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Analysis and parameters optimization of an expanding energy-absorbing structure for a rail vehicle coupler

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ABSTRACT

This paper describes the energy absorption and crashworthiness optimization of an expanding structure under axial loading, which has been applied to a rail vehicle coupling device. An experiment was set up to study the energy absorption characteristics of the coupling device. Based on the structure of the device, a finite element (FE) model was established and validated by experimental results. The valid FE model was used to predict the responses of the expanding structure. A full factorial design and a central composite design of experiments (DOE) were used to take samples for the variables (friction coefficient (μ), thickness of deformable tube (T) and slope angle of conical mandrel (α)). Based on these samples, an approximation model was built with the moving least squares method (MLSM). Main effects analysis was performed with the full factorial design results and it was found that T had the most significant effect on the average force (F_{avg}), while α most influenced the specific energy absorption (*SEA*). Considering F_{avg}, fracture and buckling of the structure as constraints, parameters optimization was carried out using the adaptive response surface method (ARSM) to gain a higher *SEA*. Finally, the optimum parameters ($u = 0.25$, $T = 5.5$ mm, $\alpha = 34.5^{\circ}$) with the *SEA* value of 34.8 kJ/kg was obtained. The value of *SEA* increased by 45.55% compared with the initial results.

1. Introduction

With increasing railway speed, vehicle crashworthiness design has drawn more and more attention from researchers [1]. To protect passengers from injuries when collisions occur, various energy-absorbing structures have been designed and installed in unmanned areas of railcars [2–5]. Due to their significant advantages, thin-walled tubes are widely used as impact energy-absorbing structures. In recent years, circular tubes have received widespread attention due to their excellent energy dissipation characteristics [6]. Multiple experiments about deformation modes of circular tubes have been carried out, under axial and lateral loading [7]. Zhu [8] and Baroutaji [9] experimentally and numerically studied the deformation of circular tubes under lateral impact. The relation between energy absorption and impact position, geometrical factors were reported to describe the deformation characteristic. For the axial loading of circular tubes, different deformation modes, e.g. axisymmetric collapse [10–13], non-axisymmetric collapse [14–16], and inversion collapse [17,18] were investigated by researchers theoretically, experimentally and numerically. In addition, expansion of deformable tubes under axial compression is another efficient process for energy absorption [19]. The deforming process is comparatively steady and the impact forces are relatively smooth in the expansion of deformable tubes under axial compression compared with another collapse modes. For this reason, the expansion tubes are used as main energy absorption component for urban railway vehicle couplers.

The energy absorption characteristic of expansion tube has been widely studied by researchers. Yan et al. [20] proposed a theoretical analysis model that considered shear deformation brought by bending. Abri et al. [21] developed analytical and numerical models describing the expansion process of a thick-wall solid tubular based on kinematics and equilibrium conditions. Jakirahemed et al. [22] investigated the percentage contribution of process parameters namely punch angle, tube temperature and expansion ratio on energy absorption of thin walled tubes during expansion. The authors also found the tube buckled at lower punch angle and higher expansion ratio. Almeida et al. [23] found that friction plays a key role in the overall formability of tube expansion and reduction. A.C. Seibi et al. [24] conducted experimental and numerical studies on steel and aluminum tubes and observed a spring back phenomenon at the tip of the expanded tubes. Yang [25] experimentally and numerically investigated energy absorption capacity of circular 5A06 aluminum tubes which were flared and expanded by four different conical–cylindrical dies. In their study, an initial stage of the load–stroke curve with an oscillation, and then a steady-state force was found during the process. S. Chahardoli [26] introduced a

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new type of combined energy absorber that absorbs energy with expansion and folding modes of deformation. The authors found that the new energy absorber was of greater energy absorption than those of conventional absorbers.

Much of the researches on expansion tubes were focused on the energy absorption characteristic and the parameters influencing the energy absorption responses. However, there were little studies involving the crashworthiness optimization for mechanical devices comprising expansion tubes. Expansion tube is the most important absorber in the coupler of urban rail vehicle and the present study aimed to obtain the optimum configuration of the expansion tube for the coupler crashworthiness design with optimization method.

At present, the combination of experimental technique and finite element method (FEM) is widely adopted by researchers for the analysis and study of the thin-walled tubes. FEM is a powerful tool to study the energy absorption characteristic of mechanical devices. With the help of FEM, the factorial analysis can be conducted more easily. The design of experiment (DOE) is always adopted to conduct the factorial analysis, and furthermore the researchers can evaluate the main and interaction effects of the variables on the responses of the energy absorbing system with this method. The surrogate model method is an alternative method in industrial product design field, with which a large number of simulation calculations can be avoided. Researchers have widely employed this method to realize the optimization of energy absorbing structures. For the optimization of thin-walled tubes, several works [27–30] have been performed to maximize their energy absorption capacity with the method mentioned above.

