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Multi-objective crashworthiness optimization of tapered thin-walled tubes with axisymmetric indentations

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ABSTRACT

In this paper, the effects of tapering and introducing axisymmetric indentations on the crash performances of thin-walled tubes are investigated. The crash performances of the tubes are evaluated using two metrics: the crush force efficiency (CFE, the ratio of the average crushing load to the peak load), and the specific energy absorption (SEA, absorbed energy per unit mass). The optimum values of the number of the axisymmetric indentations, the radius of the indentations, the taper angle and the tube thickness are sought for maximum CFE and maximum SEA using surrogate based optimization. In addition, multi-objective optimization of the tubes is performed by maximizing a composite objective function that provides a compromise between CFE and SEA. The CFE and SEA values at the training points of surrogate models (metamodels) are computed using the finite element analysis code LS-DYNA. Polynomial response surfaces, radial basis functions, and Kriging are the different surrogate models used in this study. Surrogate based optimization of the tubes showed that the tubes with indentations have better crush performance than tubes without indentations. It is found that maximum CFE requires large number of indentations with high radius, small thickness, and medium taper angle, while maximum SEA requires small number of indentations with low radius, large thickness and small taper angle. It is also found that the globally most accurate surrogate model does not necessarily lead to the optimum.

1. Introduction

The driver and passenger safety are crucial elements in design of automotive structures. The main goal of the designers in the automotive industry is to design crashworthy vehicles. Energy absorbing elements (e.g., shotguns, side rails) are mainly responsible for providing the safety of both the passengers and the critical vehicle components. These elements convert the crash energy into strain energy through structural deformation. Although many different types of energy absorbers exist, the thin-walled tubes are the most common energy absorbing elements.

Crushing behavior of thin-walled tubes has been investigated by many researchers. These studies have mainly focused on tubes with cylindrical and square cross-sections [1,2], while other types of cross-sections are also investigated [3]. The tubes can be straight or tapered. For straight tubes, the tube side-walls are parallel to the tube axis. The straight tubes tend to buckle, which reduces the energy absorbing capability [4]. Therefore, tapered tubes are preferred over straight tubes, since they provide constant mean load-deflection response and are good at withstanding oblique impacts as well as axial loads [5]. The energy absorption characteristics of tapered tubes under impact loading were investigated by Nagel and Thambiratnam [6]. They studied the effect of the number of tapered sides and the wall thickness on the energy absorption behavior. In addition to tapering the tubes, several other design strategies have been suggested in literature including introducing geometrical discontinuities or imperfections in the form of indentations, grooves, dents, holes corrugations [7–15]. All these aforementioned studies have been focused on analyzing the effect of tapering or geometrical discontinuities only. This paper aims to analyze the effect of tapering and geometrical discontinuities on the crash performance of tubes.

The crush forces generated during the axial impact is one of the important parameters to be considered in designing the energy absorbers. For an energy absorber, it is not sufficient to maximize the absorbed energy, but the amount of the crush force must also be decreased for the safety of both the passengers and the crashworthiness of the vehicle components. The initial peak crush force should be reduced as much as possible. Therefore, both peak crush force and energy absorption values should be

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investigated in determining the efficiency of a crush absorber. For example, Jin and Altenhof [16] studied the efficiency of the round and square extrusions under a cutting deformation by calculating the crush force efficiency (CFE) and specific energy absorption (SEA). CFE can be defined as the ratio of the mean crush force to the peak crush force. SEA may be defined as the energy absorption per unit mass, which is an important parameter for the applications in which the weight of the structure is also crucial. Therefore, specific energy absorption value should be controlled and the energy absorber should be examined with respect to its weight efficiency [17].

The main objective of this study is to investigate the effect of various geometrical parameters such as wall thickness, semi-apical angle (i.e., taper angle), and properties of geometrical discontinuities on the energy absorption characteristics of thin-walled structures. This analysis can be performed using experimental and numerical techniques. Since experiments are expensive and time consuming, finite element simulations are generally used in automotive industry. In this study, a commercially available explicit dynamic finite element (FE) analysis code LS-DYNA [18] is used to simulate the collapse behavior of the thin-walled tubes under axial impact loading. The finite element models were validated by the previously established solutions from literature, which allowed several designs to be analyzed without having to build and test several prototypes.

