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Cut-out grooves optimization to improve crashworthiness of a gradual energy-absorbing structure for subway vehicles

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ABSTRACT

In this study, a new cut-out groove design is addressed, aiming to improve the crashworthiness of a gradual energy-absorbing structure for subway vehicles. First, the crashing characteristics of the gradual cut-out grooved energy-absorbing structure (GCGES) are studied and the finite element model (FEM) is validated by dynamic impact tests. Then, response surface (RS) models are established regarding the validated FEM. Based on RS models, the energy absorption (EA) and initial peak crushing force (IPCF) are formulated as functions of cut-out groove dimensions. In further, parametric studies are performed to evaluate the effects of design variables on collision responses. It is found that both EA and IPCF are negatively affected by the cut-out grooves. Particularly, the effect of design parameters on IPCF is obviously greater than that on EA capacity. To minimize the IPCF under the constraint of EA, optimization technology with adaptive simulated annealing (ASA) algorithm is adopted. The optimal results indicate that the IPCF decreases by 31.02% comparing with the initial designed GCGES and 63.60% comparing with the common flat surface energy-absorbing structure (FSES). From the vehicle safety view, the cut-out grooves are introduced successfully and the optimized GCGES is of considerable significance and advantages in crashworthiness application.

1. Introduction

The crashworthiness of subway vehicles has aroused significant concern in last several years. Research aiding the design of safer vehicle bodies has been one of the major topics of interest in the area of the structural design of railway vehicles in many countries [1–4]. Energy absorbing structures composed of thin-walled tubes have been widely applied to subway vehicles due to its excellent superiority in strength-weight ratio. It is fixed on the front end of crashworthy vehicles to dissipate the impacting energy to keep the safety of passengers and crew once collision accidents occurred.

To date, a plenty of works have been donated to study the impact characteristics of thin-walled tubes by using theoretical, numerical and current experimental methods. Unfortunately, there is not much relevant investigation reported in the literature about the energy-absorbing structures for subway vehicles. Only few papers can be collected in this aspect. In order to obtain optimum dimensional ratios, Javad and Mohammad [5] performed a numerical study of the crushing of thin-walled circular aluminum tubes to investigate their behaviors under axial impact loading. In further, a multiobjective optimization for vehicle crash energy absorption was performed for five crushing parameters using the weighted summation method. Xie and Zhou [6] designed a front-end energy absorbing structure based on integral analysis of the characteristics of a thin-walled metal structure and an aluminum honeycomb structure. The entire structure generated orderly and stage-by-stage deformation according to the crashing process. Recently, Peng et al. [7] studied the collision performance of a new composite energy-absorbing structure which was composed of thin-walled tubes and honeycombs for used in subway vehicles. The results showed that the proposed structure provided a controllable crashing pattern and greatly influenced by wall thickness and material of honeycombs. Yan et al. [8] presented theoretical prediction and numerical studies of expanding circular tubes which were used to connect two vehicles as energy absorbers. This kind of energy absorption device dissipates the impact kinetic energy through plastic deformation and friction.

The composed thin-walled structure performs mixed characteristics of thin-walled tubes with a large specific energy absorption (SEA) and progressively deform under impacting loads. However, the value of the initial peak crushing force which forms the first plastic hinge, is obviously much higher than the others. One way of achieving a desirable load uniformity and deceleration pulse could be obtained by introducing geometrical discontinuities in the form of grooves along the tube hence the maximum plastic moment and therefore the plastic hinges occur at these intervals [9]. To reach this target, Hosseinipour et al.

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[9–11] did some research on the grooved circular tubes by carrying out quasi-static axial crushing tests and theoretical method. They cut grooves alternately inside and outside of the tube and concluded that the load-displacement curve and energy absorbed by the axial crushing of tubes could be controlled by introducing grooves with different distances. In Ref. [9], they concluded that the resulting buckling mode is almost independent of other geometrical parameters. Grooves at short intervals force stable deformation in concertina mode, but they have no significant role in controlling deformation modes at longer intervals. In Ref. [10], they presented theoretical formulations for energy absorption and mean crushing load. The results indicated good agreement between the theory and experimental findings. Therefore the energy absorbed by the axial crushing of tubes could be controlled by the theory. Zhang and Huh [12] investigated the energy absorption characteristics of longitudinally grooved square tubes under axial compression. The grooves were fabricated by stamping and the distributions of the effective plastic strain and the thickness variation from the stamping process were considered in the crash analyses. They found that when grooves are introduced on the sidewalls, the specific energy absorption of conventional tubes can be increased and the peak force can be reduced. Recently, Darvizeh et al. [13] performed the characteristics of circumferentially grooved thick-walled circular tubes filled with low density and very low strength polyurethane foam typical of cushioning material. The obtained results showed that grooved thick-walled tubes filled with low strength foams can offer favorable energy absorption capacity and stability. Euler buckling is prevented due to the grooves and specific energy absorption is increased approximately twice that of the empty tubes. In Ref. [14], two design methods were addressed by Salehghaffari et al. to optimize the crashing performance of cylindrical metal tubes which suffered quasi-static loads. For one of the methods, a rigid steel ring was pressed fitted on top of circular aluminum tubes. For the other method, wide grooves were cut from the outer surface of circular tubes. The results indicated that the proposed design methods are efficient in improving crashworthiness characteristics and collapse modes of circular tubes under axial loading.

