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# Crashworthiness analysis and optimization of a *cutting-style* energy absorbing structure for subway vehicles

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## ABSTRACT

This study proposes a *cutting-style* energy absorbing structure to improve the crashing performance of subway vehicles through experiment and numerical simulations. The structure consists of an anti-creeper device, energy absorption tube, cutting knife and clamp. A finite element (*FE*) model of a *cutting-style* energy absorbing structure is created and validated by full-scale experimental data. Based on the validated simulation model, the influence of the design parameters, which include the cutting depth ($d$), the cutting edge angle (*CEA*) and the chip central angle (*CCA*), on the impact performance is analyzed. The parametric study found that the design parameters influence the peak cutting force ($F_p$) and energy absorption (*EA*). In addition, the structure has prominent advantage in lowering the peak interface force. Finally, the response surface method (*RSM*) is adopted to achieve maximum *EA* and minimum $F_p$ simultaneously. The optimized results show that the objectives compete with each other, and the weighting factors are of considerable significance to the most satisfactory Pareto fronts solutions. In this paper, the minimum distance selection method (*TMDSM*) is adopted to determine the most satisfactory solution. It can be concluded that when $CCA = 18.18°$, $CEA = 23.87°$, and $d = 2.87$ mm, the structure shows the best impact performance and $EA = 275.9$ kJ and $F_p = 887.2$ kN.

## 1. Introduction

The safety of passengers after railway collision accidents has always been a hot spot of attention because the casualties and severe loss of property are unbearable. For example, on July 12, 2008, a serious railway collision accident occurred in Los Angeles that killed at least 26 people, and more than 130 people were injured. A similar collision occurred in Wenzhou, China, on July 23, 2011, killing 40 people and wounding at least 200 people. Therefore, substantial investigations have focused on the crashworthiness design and the optimization of energy absorption structures.

Several investigations have addressed the crashworthiness design and optimization of energy absorption structure using numerical simulations and experiments. Thin-walled structures are widely used in civil engineering, shipbuilding, and other industries because of their low cost, high strength-weight ratio, and progressive deformation under an axial crushing load during crashworthiness analysis [1,2]. *Jones* [3] *studied the effectiveness of thin-walled structure with different section shapes under static and dynamic axial loadings by adopting an energy-absorbing effectiveness factor.* Based on the response surface method, Liu [4] optimized the cross-sectional dimensions of thin-walled structures to maximize the specific energy absorption and presented efficient, simplified models that obtained optimum results of a certain accuracy. Nia and Hamedani [5] compared various section shapes of thin-walled tubes and concluded that pyramidal and conical tubes can lower the peak force, whereas the circular tube absorbs the most energy. Hosseinipour and Daneshi [6] found that grooves on the tubes can stabilize the deformation pattern to lower the deceleration pulse.

Furthermore, cellular material, as filler material for hollow tubes, has attractive mechanical properties for improving the crashworthiness and is widely used in automotive, military, and other industrial applications [7]. Several studies [8–14] showed that aluminum foams have good energy absorption under both quasi-static and dynamic loading conditions. Paz et al. [15] found that the honeycomb-filled tube showed an improved energy absorption over the hollow tube by performing tests with a hollow tube and a honeycomb filled tube. Regarding aluminum honeycomb sandwich panels, Paik et al. [16] concluded that the aluminum honeycomb core has excellent properties with respect to the weight savings and fabrication costs based on a series of strength tests performed on an aluminum honeycomb-cored sandwich panel specimen. Santosa et al. [17] found that aluminum foam filling provided better crash behavior than aluminum honeycomb filling. Bi et al. [18]

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showed that the foam-filled tube has a significantly larger crushing force than the hollow tube. Generally, there is a large, undesirable, initial peak force, followed by fluctuation in the force-displacement curve [19]. Peng et al. [20] focused on the study of the combination of thin-walled metal composite structures and aluminum honeycomb structures and found that as the thickness or honeycomb yield strength increases, the initial peak impact force and average crashing force increase. However, most studies have only focused on the parameter optimization of the thin-walled structure and the aluminum honeycomb structures or composite structures. There are few studies on the *cutting-style* energy absorbing structure, which works on the principle that the plastic deformation of cutting chips, the *tearing* of the metal tube, and the friction force between knives and carved metal will consume the impact energy. Another essential advantage of this structure is its strong stability because the energy absorption tube can works as a guide rail.

In this paper, a finite element model of the proposed structure was established and validated by a full-scale impact experiment in the same constraint conditions. The cutting depth, the cutting edge angle and the chip central angle were set as the design parameters. Based on the validated simulation model, the influence of the design parameters on the crashworthiness performance was studied. In this work, several indicators, including the energy absorption (*EA*), the peak cutting force ($F_p$), and the average cutting force ($F_{avg}$), are defined as the crashworthiness indicators to systematically evaluate the crashworthiness of the *cutting-style* energy absorbing structure.

