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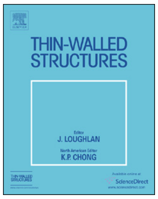

Full length article

Optimization of honeycomb strength assignment for a composite energy-absorbing structure

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ABSTRACT

This study proposes a new composite structure to promote energy absorption capability of railway vehicles by integrating characteristics of a thin-walled steel structure and aluminum honeycomb fillers. Non-linear explicit code LS_DYNA3D(971) was utilized in building detailed finite element models, which were also validated by previous test data. Considering the expensive selling price, complicated fabricating technology and low production rate of high strength honeycomb, honeycombs with appropriate strength should be selected to fill in the steel structure. Therefore, scientific sampling points were chosen from the design space using Box-Behnken design method. Analysis of variance was performed in order to explore the effects of distributed honeycomb strength in four levels on crashworthiness indicators. Response surface methodology (RSM) was well applied to perform both parametric analysis and multiobjective optimization for searching the optimal configurations. Here, two different criterion were conducted in optimization process by adopting desirability approach. It was find that the composite structure with high strength honeycombs in level-1 and level-2 and relatively low strength honeycombs in level-3 and level-4 are preferable for use. Comparing with the empty steel structure, the optimal EA capacity is promoted by 35.32% in criterion 1 and 34.35% in criterion 2, being able to bear the condition with crashing speed of 36 km/h and impacting mass of 55.3 t. It illustrates that the new composite structures can be recommended as excellent crashworthy devices.

1. Introduction

Rail crash accidents always cause severe casualties and property losses. For example, the Alexandria train collision happened on 11 August 2017 in Egypt resulted in 41 deaths and 179 injuries [http://edition.cnn.com/2017/08/11/world/egypt-train-crash/index.html]. As one kind of typical energy absorbers, thin-walled steel structures have been widely used due to their excellent energy absorption capacity and extraordinary light weight [1]. Extensive constructive works have been devoted to the basic mechanical performance, load-carrying capacity, and optimum design [2–4].

For instance, Tai et al. [5] conducted analysis of thin-walled cylinders under axial impact loads with two different materials but equal sectional areas. They confirmed that the energy absorption of high-strength steel thin-walled component is better than the mild steel thin-walled component. Fan et al. [6] performed quasi-static axial compression of thin-walled polygon tubes with four different cross-sectional shapes. Results indicate that the increase in the number of inward corners demonstrates a promising improvement in energy absorption. In terms of lateral crushing, Gupta et al. [7–9] investigated the deformation and energy absorbing behaviors of rectangular and square tubes through experiments and simulations. They figured out that tube sections collapsed due to the formation of two sets of plastic hinges. TrongNhan [10] carried out crushing and theoretical analysis of multi-cell thin-walled triangular tubes under lateral loading. In Ref. [11], he also explored the crushing of multi-cell triangular tubes made of aluminum alloy under multiple impact loadings. Sun et al. [12,13] first presented some novel variable thickness single/multi-cell thin-walled structures and derived a uniform analytical solution for their mean crushing forces. The results show that the theoretical solutions agree well with the experimental results. These novel structures can significantly improve the efficiency of material utilization for structures and reduce the peak force. It should be mentioned that the above investigations mainly concentrated on the crash behaviors of empty

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tubes.

However, the energy absorption capacity of single metal tubes is limited. In order to further increase the EA capacity of thin-walled structures, recent attention has been paid to cellular materials such as foam [14–16], honeycomb [17–19], sawdust [20], etc., filled in thin-walled structures [1]. Further more, optimization method is an efficient tool to search the best mechanical property of the filling material [21]. To consider the uncertainties of design variables and noise factors in crashworthiness optimization of foam-filled bitubal tapered structure, a reliability based design optimization (RBDO) is adopted by Sun and his coauthors [22]. Zarei et al. [23] performed axial and oblique impact crash tests on empty and honeycomb filled aluminum square tubes. Li et al. [24] developed a new alternative square honeycomb to expand the non-hexagonal metal honeycomb applications in the energy absorption fields with the aim of designing low mass and low volume energy absorbers. Jamshid et al. [25] studied the design and optimization of a multi-layer configuration of hexagonal metal honeycomb energy absorber using the genetic algorithm. It aims to maximize the energy absorption capacity and minimize the impact shock level while minimizing the total absorber size. Wang et al. [26] conducted research on matching effect of honeycomb-filled thin-walled square tubes. Results show that the geometric configuration, the matrix material properties of honeycombs as well as the impact velocity have significant influence on matching relationships.

