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A numerical study on the energy absorption of a bending-straightening energy absorber with large stroke

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ABSTRACT

This paper presents a novel energy absorber that can generate a larger deformation stroke than its free length. The effective crushing distance rate (ECDR) of this structure can exceed 1. During collision, the impact kinetic energy is dissipated by the elastic-plastic deformation of a steel plate and aluminium honeycomb. The bending theory of the steel plate is analysed to estimate the energy absorption (EA) and the mean crushing force (MCF). Then, a finite element (FE) model of the energy absorber is established, and its accuracy is validated by the theory of plate blending. When the plate thickness is 2 mm and 5 mm, the error between the simulation and theoretical results are 1.93% and 3.05%, respectively. The FE model is used to investigate the crashworthy performance. When the new absorber is deformed, the influence of the type of aluminium honeycomb, steel plate thickness and width, guide wheel radius, and number of guide wheels on energy absorption are analysed. Aluminium honeycomb with appropriate parameters can significantly reduce the peak crushing force (PCF) by up to 60.8%. The crushing force (CF) and EA increase as the plate thickness, plate width, and number of guide wheels increase but decreases as the guide wheel radius decreases.

1. Introduction

There are various types of energy absorption structures, which are widely used in trains, cars, aircrafts, ships and other transport tools. Among these structures, the most common is the thin-walled metal structure, which dissipates kinetic energy through axial plastic deformation such as folding, inversion, splitting, and cutting. A thin-walled tube can produce stable progressive buckling under axial compression. This structure has many advantages such as a controllable deformation mode, simple structure, convenient production and high energy absorption efficiency, so the structure is widely used in the crashworthiness field [1–3]. Abramowicz et al. [4] investigated the deformation of square tubes in detail according to a kinematical admissible method of analysis, and predicted four deformation modes with different width-height ratios. Wlodzimierz and Andrews et al. [5,6] performed experiments to study the deformation mode and energy absorption characteristics of circular tubes under axial crushing, and found that tubes with different lengths, diameters and thicknesses had different deformation modes, such as a diamond and concertina mode of collapse. They determined that the concertina mode has high energy absorbing ability. Based on these studies, various forms of the thin-walled structures have been investigated, such as pentagonal [7], hexagonal [8], octagonal [9], multi-cell [10,11], foam-filled [12,13] and crisscross thin-walled structures [14]. Base on the above studies, a lot of the optimized thin-walled structures have been studied. Zheng et al. [15] proposed a new laterally variable thickness multi-cell tubes that the compelling features has been fully demonstrated through theoretical, numerical, and experimental study. Sun et al. [16] introduced a novel thin-walled structures filled with graded foam fillers, the optimal system crashworthiness has also been performed by single and multi-objective particle swarm optimization methods. Variable thickness thin-walled structures has also been widely researched due their favourable energy absorption characteristics [17,18]. The results demonstrate that these optimized structures can improve the crashworthiness of thin-walled square tubes. The effective crushing distance rate (ECDR) is defined as the ratio of effective crushing distance to the total length of the energy absorber. The ECDR of this type of structure is approximately 0.7–0.8 based on numerical and experimental results [19,20].

Qiu et al. [21,22] studied a type of metal tube under free inversion based on theoretical and numerical investigations. The working mechanism of the tube is ductile mental circular tubes producing inverted deformation either externally or internally under axial loading. A tube with this type of deformation can provide a constant crushing load, while the available compression distance is only half of the total length. Yang et al. [23] studied a type of expanding energy absorption

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structure. The die was forced into and expanded the expansion sleeve to absorb the impact kinetic energy when it is subject to a large force. The energy absorber has a simple structure and can be assembled easily, however, when the axial length of the device is too large, the ECDR is less than 0.5.

Li et al. [24] studied an expanding–splitting circular tube by experiments and numerical simulations which were based on the principle of expanding and splitting of the circular steel tube, with the ECDR reaching a value of 0.9. Dong et al. [25,26] proposed a splitting--bending steel plate energy absorber which uses the advantage of the splitting and bending behaviour of steel plates based on experiments and simulations. They indicated that the deformation of this type of absorber is stable and reliable and its ECDR value is approximately 1.

Shun and Bondy et al. [27,28] designed a new energy absorber according to the energy-absorbing principle of the axial cutting of metal structures. Relative motion occurred between the cutter and the metal tube, and its ECDR value was not greater than 0.5.

In addition to the above, the energy absorption structure of the honeycomb [29,30] has also been widely researched due to its lightweight, favourable cushioning properties, large compressive stroke and controllable deformation. Kinetic energy can be dissipated by the progressive buckling of several cellular structures of honeycomb. The fabrication process of honeycomb has increasingly developed and has been widely used in the crashworthiness field [31,32]. Sun et al. [33] incorporated the concept of hierarchy into honeycomb structures with a smaller hexagon topology to replace the vertex of a regular hexagonal network, the crashworthiness performance was greatly enhanced compared with the regular honeycomb. Liu [34] proposed a U-shaped thin plate energy absorber based on the plastic forming mechanisms of stamping. The energy can be dissipated by the bending and friction of the U-shaped thin plate and the feasibility was proven through repeated quasi-static tests. Each energy absorber has a unique energy absorption mechanism and characteristics, but have one common characteristic: the ECDR value cannot exceed the free length, which means the absorber can only produce less plastic deformation than its own length, which limits the energy absorption capacity of the structure.