In this study, the optimum values of the geometrical parameters and the properties of geometrical discontinuities are sought for maximum crush force efficiency and maximum specific energy absorption. The main challenge in crashworthiness optimization is the extremely high computational costs of crash simulations. To overcome the computational challenge, researchers have focused on using surrogate models (or metamodels) that can mimic the behavior of the simulation model as closely as possible while being computationally very efficient to evaluate. Crashworthiness optimization for whole vehicles or their components using surrogate models has been performed by several researchers (e.g., [19–26]). Focusing mainly on energy absorption performances of thin-walled tubes, Refs. [27–33] used surrogate models to perform crashworthiness optimization of the tubes. In this study, surrogate based optimization of the tubes are performed to determine the optimum values of the number of the axisymmetric indentations, the radius of the indentations, the taper angle and the tube thickness for maximum CFE and maximum SEA. In addition; multi-objective optimization of the tubes is performed by maximizing a composite objective function that provides a compromise between CFE and SEA.

The paper is structured as follows. The next section provides the problem description of the crash performance optimization of the tapered thin-walled tubes with axisymmetric indentations. Section 3 presents the details of the finite element analysis of the tubes. Section 4 discusses surrogate model construction. The results of the optimization problem are given in Section 5, followed by the concluding remarks given in Section 6.

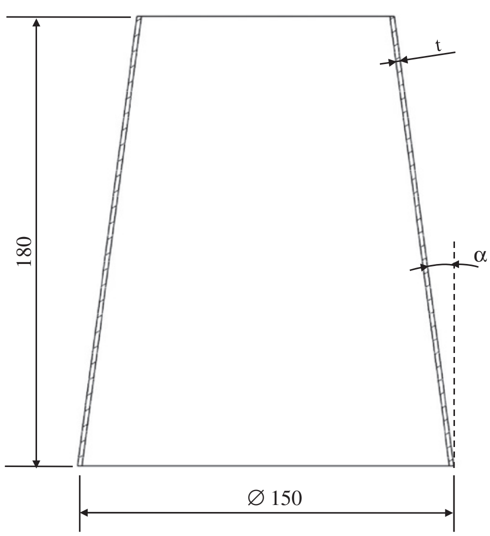

Fig. 1. The geometry of the thin walled tube (without axisymmetric indentations) having circular cross-section. The dimensions are in millimeters.

2. Problem description

The thin-walled tubes having circular cross sections have been modeled with and without axisymmetric indentations as shown in Figs. 1 and 2, respectively. The tubes have a largest diameter of 150 mm, and a length of 180 mm. For the crash performance of tubes, the following design problem is considered. The tubes are impacted with a 1500 kg rigid wall with an initial velocity of 9 m/s (see Fig. 3). This would generate an initial kinetic energy of 45 kJ in accordance with ECE R-29 requirements for trucks.

The tubes should be designed for maximum crash performance, which is evaluated by two metrics (CFE and SEA). The variables that can be tailored by a designer are chosen as the followings: (1) the tube wall thickness, t; (2) the taper angle, (α); (3) the radius of axisymmetric indentations, R_i; and (4) the number of indentations, N_i. Thus, optimization problem for maximum CFE (or maximum SEA) can be stated as

Find t,α,N_i,R_i
Min -CFE(or-SEA)
Such that $1\,\text{mm} \le t \le 2.5\,\text{mm}$

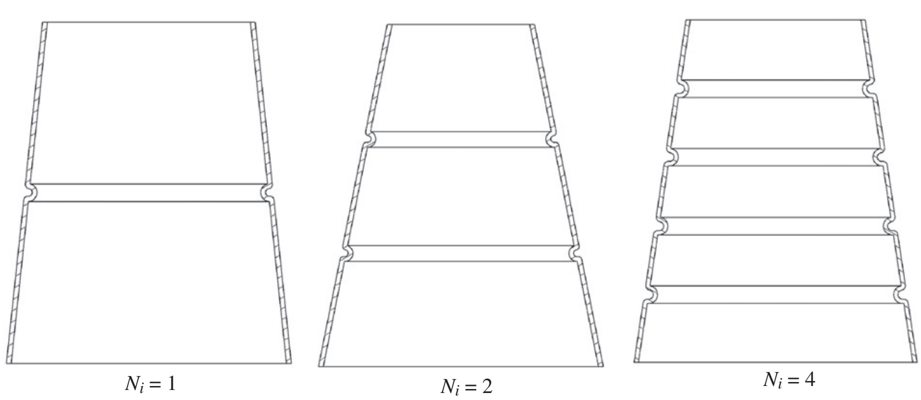

Fig. 2. The geometry of the thin walled tube (with axisymmetric indentations) having circular cross-section.