In the present study, an expansion tube which was an important part of the coupler of urban rail vehicle was investigated experimentally and numerically. This paper aims to find an optimum configuration for the expanding energy absorbing structure. An impact test was conducted to study the energy absorption characteristic of the expanding structure under axial loading. Moreover, a finite element (FE) model referring to the impact test was developed and validated by the impact test results. An experimental design was created based on full factorial design to construct approximate model. Another design of experiment namely central composite design was used to provide a verification matrix to the approximate model. The thickness of the expansion tube (T), the slope angle of the conical mandrel (α) and the friction coefficient (μ) in contact condition were applied as independent variables. The specified energy absorption (*SEA*) and the average force (F_{avg}) were select as responses. Main effects of variables on *SEA* and F_{avg} were investigated based on the full factorial design results. In addition, single objective optimization was performed by considering F_{avg}, the fracture and buckling of deformable tube as constraints to obtain a maximum *SEA*.

2. Experimental test and FE simulation

2.1. Expanding energy-absorbing Structure

Circular expansion tubes have been widely used for energy absorption as part of a coupler, which is an important energy-absorbing structure on rail vehicles, as shown in Fig. 1. The expanding energy-absorbing structure consists of two parts, a deformable tube and a conical mandrel. With a flaring shape at the end, the deformable tube (350 mm long and 7 mm thick) fits well with the conical part of the mandrel (the slope angle of 32°). Also, a backstop is set in the front end of the conical mandrel to control the deformation mode. Fig. 1 shows the thickness T of the deformable tube, the inner radius r of the deformable tube, the outside radius R of the conical mandrel, and the slope angle α. The main geometry dimensions of the expanding energy-absorbing structure are listed in Table 1.

2.2. Experimental test

To investigate the impact behavior of the energy-absorbing structure, a crash test was performed, as shown in Fig. 2. A special device was designed to install the coupler specimen. The assembly was installed in front of the load-cell barrier so that the transient impact force test system could record the load force conveniently. A velocimeter was placed at the impact location to record the impact velocity of the test trolley. A high-speed digital camera was placed above the specimen to capture the deformation of the specimen during the impact process. A 2.96 t impact trolley pulled by a wire rope were released to impact the specimen. Considering the sufficient kinetic energy required for the deformable tube deformation, the authors designed the test speed as 8 m/s. At the moment of impact, the velocimeter recorded the velocity, which was 8.08 m/s. At the same time, the trigger system sent a signal to the high-speed photography system and the transient impact force test system.

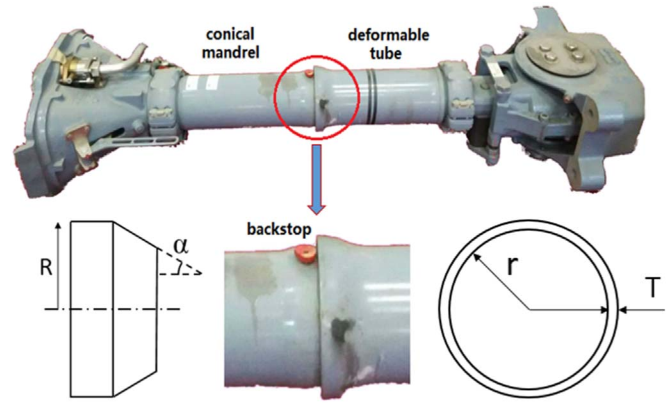

Fig. 1. Coupler specimen.

Table 1
Geometry dimensions of the specimen for experimental test.

Component	Parameters	Value
Deformable tube	Inner radius r (mm)	72
	Thickness T (mm)	7
	Section length (mm)	350
Conical mandrel	Maximum outer radius R (mm)	84
	Slope angle α (°)	32

2.3. Finite element modeling

The expanding energy-absorbing structure absorbs energy with a large expansion of the deformable tube. Apart from the deformable tube, the other parts of the expanding energy-absorbing structure showed little deformation during the expansion process, they were considered as rigid bodies. The nondeformable parts of the test specimen were not taken account into the finite element model except for the conical mandrel. Hence, the simplified FE model ignoring the backstop consists of a deformable tube, a conical mandrel and a rigid wall, as shown in Fig. 3. The rigid wall was used to substitute the test trolley. In this study, LS-DYNA, a nonlinear finite element dynamic analysis program, was used for numerical calculations. Because of the symmetry of geometry, loading and deformation modes, only 1/4 of the deformable tube and conical mandrel were modeled to reduce computation time, by applying appropriate symmetric boundary conditions at each unloaded edge of the 1/4 model. The base of the conical mandrel was fully fixed, a rigid wall, whose normal direction was parallel to the axial direction of the tubes, was set on the side of the deformable tube. The mass of the rigid wall was set to 0.74 t, which was equal to 1/4 of the quality of the test trolley, and was specified an initial velocity, 8.08 m/s, to simulate dynamic loading. Considering the characteristics of the deformation, 8-node brick element with one point