## 2. Methodology

### 2.1. Geometrical description

The energy-absorbing structure in this paper is fixed at the front end of the underframe of the subway. There are four parts of the structure, as illustrated in Fig. 1. The energy absorption tube, with an outside diameter of 195 mm and inside diameter of 171 mm, consists of tube A (axis length of 694 mm) and tube B (axis length of 185 mm). The energy absorption tube absorbs energy when carved by the knives and works as a guide rail, which can guarantee that all the knives bear the average force and the tube has a regular deformation pattern in the crash process. Sliding friction and shear slip deformation between the cutting knife and metal layer have a significant contribution to the energy consumption. The knives with a circular arc shape are fixed on the clamp that is welded on the underframe. The anti-creeper device is fixed at the front-end of tube A. To study the real situation in consideration of both the energy absorbing structure and the train, a full-scale experiment is conducted. In the real model, the energy absorbing structure is welded on the vertical plate, which is in the front of the impact trolley. *Tube A and tube B are essentially two parts of the energy absorption tube but play different roles during the impact process. Tube A is the front-end part of the energy absorption tube that can be cut by the cutting knives while tube B is the other part that support the clamp and worked as guide tube in the initial collision stage.* Specifically, a pre-cutting is designed to decrease the peak cutting force and guide a regular deformation pattern.

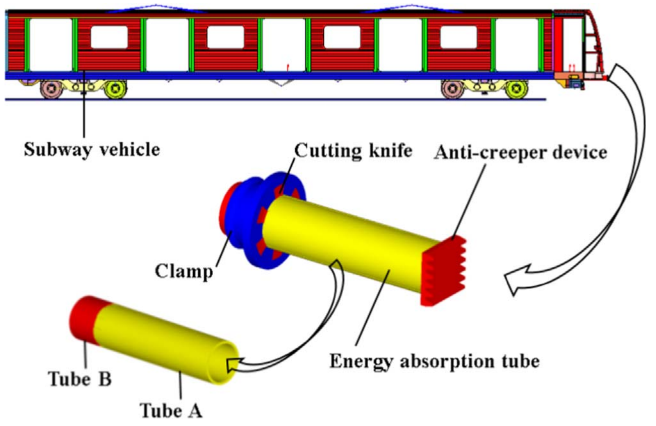

**Fig. 1.** Cutting-style energy absorbing structure.

### 2.2. Development of the finite element (FE) model

With the development of computer technology and finite element theory, the finite element method has been widely used to investigate the energy consumption process of metal energy absorbing structures. In this paper, the simulation model of the collision process is developed in Hyperworks based on the full-scale physical experiment. Furthermore, LS-DYNA, an explicit, nonlinear, FE code, is used to perform the computing. As seen in Fig. 2, the FE model includes the following parts: the energy-absorbing structure, rigid wall and impact trolley. The energy-absorbing structure is molded with solid elements. In comparison, the Belytschko-Tsay shell element formulation is used for the impact trolley.

For the consideration of both the computational efficiency and the accuracy of the model, the mesh sizes of 1–3 mm and 8–12 mm are selected for the tube and the other area, respectively. To avoid hourglass energy during the computation process, this work uses the fourth hourglass control stiffness formula. The contact between the energy-absorbing structure and the rigid wall is defined by the "AUTOMATIC_SURFACE_TO_SURFACE" contact algorithm. The self-contact of the carved chip is defined by "AUTOMATIC_SINGLE_SURFACE". The contact between all of the touching components is modeled with a static friction coefficient of 0.30 and a dynamic friction coefficient of 0.25.

In the axial crush simulation model, there is a gravity acceleration of 9.81 m/s$^2$, and the whole model weighs 25.0 t. The energy-absorbing structure, which is fixed on the front end of the impact trolley, impacts the rigid wall at a speed of 5.0 m/s.

### 2.3. Material model

The constitutive relationship of the material reflects the changes of the material properties and plays an important role in the accuracy of the impact model. In this paper, the deformation of knives can be nearly ignored; thus, the knives are modeled by hard alloy material, whereas the other parts of the energy-absorbing structure are modeled by mild steel (Q235). The Cowper-Symonds constitutive relationship model is selected because of its efficiency in reacting to the strain rate effect for a low strain rate condition [21]. The model adopts the factors associated with the strain rate, representing the yield stress, as described by the following equation:

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right](\sigma_0 + \beta E_\rho \varepsilon_\rho^{eff}) \tag{1}$$

$$E_\rho = E_{tan}E/(E - E_{tan}) \tag{2}$$

Where $\sigma_y$ is the yield stress, $\sigma_0$ is the initial yield stress, $\dot{\varepsilon}$ is the strain rate, $C$ and $P$ are the strain rate parameters of the Cowper-Symonds constitutive relationship model, $\varepsilon_\rho^{eff}$ is the effective plastic strain, $\beta$ is the hardening parameter, which varies from 0 to 1, for kinematic hardening, $\beta = 0$, while $\beta = 1$ corresponding to the isotropic hardening material. $E_\rho$ is the plastic hardening modulus, $E$ is the modulus of elasticity, and $E_{tan}$ is the tangent modulus of plastic deformation [22]. *The values of C and P can vary significantly with strain and be sensitive to a wide range of factors, such as surface finish of a test specimen, heat treatment, chemical content, etc* [23,24]. *In this paper, the study of Dietenberger* [25] *is referenced to determine the values of C and P. The material of the energy absorbing tube is mild steel and in most literature* $C = 40\,s^{-1}$, $P = 5$ [26], the hardening parameter is set as $\beta = 0.3$ [27].