Design and Numerical Simulation of a Ball Cutting Type Energy Absorber Device

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Abstract. This paper is verified by numerical simulation and experiment. Based on the principle of energy absorption in metal cutting process, this paper presents a new type of energy absorption structure, which can improve the collision performance of urban rail vehicles. The structure is composed of solid energy absorption tube, hard ball, anti-crawling board and mounting board. Based on the nonlinear dynamic simulation theory and the explicit algorithm of finite element software ABAQUS, the finite element model of the structure of the cutting type energy absorber was established, and the energy absorption process was simulated. Based on the verified simulation model, the influences of the design parameters such as the cutting depth and the number of balls on the energy absorption process are analyzed. It is found that the design parameters affect the cutting force and energy absorption, and the structure has a good energy absorption effect during the collision.

Keywords: Cutting Explicit algorithm Finite element The structure of energy absorbers Urban railway vehicle.

1. Introduction
The emergence of urban rail transit alleviates traffic congestion and improves people's travel efficiency. However, the rapid development of rail transit makes the trains running on the track denser and the number of passengers denser. There is a great safety hidden trouble, if the train collision or crash because some sudden factors, the consequence will be unimaginable. At this point, the energy absorber energy storage structure can absorb most of the collision energy in the collision process, reduce the collision impact on the car, so as to ensure the life safety of passengers to the maximum extent. The UK, the US and other countries have long carried out impact experiments on railway passenger cars and put forward the experimental scheme that each car can absorb its own impact energy [1]. A comprehensive experimental and numerical study of the crash behavior of circular aluminum tubes undergoing axial compressive loading is performed by D. Al Galib, A. Limam [2]. Zhang Xie et al. from Shanghai University of Engineering and Technology obtained the thickness of aluminum energy absorption box based on the prediction theory of equal energy absorption thickness, analyzed the energy absorption characteristics of steel and aluminum energy absorption box, and then improved the inner wall structure of the energy absorption box to get a better energy absorption box structure [3]. Nia and Hamedani in Iran compared thin-walled tubes with different cross section shapes and found that tapered and tapered
tubes reduced peak force, while circular tubes absorbed the most energy [4]. A.G. Olabi et al present an overview of energy absorbers in the form of tubes in which the material used is predominantly mild steel and/or aluminium [5]. X Huang et al found the splitting and curling of a square metal tube is an efficient energy absorbing system for a crashworthy system. There are three energy dissipating mechanisms: tearing, plastic bending and friction [6]. Jones in the UK studied the efficiency of thin-walled structures with different cross-section shapes under static and dynamic axial loads by using the energy absorption efficiency coefficient [7]. Wang Xishun of South China University of Technology, put forward a kind of railway vehicles used for the new cutting type vacuum device - the round hole broach type energy absorption device, on the basis of the round hole broach type suction can carries on the preliminary structure design, and by using the ANSYS/LS-DYNA the cutting type energy absorption device of different structure and materials, and cutting thickness are analyzed in the simulation, got the device time history curve of cutting force in the process of impact [8]. At present, there are also many researches on the material of energy absorption device structure, and the influence of the structure mode on the energy absorption efficiency. Especially at present, some aluminum foam, honeycomb tube and other materials as the filling material of energy absorption tube, have a great improvement on the crash-resistance. Jeom Kee Paik et al. conducted three-point bending crankshaft compression and side compression strength tests on aluminum honeycomb sandwich plates and analyzed the bending deformation buckling/ultimate strength and crushing strength of the honeycomb sandwich plates under the action of corresponding load components by using simplified theory, and discussed the structural failure characteristics of aluminum sandwich plates [9]. At the same time, Suchao Xie et al. from Central South University in China designed a composite energy-absorbing structure with high strength-to-weight ratio by coupling metal and aluminum honeycomb thin-wall structure, and verified the effectiveness of the equivalent models of metal thin-wall structure and aluminum honeycomb structure respectively through vehicle impact and quasi-static compression tests [10]. Central South University Honghao Zhang et al think that train energy absorption device structure optimization problems still exist, such as goal conflict the uniqueness of the optimal solution more problems and then puts forward a hybrid optimization method (M - BGV) combining the multi-objective artificial colony (MOABC), the best of the worst (BW) method, the gray relation analysis (GRA) and visekriterijumsko kompromisno rangiranje (VIKOR), to solve the problem of the structure optimization of the train collision energy absorption structure [11].