Optimization design, as a more practical design methodology, directs at addressing a number of design principles, which has become an attractive research topic in crashworthiness design lately [15,16]. With the application of surrogate models, optimization process could be more efficient. Tran et al. [17] studied triangular tubes with multi-cell on the aspects of theoretical prediction and crashworthiness optimization design under the impact loading. In the process of multiobjective crashworthiness optimization, Deb and Gupta method was utilized to find out the knee points from the Pareto solutions space. In aims to get enhanced crashworthiness and occupant protection, Reddy et al. [18] put forward a new strategy to improve energy absorption efficiency of thin-walled columns by introducing extra stable corners in the cross-section. Yin et al. [19] performed multiobjective optimization of two kinds of functionally lateral graded foam-filled tubes (FLGFTs), aiming to achieve the maximum specific energy absorption (SEA) and the minimum peak crushing force (PCF). The results indicated that the optimal FLGFT performs more excellent energy absorption characteristics than ordinary uniform foam-filled tube (UFT). Qi et al. [20] considered a class of axisymmetric thin-walled square (ATS) tubes with two types of geometries (straight and tapered) and two kinds of cross-sections (single-cell and multi-cell) as energy absorbing components under oblique impact loading and found that the multi-cell tapered (MCT) tube has the best crashworthiness performance. In addition, multiobjective optimization design (MOD) of the MCT tube is performed by adopting multiobjective particle swarm optimization (MOPSO) algorithm to achieve maximum specific energy absorption (SEA) capacity and minimum peak crushing force (PCF).

In general, the IPCF, formed due to the collapse of the initial plastic hinge, is equal to the PCF in a typical relationship of force versus displacement of axial crashing behavior with progressive folding [21]. When collision accidents happened, the IPCF is able to determine the occupant's survival rate; therefore, severe occupant's injuries or even death are caused by a large IPCF [22]. However, there was a limited literature referring the cut-out grooves application to the energy-absorbing structure composed of thin-walled tubes for subway vehicles.

Therefore, in this study, a gradual energy-absorbing structure with cut-out grooves (GCGES) is proposed. The structure is expected to present excellent energy absorption capacity, desirable load uniformity and stable deformation by employing gradual stages design method and cut-out grooves fabrication. The crashing performance of this new designed structure under dynamic impact loads is modeled in LS-DYNA software package and the finite element model (FEM) is validated using experimental results. After the verification of the FEM, response surface (RS) models are established to formulate the mathematical relationship between the crashworthiness responses and cut-out groove dimensions. In addition, the effects of design variables on the evaluation indicators are analyzed through parametric study. Finally, adaptive simulated annealing (ASA) algorithm is selected as optimizer to seek for optimal configurations of cut-out grooves, aiming to improve the crashworthiness of the GCGES. Thus, the optimal design of GCGES which may present an excellent crashworthiness performance could be obtained.

2. Methods

2.1. Details of the structure

Fig. 1 shows the gradual cut-out grooved energy-absorbing structure (GCGES) which is typically fixed to the front end of subway vehicles. The energy-absorbing structure is connected by welding of a front-end beam, rear-end plate, outer-side beams, inner-side beams, cross beams and longitudinal beams with rectangular cross-section [23]. Particularly, cut-out grooves are fabricated in each single tube (see Fig. 1). The local resection of each edge is made to reduce the material of grooves. The geometric parameters of cut-out grooves are longitudinal dimension (A), lateral dimension (B), vertical dimension (C) and groove depth (D). For each design variables, the initial values are 40 mm, 15 mm, 30 m and 6 mm, respectively. In general, the GCGES is designed in four stages to keep orderly deformation and stable energy absorption with symmetrically in the lateral direction. In the process of dynamic impact, the number of longitudinal beams increases gradually from the initial stage to the last stage. Specially, when the structure impacts with the rigid wall directly, the cut-out grooved longitudinal beams will suffer axially impact loads. Meanwhile the outer-side beams and inner-side beams will suffer oblique impact loads.

2.2. Structural crashworthiness indexes

In aims to assess the crashing performance of the GCGES, structural crashworthiness indexes ought to be defined. The important indexes, e.g. energy absorption (EA), initial peak crushing force (IPCF), peak

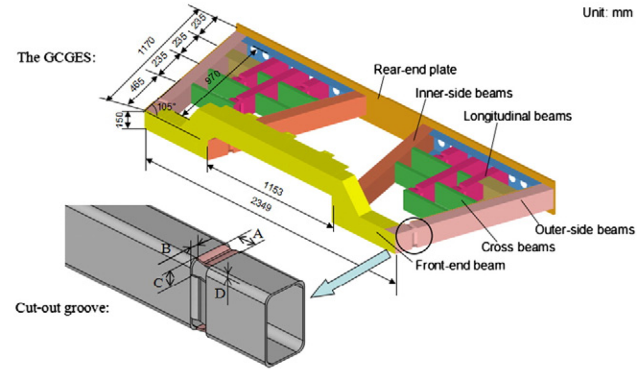

Fig. 1. The GCGES with detailed cut-out grooves for subway vehicles.