The tension levelling process is often used to improve the strip shape of metal plates [35,36]. The residual stress can be eliminated by tension levelling deformation of the plate under the constraint of straightening rollers. In this process, the plate stores a large amount of plastic internal energy [37]. In this paper, a new energy absorption structure with a large stroke distance and the ability to generate greater deformation stroke than free length is proposed based on elastic-plastic deformation. It can be applied to moderate and dissipate the energy of an object moving with a certain track, such as cushioning protection for small carrier vehicles with rails, braking of the solid transfer in the pneumatic tube system, recycling of the falling object and others. The energy absorber can be installed in the end of the track. The path of the moving body runs through the energy absorption space in the middle of the energy absorber. Thus, the moving body impacts the energy absorber with a positive direction and continues moving forward with the steel plate at a decreasing speed. The impacting kinetic energy can be dissipated continually until the moving body stops.

The various energy absorbers being applied include the thin-walled metal structure [38], the axial cutting of metal structures [39], the expanding energy absorption structures [40], etc. However, these structures have some deficiencies. The thin-walled metal structures always have the defect of an unsatisfactory crushing force. Cutting of metal structures also exists following defects in the application: First, there are potential security risks regarding high speed and high temperature flying metal debris threatening the surroundings. Second, considerable heat generated by high-speed cutting will cause tool performance to deteriorate drastically. Expanding energy absorption structures have high requirements for the structure design. All these defects may destroy the structure of the moving body. However, the energy absorber presented in this paper can overcome these disadvantages with no flying metal debris, favourable stability regarding crushing and low structural requirements. More importantly, ECDR can exceed 1, which is far more than the current energy absorbers, and greatly enhances the energy absorption capacity of the device.

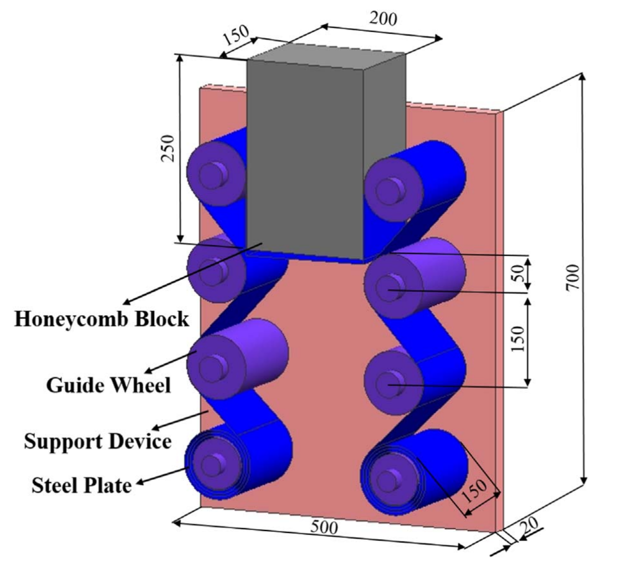

Fig. 1. Model of the energy absorber.

In this paper, the structure of the energy absorber with a large deformation stoke is introduced, and the theory of plate bending is analysed, which is used to estimate EA and MCF. Next, a finite element model of the energy absorber is established to investigate the crashworthy performance using the explicit non-linear finite element software LS_DYNA. The FE modelling accuracy is validated by the theory of plate bending. Finally, the influence of different parameters of honeycomb and geometric parameters such as plate thickness and width, radius of guide wheels, number of guide wheels on the mechanical properties of the energy absorber are analysed.

2. Geometrical description

The energy absorber consists of buffer aluminium honeycomb, a steel plate, guide wheel and support device. The geometric model is shown in Fig. 1.

In Fig. 1, the guide wheel radius is 50 mm, and the guide wheels are installed on two support plates. The support plate is 700 mm × 500 mm × 20 mm. The front of the support plate is hidden in the model to show internal parts. The steel plate winds around the guide wheels and the honeycomb aluminium is installed on the top of the steel plate, which is subject to impact force. The thickness of the steel plate is 5 mm, and its width is 150 mm. The length of the steel plate is controlled by the number of coils at the end of the plate as required. The honeycomb structure is primarily used to reduce the initial peak force and prevent the metal plate from breaking at the initial stage of the collision. The honeycomb is 250 mm long and 150 mm × 200 mm in dimension. The pore directions of the honeycomb structures are aligned with the direction being impacted. The steel plate is the main energy-absorption component, which is used to dissipate the kinetic energy by repeating the elastic-plastic deformation of bending-straightening. When the plate exceeds the bottom of the device, it can move contiguously backward, which improves the energy absorption capacity of the device. The material used for the plate is mild steel.

The guide wheel is the component that leads to the elastic-plastic deformation of the steel plate. Rolling bearings are installed in the guide wheels. There are two reasons for installing the bearings. First, if the friction between the steel plate and the guide wheels is too large, the tension of the steel plate in the lengthwise direction may be