In terms of the energy-absorbing structures applied to railway vehicles, Xie and Zhou [27] assessed the impact characteristics of a thin-walled metal structure with three types of aluminum honeycombs. The results indicated that the larger the plateau stress acting on the honeycomb, the greater the contribution made by the honeycomb to the overall energy dissipation of the structure. Peng et al. [28] proposed a cutting-style energy absorbing device, which consists of an anti-creeper device, energy absorption tube, cutting knife and clamp. In Ref. [29] they also introduced a duplex structure, which is composed of anti-climbing gear, square shells, a diaphragm, rear-end plate, supporting guide bar and energy-absorbing component. Avalle and Chiandussi [30] dealt with the optimization of a tapered tubular steel component to be used as an energy-absorbing device in the front structure of a vehicle body. Xu et al. [31] addressed a gradual energy-absorbing structure made of nested thin-walled square tubes, and optimized the thickness parameters of each part.

Our previous studies in Ref. [32–34] has proposed a new thin-walled steel structure, which is able to dissipate the energy with impacting mass of 55.3 t and crashing speed of 25 km/h. Even though the energy-absorbing structures in published works can satisfy the collision condition listed in BS EN 15227:2008, higher vehicle running speed requires more safe impact velocity. Beside, there are still few research papers that investigate the optimization of honeycomb strength assignment for composite energy-absorbing structures applied to railway vehicles.

In this paper, a new composite structure is investigated to promote the energy dissipation capability for satisfying the collision speed of 36 km/h with other environmental variables unchanged. Detailed finite element models were firstly built in LS-DYNA environment, also separately validated by previous experimental results. In order to find the optimal design of the composite structure, optimization method is then implemented by adopting surrogate models and the desirability approach. Here, honeycomb strength distributed in four sections were defined as design variables, and energy absorption (EA) and load uniformity (LU) were set as objectives. Unlike most of the traditional optimization design, two types of criterion were analyzed, because the desirability approach can offer flexibility in weighting and assign different importance values for each individual response. Optimal designs of the composite structure may be recommended as excellent energy absorbers in practical engineering.

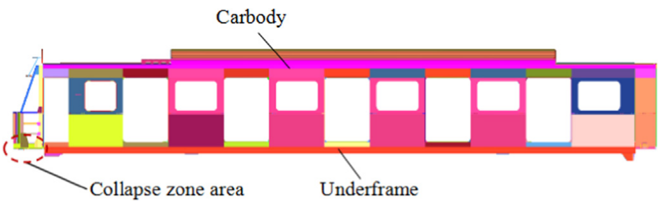

Fig. 1. Schematic for the installation of the composite structure in a certain railway vehicle.

2. Model description

2.1. Thin-walled steel structure

As shown in Fig. 1, the energy-absorbing structure is generally mounted on the front end of the underframe, known as the collapse zone area of a certain crashworthy vehicle. The thin-walled steel structure is almost the same as those in our previous studies on design strategy and structural optimization [32–34]. Functions of the structure are not only absorbing the kinetic energy in crash accidents, but also bearing loads from rear-end parts and related equipment in normal condition. The geometric configuration of the steel structure is presented in Fig. 2 [32], where the steel structure is mainly welded together by side beams, inner beams, middle beams, cross beams and the front beam. Thin-walled tubes and channels are distributed in four levels (Fig. 4). Various sizes of rolled hollow sections and channels are fabricated as energy absorption components. The entire structure is closed and provides a smooth contact surface in collision process. In order to control stable deformation of honeycombs, diaphragms are added to enhance the structural strength, which is different from the previous design. In addition, collapse initiator features are manufactured for all rectangular tubes to decrease the peak force on each level, and a typical one is marked in Fig. 2(b). For more details, readers can refer to [34].

2.2. Honeycomb filler

Honeycomb fillers have recently attracted wide attention due to their excellent energy absorption capacity and lightweight property. Aluminum honeycomb structures made by expansion process are typically manufactured from aluminum alloys by an in-plane expansion process, which results in two of the six cell walls having double thickness [23,35]. Fig. 3 illustrates the parameters of a typical honeycomb core with regular hexagonal cells, where W is the width of the honeycomb core; L is the length of the honeycomb core; H is the thickness of the honeycomb core; w and l are cell wall width and length; h is cell wall thickness and θ is cell wall angle. In this paper, experiments of two types of honeycombs (Honeycombs I and II, respectively) are investigated to view their energy absorption capacity and determine the boundary of honeycomb strength, thus assessing whether it can satisfy the condition with impacting mass of 55.3 t and crashing speed of 36 km/h. Dimensions ($w \times l \times h \times \theta$) of cell units are $1.0\,\text{mm} \times 1.0\,\text{mm} \times 0.06\,\text{mm} \times 30^\circ$ and $2.0\,\text{mm} \times 2.0\,\text{mm} \times 0.06\,\text{mm} \times 30^\circ$. The dimensions of rectangular honeycombs filled in inner beams, side beams and middle beams match the empty thin-walled tubes (Fig. 2). About 25% space is left for the expansion of fillers during collision process. In addition, thin-walled diaphragms were welded in rectangular tubes to uniformly separate aluminum honeycomb fillers into small parts, avoiding unstable deformation in long blocks. The thickness of diaphragm is larger than that of honeycomb, which ensures that the entire structure is closed and also offers a flat contact surface during a crash. Therefore, the deformation modes are controlled.