The structure of the energy absorber can be divided into three types according to the failure mode of the material: crushing type, expansion type and cutting type. Among which cutting type is the most studied in recent years, because it is found that the energy absorption mode of metal material with large plastic deformation and material fracture after deformation is better than that of metal material with large plastic deformation only. According to this conclusion, it is speculated that the metal crushing process is likely to be a more energy-absorbing process. The energy-absorbing process carried out by any effective energy-absorbing device must be an irreversible and controllable process [12]. Metal cutting process is a very complex nonlinear process of energy conversion and material consumption. In the process of metal cutting, the process in which the tool cuts the workpieces and generates chips is a metal breaking process, and it is a typical irreversible energy dissipation process, which can consume a large amount of energy in a short time.

In metal cutting is used for the domain of urban rail train front-end energy absorption device, there had been a lot of people study is focused on with a sharp cutting tool as a cutting tool, as previously discussed Wang Xishun [8] from South China University of Technology, put forward a new type of cutting for railway vehicle type energy absorption device - the round hole broach type suction can implement. Guowei Liu [13] from Central South University also use the structure principle of the device for railway vehicle collision energy absorption as shown in figure 1. Yong Peng [14] et al designed the structure consists of an anti-creeper device, energy absorption tube, cutting knife and clamp, and improved the crashing performance of subway vehicles through experiment and numerical simulations.
In this paper the author summarizes the existing research conditions and thinks that the tools can be improved to cut the energy absorption tube, not necessarily sharp tools. Cutting tool cutter blade may occur under the impact of the strong deformation, the influence degree of the sharp edge cutting process, which affects the impact energy absorption. The tool can be improved into hard balls. Finite element software ABAQUS is used for simulation to study the cutting force and energy absorption effect in the cutting process, the cutting depth of small balls, the number of balls and other structural parameters, analyze their influence on the process, and finally judge the feasibility of the application of the new type of energy absorption device.

2. Ball cutting type energy absorber device

Ball cutting energy absorption units by solid energy absorption tube, installation seat, anti-creeper and balls. The installation plate is used to install the energy absorption device on the car body. The energy absorption components composed of the energy absorption tube and the ball buffer energy absorption during the collision. The anti-creeper prevents the train from climbing by engaging with each other through the anti-crawler teeth of mounting plate. In the event of a collision between two carriages, the ball absorbs the impact energy by cutting the suction tube, and at the same time the energy is also converted to friction heat energy between the balls and the solid energy absorption tube. However, during the collision, most of the kinetic energy in the system is converted into deformation energy of the structure, and some of the kinetic energy is dissipated in the form of heat energy. In order to simplify the simulation process, only the changes of kinetic energy and deformation energy are considered, not the loss of heat energy.

3. Numerical simulation of energy absorption process of ball cutting energy absorber device

3.1. Nonlinear dynamic simulation theory

The cutting energy absorption process is a complex nonlinear dynamic process. The governing equation in ABAQUS is briefly described as follow [13].

Figure 1. Schematic diagram of structure of cutting type energy absorption device

Figure 2. Structure drawing of ball cutting type energy absorber device
Let's take the initial moment of the particle coordinates $X_i (i = 1, 2, 3)$, at any time $t$, the coordinate of the particle is $x_i (i = 1, 2, 3)$, so the equation of motion of the particle is

$$x_i = x_i(X_i, t), i = 1, 2, 3$$  \hspace{1cm} (1)

When it is $t=0$, the initial conditions is

$$\begin{cases}
x_i(X_i, 0) = X_i \\
x(X_i, 0) = V_i(X_i, 0)
\end{cases}$$  \hspace{1cm} (2)

Conservation of mass equation

$$\rho_0 = |J_t| \cdot \rho$$  \hspace{1cm} (3)

$\rho_0$ is the initial density, $J_t$ is the current density; $\rho$ is deformation gradient

Equations of motion

$$\sigma_{ij,j} + \rho b_i = \rho \ddot{x}_i$$  \hspace{1cm} (4)

$\sigma_{ij}$ is cauchy stress; $b_i$ is the volume force per unit mass; $\ddot{x}_i$ is the acceleration.

