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Multiobjective crashworthiness optimization of hollow and conical tubes for multiple load cases

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ABSTRACT

Much attention of current design analysis and optimization of crashworthy structures have been largely paid to the scenarios with single load case in literature. Nevertheless the designed structures may often have to be operated in other load conditions, thus raising a critical issue of optimality. This paper aims to understand and optimize the dynamic responses and energy absorption of foam-filled conical thin-walled tubes under oblique impact loading conditions by using multiobjective optimization method. The crashworthiness criteria, namely specific energy absorption (SEA) and crushing force efficiency (CFE), are related to loading parameters and design variables by using D-optimal design of experiments (DoE) and Kriging model. To obtain the optimal Pareto solutions of hollow and foam-filled conical tubes, design optimization is first performed under different loading case (DLC) using multiobjective particle swarm optimization (MOPSO) algorithm separately. The optimal designs indicate that hollow tube has better crashing performance than the foam-filled tube under relatively high impacting velocity and great loading angle. To combine multiple load cases (MLC) for multiobjective optimization, a double weight factor technique is then adopted. It is found that the optimal foam-filled tube has better crashing performance than empty conical tube under any of overall oblique loading cases concerned. The study gains insights in deriving multiobjective optimization for multiple load cases, providing a guideline for design of energy absorber under multiple oblique loading.

1. Introduction

Design optimization signifies a key area of rapid development in automotive industry over the past two decades. On the one hand, energy crisis and environmental concerns place higher and higher requirements in lightweight and usage of materials and fuels. On the other hand, socioeconomic and healthcare demand raises tighter and tighter technical requirements in road safety. The former typically reduces weight and save space, while the latter often needs to go an opposite way. For this reason, crashworthiness design of vehicular structures and components draw considerable attention and major effort has been made to balance them by maximizing the energy absorption and minimizing impact forces with minimum weight. In this regard, thin-walled structures have proven fairly effective and been widely studied and employed in vehicles. Some of the simple structural elements include straight columns with circular [1–3], square or rectangular [4–6] cross-sections [7]. To enhance the energy absorption capacity without too much weight penalty, foam filler is considered effective because it allows undergoing large deformation at a nearly constant load under severe crushing load [8–21]. Recently, increasing attention has been paid to explore the optimal configurations of new foam filled thin-walled structures for further improving crashworthiness [22–29].

Comparing with those abovementioned straight tubes, conical tubes have been considered more preferable as an energy absorber because they can provide a more stable crush response and smaller peak impact force [30]. Its probability of buckling collapse is relatively low in an impacting angle ranging from 5–15° [31,32]. From the previous study, a circular conical tube was reported more effective in yielding a progressive folding deformation than the square or rectangular counterparts [33,34]. Thus a combination of conical tubes with foam filler appears attractive to enhance crashworthiness. For example, Gupta et al. [35] investigated the impacting responses of a foam filled conical composite tube, and they found that the energy absorption of foam filled conical tube was greater than the empty counterparts. Ahmad et al. [36,37] studied the crushing response of foam-filled conical tubes under quasi-static and dynamic axial loading, and they revealed that the energy absorption of foam filled conical tubes was high and the

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deformation was stable. Hou et al. [38] compared the optimizations of different conical circular tubes with and without foam fillers, and they identified the advantages of foam-filled tapered tubes over other configurations. More recently, Song et al. [39] explored the different surrogate modeling techniques for design optimization of foam-filled squared tapered tubes.

The abovementioned studies focused on the crushing response and design of foam-filled columns for straight axial loading. In real life crashing event, nevertheless, a vehicle rarely encounters either completely axial or transverse loads, but rather happens in a combination of oblique (or off-axis) impacting direction. To take into account the effect of oblique loading, Han and Park [40], for example, analyzed the crush behavior of square column subjected to oblique loads, and they found that loading angle played an important role from the axial progressive collapse mode to the global bending mode. Reyes et al. [17,41,42] investigated the empty and foam-filled square columns under the quasi-static oblique loading conditions and they showed that the energy absorption decreased as loading angle increased. Nagel and Thambiratnam [43–45] explored the energy absorption characteristic of tapered thin-walled rectangular tubes, and found better stability than the straight tube when the oblique impact occurred. Hosseini-Tehrani et al. [46,47] studied crushing behaviors of polygonal and tapered tubes subjected to oblique loads. Liu [48] studied crash characteristics of truck chassis under different impact scenarios. More recently, Ahmad et al. [38] demonstrated the advantages of using foam-filled conical tubes as energy absorbers under oblique loads. Qi et al. [49] performed multi-objective optimization for the multi-cell tapered square tubes under oblique impact loading. Tarlochan et al. [50] demonstrated the merit of multicriteria design of different thin-walled tubes under axial and oblique loads. Yang and Qi [51] explored empty and foam-filled square columns under oblique loading and found that optimum was different under different loading. Despite such analyses and designs for oblique impacting loads, a real vehicle crash can also occur at different impact velocities, which influence crashworthiness as well. There has been lack of how to deal with oblique loadings at different impact velocities and few have considered multiple load cases altogether for design analysis and optimization.

