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The impact performance of honeycomb-filled structures under eccentric loading for subway vehicles

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ABSTRACT

When a train collision occurs, it is impossible for the vehicle to produce a completely axial collision. To improve the energy absorption performance of the energy-absorbing structure under an eccentric collision, in this paper, a FE model of the energy absorption structure for subway vehicles was created and validated by experimental data. Based on the validated FE model, the collision performances under a vertical offset of 0–80 mm and a horizontal offset of 0–40 mm are studied via simulation. The results show that the original structure is prone to instability when the horizontal offset is greater than 30 mm, so it is necessary to perform an optimization. Based on the bending strength, the cross-sectional shape of the guide was changed. The results show that there is no instability phenomenon in the improved structure I1 under all horizontal offsets. Under the horizontal offset of 40 mm, compared with the original structure, the energy absorption increased by 175.89%, and the peak force also increased by 14.46%. Based on the concept of gradient material, the honeycomb strength in the structure is changed into a gradient distribution, and the results show that the improved structure I2 also did not show any instability phenomenon under all horizontal offsets. Under the horizontal offset of 40 mm, compared with the original structure, the energy absorption increased by 171.88% and the peak force decreased by 1.92% at the same time.

1. Introduction

Although the possibility of collision accidents on trains is much lower than other transportation methods, collision accidents still occur, resulting in serious casualties and economic losses [1]. For example, On February 9, 2016, two commuter trains crashed in Germany, killing at least 10 people. On June 22, 2009, two subway trains collided in Washington, resulting in 9 deaths. To reduce the injury rate of passengers and staff in train collision accidents, an energy-absorbing structure is installed at the front of the subway vehicle usually. Thus, the energy absorbing capacity and characteristics of the energy-absorbing structure has become the focus of much research.

Yu and Lu [2] studied the deformation of such material via a theoretical model and a large number of experimental results of square tube, circular tube and other thin-walled structures under axial compression. Some other constructive work was also conducted with the emphases on mechanical behavior of multi-cell tubes to get more excellent deformation mode [3]. Honeycomb material is widely used in the railway industry because of their unique mechanical properties [4]. For example, in order to save the body mass while maintaining the body strength, Korean Tilting Train express(TTX) adopts a foam filled sandwich panel body [5], moreover, Ko et al. [6] suggest a standardized finite element model for the carbody structures of various railway vehicles made of sandwich composites. On the application of energy absorption, Wang et al. [7] constructed theoretical formulas model to directly calculate the energy absorption capacity of any given conventional honeycomb block. Hozhabr Mozafari et al. [8,9] analyze the in-plane compressive response and out-of-plane impact response of foam-filled honeycomb structure by experiment and simulation. Meran et al. [10] found that a passenger car incorporating the crash energy management(CEM) system which include honeycomb structured boxes has a superior crashworthiness performance to that of the conventional passenger car. In order to obtain better energy absorption properties, researchers usually combine honeycomb material with thin-walled structures. Zhou et al. [11] found that because of the interaction effects of thin-walled metal structure and aluminium honeycomb structure, the energy that the combined structure absorbed exceeded the sum of the energy absorbed by the thin-walled metal structures and honeycomb

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structures when loaded separately, Zarei [12] also came to the same conclusion through experiments. Wang et al. [13] extensively explain the reason for this by analyzing the comprehensive matching effect between the inside honeycomb core and outside thin-walled metallic square tube of honeycomb-filled structure. Peng et al. [14] found that their proposed composite energy-absorbing structure could not only produce regular folds in the diaphragm, but could also absorb more energy due to the filled honeycomb material. Some more novel honeycomb structures were developed so as to obtain high energy absorption capacity, including the tandem-honeycomb-filled structure [15] and the CFRP tubes-filled into honeycomb structure [16]. Xie et al. [17] design a new-type composite energy absorbing structure by combining the characteristics of thin-walled metal structures and aluminium honeycomb structures, in addition, they found that aluminium honeycombs with higher plateau stresses can be used for improving the energy-absorption capabilities of such energy absorbing structures through simulation analysis.