Energy conservation equation

Since only the change in kinetic energy and deformation energy is considered, the change in both is equal to the work done by the external force, i.e

$$\frac{dk}{dt} + \frac{dw}{dt} = \int \rho \cdot b_i \frac{\partial u_i}{\partial t} dV + T_i \cdot \frac{\partial u_i}{\partial t} dS$$  \hspace{1cm} (5)

$w$ is the unit deformation energy, $k$ is the unit kinetic energy; $u_i$ is the displacement in the direction, $T_i$ is the surface force, $S$ is the unit area.

Boundary conditions

1. Surface force boundary conditions: $\sigma_{ij} \cdot n_j = T_i(t)$ On the surface force boundary $S^1$, $n_j$ is the outer normal direction cosine of the surface force boundary of the system $S^1$, $T_i(t)$ is the surface force load.

2. Displacement boundary condition: $x_i = K_i(t)$ On the displacement boundary $S^2$, $K_i(t)$ is given is the displacement function.

3. Jumping conditions at discontinuities of sliding contact surfaces: $(\sigma_{ij}^+ - \sigma_{ij}^-)n_j = 0$ On the contact boundary $S^3$, when it is $x_i^+ = x_i^-$ the formula is valid.

3.2. The constitutive model of the material

Material model is the most basic element in metal cutting simulation technology and has great influence on simulation results. When the material is cut, the nonlinear behavior occurs, and it is no longer linear.
elastic behavior. Large strain temperature and high strain rate are the main characteristics of nonlinear behavior. Therefore in the simulation, the material constitutive model should be able to accurately represent these characteristics. At present, the research on this is not fully mature, so no constitutive model can be applied to any cutting simulation process. In the simulation of cutting energy absorption, there are three effects: strain hardening effect, strain rate strengthening effect and heat softening effect. Therefore, the constitutive model in this paper adopts Johnson-Cook, the most widely used thermoplastic constitutive model, and the equation is

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n) \left[1 + C \ln \left(\frac{\bar{\varepsilon}}{\bar{\varepsilon}_0}\right) \right] \left[1 - \left(\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}}\right)^m\right]$$

(6)

In the formula (6), the expression in the first parenthesis expresses the elastic-plastic behavior of the material, the first parenthesis expresses the viscosity of the material, and the second parenthesis expresses the thermal softening effect of the material. A, B, and N represent the strain strengthening term coefficient of the material. C denotes the strengthening term coefficient of material strain rate; M represents the thermal softening coefficient of the material.[14]

In this paper, 45 steel material was used for finite element simulation, and the constants in the Johnson-Cook model were shown in Table 1

| A (MPa) | B (MPa) | n   | c    | m   |
|--------|--------|-----|------|-----|
| 507    | 320    | 0.28| 0.064| 1.06|

### 3.3. Criteria for the separation of chip and parent material

Reasonable chip separation criteria should be able to correctly reflect the mechanical and physical behavior of the workpiece, its critical value should not change with the change of cutting conditions after the cutting material is determined, and is conducive to computer implementation. At present, the chip separation criteria applied to cutting simulation mainly include geometric criteria and physical criterias [11].

In this paper, the ball cutting material causes large deformation of the material. When the ball and material cutting shear, stress reach the yield criterion of the material, the material will fail. Combining the failure criterion of Johnson-Cook model and the failure element deletion technology in ABAQUS software, the chip can be separated from the parent material.