Note that while design optimization enables us to enhance safety of occupants and crashworthiness of vehicle to a considerable extent, significant challenge remains to consider unpredictability of crush, including crushing direction and velocity etc. Under different impact conditions, crashing performance may differ drastically and the optimality for one loading condition may not be held for other loading conditions [52]. From design perspective, an optimized crashworthy structure is expected to accommodate not only a single loading case (SLC), but also multiple load cases (MLC). For this purpose, this paper will first explore different SLC (DLC) based designs and then explore multiobjective optimization for MLC.

2. Finite element modeling for crashworthiness analysis

2.1. Finite element modeling

Fig. 1 shows a schematic for the foam-filled conical thin-walled tubes subjected to an oblique loading. The length of the tube is considered $L=230$ mm [18,49], the diameter of bottom end of the conical tube remains unchanged at $D_b=80$ mm [32,37,49]. The diameter of the top end ($D_t=2R_t$) can be varied with the taper angle θ. The oblique impacting load is applied from the rigid wall with different incident angle α and impacting velocity v. To generate enough kinetic energy similarly to vehicular crashing, an additional mass of 200 kg is attached to the rigid wall. The bottom end of conical tube is fixed in the ground. Such geometry is determined from typical dimensions of the front rail of a passenger car given in literature [53].

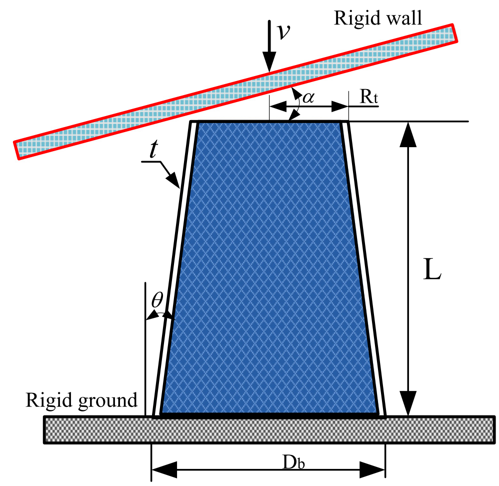

Fig. 1. Schematic of the conical tube with foam-filler subjected to oblique and multiple load conditions.

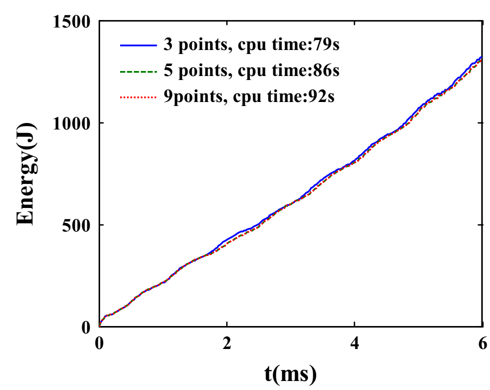

Fig. 2. Energy–time curves for empty tube with 100 km/h impacting velocities and different integration points.

LS-DYNA was used to analyze the crashing behavior and energy-absorbing capacity of the taper tube. The tube was modeled using the Belytschkoe–Tsay shell elements with three integration points across the thickness and one integration point in the element plane. To validate the convergence of different integration points across the thickness, Fig. 2 shows the energy absorption performance of different integration points with the same time history.

It can be seen that the energy absorption curve of these different integration points is very close. The maximum energy absorptions for the three, five and nine integration points are 1320J, 1314J and 1314J, respectively. Clearly, the three integration point elements are already sufficient accurate for simulation analysis. At the same time, the computational time using the 3 integration point elements reduced about 10% than the 5 integration point. Therefore, the elements with three integration point across the thickness were chosen by considering the computational cost and simulation accuracy. A similar result was also obtained in reference [54].

The aluminum foam was modeled using 8 node solid elements with the reduced integration techniques and hourglass control to avoid volumetric locking and spurious zero energy deformation modes [55]. Borvik et al. [56] suggested that twice of tube shell mesh size should be adequate to model the foam-filler materials, therefore, the element size of 2 mm and 4 mm were adopted for