However, in an actual collision, it is impossible for the vehicle to produce a completely axial collision. On 9 February 2016 two commuter trains hit each other head-on at a bend on a single track line in Germany as shown in Fig. 1(a). The drivers' cabs of both trains are wedged into each other. One side of one train is completely torn open and the other train bored into it. Both trains were partially derailed by the head-on crash. On 22 June 2009 Washington Metro Train 112 rear-ended stopped Train 214 which resulted in Cars of both trains were ripped open and two cars of one train lying atop the cars of the other train as shown in Fig. 1(b). Both of crashes happened on the bend and are not completely axial collision. Actually, the flexible elastic suspension device between vehicle and bogie, the movement of the wheel rail caused by the conical tread design, the abrasion of wheel-sets, vibration in motion and random irregularity of the track all caused vehicle offset in the vertical and horizontal directions. Therefore, standard EN15227 [18] presented the acceptance criterion for the overriding limitation for scenario 1 (identical train unit collision), where the validation process demonstrates that, with an initial vertical offset of 40 mm at the point of impact, the criteria for deceleration and survival space are achieved. Wan et al. [19] gave a method for calculating the horizontal offset of rail transit vehicles, and gave the curve between the maximum horizontal offset and the speed of the vehicle. To reduce the casualties and economic losses under eccentric impact, it is necessary to carry out the study of the energy absorption characteristics of the energy-absorbing structure under an eccentric collision.

Eccentric impacts are common, along with oblique impacts and offset impacts. For oblique collisions, Zou et al. [20] analyzed the collision behavior of eight multi-cell square tubes at the oblique loading angle and found that at a small angle, all structures show patterns similar to the progressive buckling modes under axial loads. However, at large angles, all structures show a bending-dominated deformation pattern, which leads to a decrease in the energy absorption and peak force. Pirmohammad et al. [21,22] found the same law when analyzing the oblique impact performance of other cross-sectional shapes of thin-walled tubes. The results of Othman et al. [23] showed the performance of the composite square tube filled with polymer foam is better than empty composite tubes under oblique loads through experimental results. Through experimentation, Gao et al. [24] also found that a foam filled tube with common cross section has better energy absorption capacity than an empty tube at multiple angled load angles. Research on offset collisions is relatively rare. Ismail et al. [25] analyzed the eccentric collision of high strength steel tubes, where the results showed that the energy absorbed increased and the crush force efficiency decreased when the eccentric compression loading increased.

Most of the research on energy absorption characteristics of energy-absorbing structures are focused on axial impacts at present [26–31], however, there are few relevant studies reported on offset impact. The goal of this paper is to study the impact performance of honeycomb-filled structures under eccentric loading, and improve the crashworthiness of structures under eccentric loading. According to standard EN15227 and the curve between the maximum horizontal offset and the speed of the vehicle, the collision performance of a subway vehicle energy absorption structure under a vertical offset of 0–80 mm and a horizontal offset of 0–40 mm is studied via simulation, and improved it based on simulation results.

2. Numerical analysis

2.1. Finite element model

The honeycomb-filled energy-absorbing structure is shown in Fig. 2(a). The structure is composed of main energy absorbing parts—a thin-wall tube and honeycomb, a diaphragm for separating the honeycomb, a front-end plate, a rear-end plate and a guide. The honeycomb is embedded between the diaphragms, with the distribution shown in Fig. 2(b).

The structural dimensions are shown in Fig. 3. The total length L_{all} is 1006 mm, and the front and rear end plate thickness is 6 mm and 10 mm, respectively. The length L of the thin walled tube is 787 mm, both ends are rectangular with a fillet, the front section size is 280 mm × 188 mm and the end section is 280 mm × 232 mm. The front of the thin-walled tube is provided with an induction structure. The thin-walled tube thickness t_w = 2.5 mm, the diaphragm thickness t_D = 3 mm. The fill consists of two different sizes of honeycomb according to the location of the diaphragm. All honeycomb structure section sizes are 150 mm × 90 mm, H_A and H_B axial dimensions are 97 mm and 62 mm, respectively.

In this paper, finite element simulation analysis is carried out by nonlinear finite element software LS-DYNA; the finite element model of

Fig. 1. (a) Bad Aibling rail accident, (b) Washington Metro train collision.