashworthiness of TWB structures by using experimental and simulation methods. For example, a series of high-strength steel (HSS) TWB structures with different orientations of weld line were studied through the three-point bending and axial crushing tests to evaluate the effects of different parameters, such as weld line locations and material combinations, on energy absorption characteristics and deformation behaviors by Xu et al. [19,20]. Shi et al. [21] studied the influences of different weld modeling methods on mechanical behaviors of tailor-welded blanks involved in vehicle impact such as failure position, deformation, and energy absorption. Gedikli [22] used numerical analyses to investigate the crashworthiness performances of tailor-welded tubes made of aluminum and high strength steels.

In addition to the finite element analysis and experimental investigations, significant efforts have been devoted to design for TWB structures. For example, Shin et al. [23] combined topology, size and shape optimization to design the inner panel of a door made by TWB. A multidisciplinary optimization of an automotive front door with the TWB structure for stiffness, natural frequency and side impact crashworthiness criteria was conducted by Song and Park [24]. Pan et al. [25] optimized a B-pillar with a TWB structure subjected to roof crush and side impact. Xu et al. [26] proposed a comprehensive study on the redesign of the multiple component TWB structures consisting of the inner door panel and B-pillar of a passenger car.

Nevertheless, these abovementioned studies on TWB structures have largely restricted on deterministic optimization, in which all design variables and parameters involved are assumed to be certain. However, real-life lightweight problems usually involve some degree of uncertainties in operational conditions, material properties, geometries, manufacturing precision, etc. [27,28]. It has to be pointed out that in general, a deterministic optimization tends to push a design toward one or more constraints until these constraints become active, thereby leaving very little or no room for tolerances in modeling and/or manufacturing imperfections [29–31]. For this reason, nondeterministic problems in reality solved by deterministic optimization algorithms could lead to unreliable design. To address the issue, reliability-based design optimization (RBDO) has been proposed. Recently, many researchers have successfully applied it for crashworthiness design in automotive engineering. For example, Zhu et al. [32] presented RBDO for the lightweight of automotive structure to maximum the crashworthiness performance. Youn and Choi [33] presented an effective reliability-based design optimization methodology integrating the hybrid mean value (HMV) method with response surface (RSM) for crashworthiness of vehicle side impact. Another two investigations on the reliability-based design for vehicle crashworthiness of side impact was conducted by Du and Chen [34] and Sinha [35]. Li et al. [36] developed a reliability-based multiobjective optimization algorithm by using a new interval strategy to model uncertain parameters for crashworthiness design of vehicle frontal structures. To the author's best knowledge, there are few researches on the reliability-based design optimization for crashworthiness of high strength steel TWB structures.

This study aims to investigate the crashworthiness behaviors of high strength steel TWB structures by using experimental and numerical techniques and then to conduct reliability based design optimization (RBDO). Firstly, a series of experiments of different TWB configurations are performed to understand the crashing behaviors and validate the FE models. Secondly, a parametric study is carried out with reference to the possible design variables, such as the wall thickness, the location of weld line, material properties and the impacting angle. The validated FE model is then used to construct surrogate model for a global sensitivity analysis (GSA), thereby quantifying the relative effect of each variable. Finally, a reliability-based design optimization is formulated by involving both variances of design variables and parameters.

2. Experimental test and finite element modeling

2.1. Geometry and materials

The shape and dimensions of the specimen were determined in reference of actual automotive front rail. Fig. 1 shows the dimensions of the hat-shaped specimen used in this study, which has been taken as an example to demonstrate the discrete robust optimization progress previously [37]. The cross-section is a simple hat shape with weld flanges for joining the specimen to a flat bottom plate. The corner radii at the top edges and near the weld flanges were R=4 mm. The flange width of the hat-shape sections was kept as a constant of 30 mm. The specimen is tailor-welded together by two segments with different material/thickness (Fig. 1 (a) and (b)). The length of each segment is L=200 mm. In other words, the weld line is located in the middle of the specimen. The hat-shaped part and the flat plate were joined together by spotwelds at intervals of 20 mm (Fig. 1(b)).

In order to investigate the effect of the different tailor-welded combination on the crashworthiness, three representative TWB configurations: Case 1: the same material grade (DP590) with different wall thicknesses (1.0 mm, 1.5 mm); Case 2: different material grades (DP590, DP780) with the same wall thickness (1.5 mm); Case 3: different material grades (DP590, DP780) with different wall thicknesses (1.0 mm, 1.5 mm), were used to perform crashing tests, respectively. Fig. 2 lists the experimental specimens of these three different combinations, and each case was repeated two times. The back end of specimens are fixed on a sled car (Fig. 3), while the front end of the specimens impacts onto a rigid wall at a pre-set initial velocity of 30 km/h. The crashing force, displacement and acceleration, etc., are recorded using an AD-