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Study on the energy absorption of the expanding–splitting circular tube by experimental investigations and numerical simulations

Jian Li, Guangjun Gao*, Haipeng Dong, Suchao Xie, Weiyuan Guan

Key Laboratory of Traffic Safety on Track of Ministry of Education, School of Traffic & Transportation Engineering, Central South University, Changsha 410075, China

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This paper presents experimental and numerical investigations of a new type of combined energy absorber which working on the principle of expanding and splitting of the circular steel tube. In the first phase of deformation the tube is expanded by the cylinder part of the die. Second phase of deformation characterizes splitting of the expanded part of the tube into strips along the initial sawcuts by the cone part of the die. The strips bend outwards with certain radius to the end of the second phase. Quasi static compression test shows that this type of energy absorber is completely feasible and the combined absorber has 95.34% higher maximal force in compare with absorber which uses only expansion process of deformation. Using this system of deformation, the total energy absorption is obtained by the three mechanisms: elastic–plastic bending of the tube, splitting of the tube wall and friction between the tube and the die. The effect of friction coefficient is studied by simulation, it is found that the effect on friction energy is significant but negligible on splitting energy and plastic energy.

1. Introduction

With the rapidly increasing number of traffic vehicles, the possibility of collision accident is becoming higher and higher. The caused casualties and property losses are huge, so the crashworthiness research of automobile, train, airplane and other means of transport draws more and more attention [1–3]. In the past few years, studies are focused on dissipating the impact kinetic energy with stable, ordered and controllable way, and reducing the damage to occupants [4]. Hence energy absorption structure is the core part of crashworthiness structure. For the extensive range of deformation modes, efficient energy absorption ability and bargain price, thin-walled structure has been widely used in the crashworthiness design of traffic vehicles [5–6].

Over the last five decades, much experimental, analytical and simulation work has been undertaken to investigate various energy dissipation mechanisms of thin-walled structure, such as axial collapsing [7–14], flattening [15–17], inversion [18–20], bending [21–22], expansion [23], splitting [24]. Each energy dissipation mechanism has its own characteristic, and also has the corresponding application in practice. In the present study, the mechanisms of expansion and splitting were subject of the investigations.

The energy dissipation mechanism of expansion of circular tube is widely studied for its stable maximal force and high energy absorption efficiency. The expansion of circular tube dissipates collision energy by elastic–plastic bending of the tube and friction between the tube and the die. Eddins [25] first proposed the expansion of circular as an energy absorption way, which may be applied to aircraft soft landing system. Daxner et al. [26] described two instability phenomena which affect the degree of deformation in the tube expansion process: (a) loss of global stability due to elasto-plastic 'concertina' buckling of the straight part of the tube, (b) diffuse necking caused by local loss of material stability in the conical part of the tube. Almeida et al. [27] studied the influence of process parameters, including wall thickness, shape, fraction and length of the conical section of the tubular parts, on the overall formability of tube expansion and reduction. Shakeri et al. [28] investigated the expansion deformation process of circular tube under axially quasi-static loading by experiment, numerical simulation and theoretical analysis, proposed a simple kinematical model for expansion of circular tube to predict the driving force, there were several assumptions in analytical model: (a) the material is regarded as rigid-plastic model, (b) there is no variation in tube thickness during expansion process, (c) horizontal and vertical axes are considered as the principal axes of stress and strain. It is found that numerical simulation and analytical model agree well with the experiment. Choi et al. [29] studied the effects of the variation of punch angles on the energy-absorbing characteristics of expansion tubes, and found that shear friction factor was inversely proportional to the punch angles, and a specific punch

* Corresponding author.

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angle existed at which the absorbed energy and expansion ratio remained constant. Karrech et al. [30] also proposed a analytical model for expansion of circular tube under tension to predict the driving force and validated through finite element analysis, the friction effect and the variation of contact pressure at the mandrel-tube interface, thickness along the expanded zone and yielding threshold due to material hardening were all taken into account in the analytical model. The influences of structural parameters of the expansion of circular tube on the driving force were analyzed in detail and it was found that the drawing force varies linearly with respect to the tube radius. A non-linear behavior in terms of friction coefficient, conical angle, and expansion ratio was demonstrated. By means of a comprehensive numerical and experimental investigation, Yang et al. [31] analyzed the deformation process of expansion of circular tube in detail. According to the deformation characteristic of the circular tube in expansion process, the deformation process of expansion of circular tube could be divided into three typical deformation modes: (a) tube tip-conical surface contact mode (T–C mode), (b) tube wall–conical surface contact mode (W–C mode), (c) tube wall–conical and cylindrical surface contact mode (W-CC mode), effects of tube dimensions and semi-angle of the die on steady-state force and energy absorption efficiency were also investigated and it was found that for tubes with the same thickness a larger semi-angle of the die leads to greater specific energy absorption capacity.