### 3.4. Finite element model

To facilitate the calculation and simulation, the simplified modeling of the energy absorption device structure is shown in the figure below. As shown in Figure 2, the impact block is on the far left, and the energy suction device is on the right. Figure 3 shows the position of the cut ball relative to the energy suction pipe. Figure 4 shows the position of the ball in the groove inside the mounting plate.
In the model, except for the solid energy absorption tube, the ball, mounting plate and the impactor are all regarded as rigid bodies. The structural material of the solid energy absorption tube is 45 steel and the related properties are set in ABAQUS. The diameter of the ball is 20mm, the diameter of the solid energy absorption tube is 67.5mm, and the effective energy absorption length is 370mm. Finally, in ABAQUS software, steps such as assembly interactive definition of material properties, setting boundary conditions and mesh generation are successively carried out. In this study, explicit analysis algorithm is adopted to improve the calculation accuracy.

Table 2 Materials and parameters of the suction pipe

| Materials   | Density (Kg/m³) | Elasticity modulus (GPa) | Poisson’s ratio |
|-------------|-----------------|--------------------------|----------------|
| 45 steel    | 7800            | 210                      | 0.3            |

In this simulation, two parameters were selected to study their influence on the energy absorption capacity of the energy absorber. They were: the number of pellets cut and the thickness of the cutting layer. The input parameters are shown in Table 3. Figure 3 shows the positions of the number of different cut balls around the energy absorption tube, which are placed symmetrically. Figure 5 shows the relative position of the ball in the suction pipe under different cutting thicknesses.

Table 3 Two factors three horizontal orthogonal table

| Simulation of the order | Number of balls | Cutting thickness (mm) |
|-------------------------|-----------------|------------------------|
| 1                       | 3               | 4                      |
| 2                       | 3               | 6                      |
| 3                       | 3               | 8                      |
| 4                       | 4               | 4                      |
| 5                       | 4               | 6                      |
| 6                       | 4               | 8                      |
| 7                       | 6               | 4                      |
| 8                       | 6               | 6                      |
| 9                       | 6               | 8                      |
Figure 4 Schematic diagram of different cutting ball number positions

Figure 5 Schematic diagram of the ball’s position in the solid energy absorption at different cutting thicknesses

4. Simulation results and discussion

4.1. Stress-strain distribution

In the process of simulation of energy absorption, the ball can give along the suction tube axial displacement, ball extrusion materials, contact with endergonic pipe material under the extrusion of balls, squeezed metal began to produce elastic deformation, when the stress reaches the yield limit of metal materials, metal cutting layer began to slip, separation with the parent material. Then it flows out along the sphere of the ball. In the process of flowing out, it will rub against the sphere of the ball and slip again. Finally, it will form chips.

Figure 6 (a) Stress nephogram in the process of cutting energy absorption. (b) Equivalent strain nephogram in the process of cutting energy absorption

Figure 6 is one of the author's many simulation analyses results. The number of cutting balls is 4 and the cutting thickness is 8mm. It can be seen in FIG.5a that the stress is most concentrated in the front and both sides of the small ball, and radiates from the surrounding area. The stress gradually decreases,
indicating that the chip starts to form in the front of the small ball and is separated from the mother on both sides of the small ball. It is found in FIG. 5 b that the equivalent plastic strain of the energy absorption tube is mainly concentrated in the area where the ball has been cut and the energy absorption is concentrated in the area where the ball has passed.

4.2. Standard for energy absorption efficiency of ball cutting type energy absorber structure
In order to evaluate the energy absorption efficiency of the energy absorber, the efficient structure of the energy absorber can be evaluated from the cutting force and absorbed energy of the energy absorber, which should produce controllable deformation mode during the impact process, at the same time, the maximum energy absorption and the minimum cutting force should be achieved, and the cutting process load should be stable.