Splitting of thin-walled structure is an efficient energy dissipation mechanism, which is used to dissipate collision energy in many structures such as automobiles and trains. The splitting of thin-walled structure was first introduced by Stronge et al. [32], who pressed the square metal tube against a die and then the square tube was torn to absorb energy. They also identified several energy dissipation mechanisms: fracture energy associated with tube splitting and plastic deformation associated with the development of the curl and frictional work as the tube interacted with the die. Reddy et al. [33] investigated the behavior of splitting circular metal tubes under both quasi-static and dynamic condition and found that the tube split as a number of axial cracks formed and the end strips were bent outwards into curls. Such an energy dissipation system has a stroke of above 90% of the tube length although it is not as efficient as axial crushing or inversion mode. Based on the experimental work conducted by Reddy, Atkins [34] studied the number of cracks formed during axial splitting of ductile metal tubes and suggested that stable cracks would propagate as a result of competition between plastic flow and fracture. By means of experimental investigate and theoretical analysis, Huang et al. [35–36] studied the axial splitting and curling of circular and square metal tubes. By introducing pre-cutting slits at the lower end of each tube, the tube split axially and the strips curled outward with a certain radius at a constant force. Good agreement between experiments and theory was also obtained. Research results showed that split and curl of metal tube was an efficient and long stroke energy absorption devices. Recently, Jin et al. [37] proposed an analytical model for the steady-state axial cutting of circular tubes by a cutter with multiple blunt blades and with or without the presence of a curved surface profile deflector through the use of the principle of virtual power. The proposed analytical model was validated by experimental data and the effects of tube wall thickness, number of cutter blades, and extrusion diameter were investigated. A good correlation was found between the theoretical predictions and experimental observations. Chung et al. [38] investigated axial splitting of thin-walled aluminum tubes under the blast load by a special cutter, and plastic explosive was used to accelerate the circular extrusions onto a cutting die backed by a curved deflector. It was observed that localized plastic deformation and dynamic progressive buckling have a significant effect on structure during the cutting process. NikNejad et al. [39] derived some theoretical relations to predict the instantaneous axial force of the circular metal tubes during the splitting process under the axial compression, which could estimate the instantaneous axial load, maximum splitting load, steady force and curl radius of the tubes. Tanaskovic et al. [40] studied a type of absorber of kinetic collision energy that works on the principle of shrinking and splitting a tube of circular cross section. They found that combined method of energy absorption enables greater absorption power with compact dimensions.

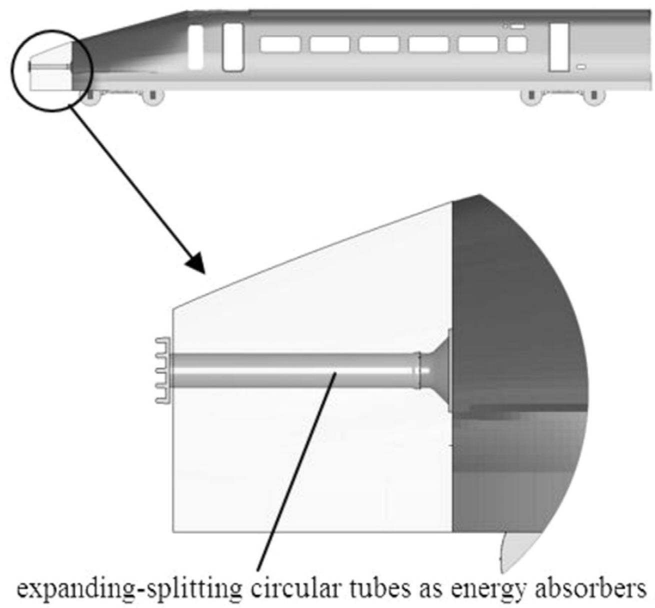

Fig. 1. Expanding–splitting circular tubes as energy absorbers in train structure.

As can be seen above, a lot of researches have been done on the expansion and splitting of thin-walled structure, but they all studied it separately. In order to increase the energy absorption and deformation stability of thin-walled structure under axial loading, this paper proposes a new type of energy absorber which combines expansion and splitting of a circular metal tube, the combined absorber dissipates kinetic energy by means of elastic–plastic bending/stretching, splitting and friction. Fig. 1 shows an example for the possible use of the expanding–splitting circular tube as energy absorber in train. Based on this, this paper designs a special metal circular tube and die, and carries out quasi static compression experiment. Then the details of the deformation processes are examined by using the explicit non-linear finite element software LS_DYNA. From the results of numerical simulation, the distribution of energy dissipation is discussed. Subsequently, the effect of friction coefficient on the energy absorption and energy fraction of each energy dissipation mechanism is studied.

From the previous research results and structural characteristic of the combined absorber, it can be found that the combined absorber has the following advantages: (a) Combined absorber gives stable deformation of the tube and approximately constant value of the force after reached maximum value to the end of the deformation process. (b) For the same circular tube structure, the ability of energy absorption of the combined absorber greatly increases when compared with expansion of the circular tube. (c) Since the circular tube is torn and curled after expansion, the effective stroke of the combined absorber in practical application can reach more than 90%. However, the max effective stroke of expansion circular is 50%, the effective stroke of collapse deformation is usually less than 70%. (d) There are two contact points