![Figure 7](image)

**Figure. 7** A schematic diagram of cutting force-displacement curve of energy absorber structure

In Figure 7, $F_P$ is the peak cutting force, $L_E$ is the effective cutting stroke, and $F_M$ is the average cutting force. The work done by the cutting force in the effective energy absorption stroke is $E_{absorbed}$ by the energy absorption tube. In order to ensure no damage during the train collision, the maximum impact force shall not exceed $F_P$, and the impact energy shall not exceed the energy absorption range $E$ of the energy absorption tube.

4.3. The influence of cutting thickness on the energy absorption of the ball cutting absorber structure
The cutting thickness was 4mm, 6mm and 8mm respectively for simulation analysis and experimental implementation.

![Figure 8](image)

**Figure. 8** (a) The cutting force-time curve; (b) absorbing energy-time curve with different cutting thicknesses when the number of balls is 3
According to Figure 8, Figure 9 and Figure 10, it can be seen that when the number of cutting balls is 3, 4 and 6, At 35ms, the cutting force at different cutting thicknesses basically reached its peak value, and then the cutting force decreased and was in a fluctuating state. At 75ms, the fluctuating state of the cutting force decreased and gradually became stable. At 175ms, that is, the ball has nearly reached the end of the suction tube, and then the cutting force starts to increase gradually. At this time, the ball is located at the connection between the anti-climbing plate and the energy absorption tube, where the cylinder of the energy absorption tube meets the anti-climbing plate. There is a large accumulation of stress and strain, and there may be chip accumulation, so the cutting force gradually increases.

In Figure 8, Figure 9, and Figure 10, it can be seen that when the number of balls cut is 3, 4, and 6, With the increase of cutting thickness, the peak cutting force and the steady cutting force increase. The smaller the cutting thickness is, the smaller the difference between the peak cutting force and the corresponding cutting force in the stable state is, and the fluctuation range in the stable state is smaller. The energy absorption trend of the energy absorption tube under different cutting thickness is consistent, which increases with the passage of time and gradually tends to be stable at last. With the increase of cutting thickness, the energy absorption of the energy absorption tube increases.

It is found that the energy absorbed is linearly related to the cutting thickness. When the number of cutting balls is 3 and 6, the absorption energy difference between the cutting thickness of 8mm and 6mm is obviously greater than that between the cutting thickness of 6mm and 4mm. However, when the number of cutting balls is 4, the energy difference between the cutting thickness of 8mm and 6mm is significantly smaller than the energy difference between the cutting thickness of 6mm and 4mm. In addition, under the same number of pellets, the fluctuation of the stationary load stage of different cutting thickness is similar, which indicates that the cutting thickness may not be the most important factor.
affecting the stationary load at this time. In terms of the absorbed energy, the cutting thickness has a greater contribution.

4.4. The influence of the number of balls on the energy absorption of the ball cutting absorber structure

The number of balls is 3, 4, 6 for simulation analysis and experimental implementation.

![Figure 1](image1.png)

**Figure.11** When the cutting thickness is 4mm, (a) the cutting force-time curve; (b) the absorbing energy-time curve of different Number of balls

![Figure 2](image2.png)

**Figure.12** When the cutting thickness is 6mm, (a) the cutting force-time curve; (b) the absorbing energy-time curve of different Number of balls

![Figure 3](image3.png)

**Figure.13** When the cutting thickness is 8mm, (a) the cutting force-time curve; (b) the absorbing energy-time curve of different Number of balls
In the same way, according to Figure 11, Figure 12 and Figure 13, it can be seen that when the number of cutting balls is 3, 4 and 6, at 35 ms, the cutting force at different cutting thicknesses basically reached its peak value, and then the cutting force decreased and was in a fluctuating state. At 75 ms, the fluctuating state of the cutting force decreased and gradually became stable. At 175 ms, that is, the ball has nearly reached the end of the suction tube, and then the cutting force starts to increase gradually. At this time, the ball is located at the connection between the anti-climbing plate and the energy absorption tube, where the cylinder of the energy absorption tube meets the anti-climbing plate. There is a large accumulation of stress and strain, and there may be chip accumulation, so the cutting force gradually increases.

It can be seen in Figure 11, Figure 12, and Figure 13 that when the cutting thickness is 4 mm, 6 mm, and 8 mm, with the increase of the number of balls, the peak cutting force and the steady cutting force increase. When the cutting thickness is 4 mm and 6 mm, and the number of cutting balls is 4, the difference between the peak cutting force and the corresponding cutting force in the stable state is the smallest, and the fluctuation range in the stable state is smaller. When the cutting thickness is 8 mm, the number of cutting balls is 3, which is the most stable. The energy absorption trend of the energy absorption tube under different number of cutting balls is consistent, which increases with the passage of time and gradually tends to be stable at last. With the increase of the number of cutting balls, the energy absorption of the energy absorption tube increases.

It is found that the energy absorbed is linearly related to the number of balls. However, when the cutting thickness is 8 mm, the cutting force and energy absorption of the number of cutting balls is 6, which are greatly deviated from the case when the cutting thickness is 4 mm and 6 mm. In addition, when the cutting thickness is the same and the number of cutting balls is 4, the fluctuation of the stationary load stage of the cutting process is minimal.

To sum up, in the case of this simulation, the cutting force and absorbed energy of the energy absorber structure increase with the number of cutting balls and the thickness of cutting, but the relationship between them is not simply proportional. This may be because the material to be cut is divided into several material units in the direction of the cutting thickness, they differ in their degree of damage in contact with the balls. Therefore, more simulation data with different parameters may be needed to verify the simulation data with only a few parameter values selected in this paper, and the equation relationship between them cannot be listed. Therefore, no in-depth study is conducted.

Figure 14 Chips of different cutting thicknesses (a) 4 mm; (b) 6 mm; (c) 8 mm
In fact, in the process of metal cutting, the metal material begins to produce elastic deformation after being acted on by the tool. As the tool continues to cut in, the stress and strain within the metal continues to increase. When the yield point of the material is reached, plastic deformation begins to occur and the metal lattice slips. As the tool continues to move forward, the stress reaches the breaking strength of the material, resulting in extrusion and chip formation. In the strict sense, cutting is similar to extrusion. Because cutting is the same as locally compressing the metal, causing the metal to slip along a direction of maximum shear stress, the squeezing of the ball in this paper is still called cutting. However, in the simulation of ball cutting, the ball chips produced less, especially with less cutting thickness and less chips. This is because in the material constitutive model of ABAQUS, the divided material units will fail when they reach the breaking strength, thus realizing the element deletion. In the cutting process of the tool, the material unit realized by the tool fails less, so the chip is more in the cutting process of the ball, the ball and the material unit contact deformation are more, so that it reaches the failure deformation is also more, so the chip is less. Figure 14 shows the chip at different cutting thicknesses, and the chip increases as the thickness increases. Figure 15, it can be found that the chip situation of different number of cutting balls: the chip does not increase with the number of balls. In 4 balls, the chip was the most, the fluctuation was the least and the most stable, and this can also be in the last section in the discussion of cutting force. The four balls, load is the most stable, the increase in chips indicates fewer units of material with complete failure, to cause a decline in the cutting force, the energy absorption decreases, but the degree of fluctuation will reduce, the endergonic process more stable. But these conclusions are based on a single factor. This simulation is based on the cutting thickness, the number of balls to comprehensively consider the degree of contribution.

5. Conclusions

(1) In this study, a new design of cutting type energy absorption structure is proposed. The ball cutting is used to improve the previous cutting tool type, and the research and simulation analysis are carried out by using nonlinear finite element software ABAQUS.

(2) The ball cutting absorbing mode has the advantages of strong absorbing ability, easy control of peak cutting force and controllable process of absorbing energy. The structural parameters of the ball cutting type energy absorption device have a great influence on the energy absorption efficiency, which can be improved by improving the structural parameters. In this paper, the number of ball and the cutting thickness are studied.

(3) The ball cutting type energy absorption device has a good application situation, and more parameters such as the material properties of the ball, the material properties of the energy absorption tube and the failure criteria are worth further exploring.

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