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Optimal shape design of thin-walled tubes under high-velocity axial impact loads

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ABSTRACT

In this study, the objective is to maximize the crashworthiness of thin-walled tubes under axial impact loads by shape optimization. As design variables, parameters defining the cross-sectional profile of the tube as well as parameters defining the longitudinal profile like the depths and lengths of the circumferential ribs and the taper angle are used. The methodology is applied to the design optimization of a crash-box supporting the bumper beam of a vehicle for the loading conditions in standard EuroNCAP crash tests. The crash event is simulated using explicit finite element method. While the crash-box is fully modeled, the structural response of the remaining parts during the tests is taken into account by developing a lumped-parameter model. A hybrid search algorithm combining Genetic and Nelder & Mead algorithms is developed. The results indicate significant improvement in the crashworthiness over the benchmarks designs.

1. Introduction

Thin-walled tubular structures are preferred in applications requiring high performance under impact loadings. In automobiles, thin-walled tubular parts are used to absorb impact energy in a potential crash. These parts should be designed to minimize the damage to the main parts of the vehicle and protect the occupants from injury by absorbing the collision energy. Their effectiveness in preventing injury under such impact loads is called crashworthiness. The performance of these parts can be significantly improved by optimizing their shapes.

There are a number of studies in the literature on the optimization of tubes made of metals (usually steel and aluminum) under axial impact loading. In these studies, tubes are considered as either empty [1–14] or filled [12,15–23]. Yamazaki and Han [1] studied square and cylindrical tubes hitting a rigid wall with a velocity of 10 m/s. They maximized the total energy absorption while maintaining the mean crushing force at a certain limit by varying the thickness of the tube and the section radius. Lee et al. [2] studied tubes with circular cross-section hitting a rigid wall with a velocity of 10 m/s and additional mass of 500 times the mass of the tube. Their design parameters were the wall thickness, radius, and length of the tube. Sheriff et al. [3] used the bottom diameter, height, and taper angle as design variables to maximize the total energy absorbed in circular cross-section tubes. Avalle and Chiandussi [4] optimized cylindrical tubes with tapered tip for uniform reaction force distribution. They varied the length of the tapered tip and the tip diameter. Hou et al. [5,6] optimized square and hexagonal single-cell and multi-cell tubes using base dimensions and thickness as design variables for minimum peak force and maximum specific energy absorption, i.e. energy absorption per unit mass. Acar et al. [8] varied taper angle and number of ribs on the surface in order to maximize the ratio of the mean crush force to the peak force and the specific energy absorption. Qi et al. [9] analyzed single and multi-cell square tubes under oblique impact. Their objective was to increase the specific energy absorption and minimize the peak crushing force by changing the taper angle and the wall thickness. Liu [10] optimized the wall thickness and the side length of a box-shaped column to maximize the specific energy absorption with a constraint on the peak force. Liu [11] considered straight and curved octagonal and hexagonal tubes and selected the side length and the wall thickness as variables. The objective was to maximize specific energy absorption of the columns while constraining the peak force. Yang and Qi [12] studied empty and filled tubes with a square cross-section under axial or oblique impact. Their objective was to increase the specific energy absorption and minimize the peak crushing force by varying the wall thickness, cross-section width, material yield strength, and filler material density. Zarei and Kröger [13] optimized empty cylindrical tubes by taking their length, diameter, and thickness as design variables for increased total energy and specific energy absorption. They extended that study to tubes filled with honeycomb [16] and foam [17] by considering their densities as variables. Kim and Arora [14] studied representation

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of tapered tubes with uniform ones with square-sections in the force–displacement domain. With these force representations, a model with a single degree of freedom that simplified the analysis of the tube structure was identified. Santosa and Wierzbicki [15] studied the axial crushing resistance of a square-box column filled with aluminum honeycomb or foam under quasi-static loading conditions. Sun et al. [20] optimized crash-boxes with functionally graded foams for maximum specific energy absorption and minimum peak force. They assumed the foam material as layered and they varied the density of these layers. Hanssen et al. [18] used formulas derived based on experimental data relating design parameters to average force, maximum force, and stroke efficiency in order to obtain optimum designs of columns for minimum reaction force and maximum energy absorption. Ahmad and Thambiratnam [19] conducted a parametric study on empty and foam-filled tubes under axial impact loads using the wall thickness, taper angle, foam density, impact mass, and impact velocity as variables. Yin et al. [21] studied honeycomb-filled single and bitubular polygonal tubes. The variables were the wall thickness and the side length. The objective was to maximize the specific energy absorption and to minimize the peak force. Bi et al. [22] studied foam-filled single and multi-cell hexagonal tubes, which were crushed under a rigid wall moving downward with a velocity of 2 m/s and penetration depth of 100 mm. The variables were chosen to be the wall thickness and the side length of the section, and the foam density. The objective was to increase the specific energy absorption while keeping the mean crushing force larger than a certain limit to ensure a certain structural rigidity. Tarlochan et al. [23] conducted a parametric study on foam filled tubes under axial and oblique impact loading. They compared tubes having circular, square, hexagonal, octagonal, ellipsoidal cross-sections with the same circumference in terms of energy absorption and crush force efficiency.

The previous researchers generally developed approximate expressions for the objective functions using response surface methodology [1–6,8–11,13,16,17,20–22], Kriging [12], moving least-squares approximation [14], and artificial neural network [7]. After obtaining the surrogate models, they used genetic algorithms [3,16,17], leap-frog [7], particle swarm optimization [9,20,12,21], non-linear programming [5,6,8], or multi-first order method [4] as search algorithms.

The cross-sectional shapes of the tubes considered by the researchers were circular [1–4,8,13], square [1,5,7,9,10,12,16–20], hexagonal [6,11,21–23], or octagonal [11,21]. Some of the previous studies focused on straight columns with uniform cross-section along the length [1,2,5–7,9–13,16–18,20–22], some of them introduced taper angles [3,4,8,19], and some [8,7,16,17] introduced ribs with predefined shapes.

In the present study, a larger number of geometric parameters are used as optimization variables in comparison to the previous studies. The parameters defining the shape of the cross-sectional profile (the coordinates of key points defining the spline curves) and the longitudinal profile (depths and widths of the circumferential ribs, and the taper angle), and the wall thickness are varied. To the authors' knowledge, the shapes of the ribs are optimized for the first time in this study; in the previous studies, on the other hand, they were taken as constant. The ribs can be inward or outward. The taper angle can be positive or negative. Besides, the loading conditions considered in almost all the previous studies were either drop tests i.e. an object being dropped on a column, or a column with a mass at the rear hitting a rigid wall. In this study, the methodology developed for the optimum shape design of tubular structures is applied to the crash-boxes (or brackets) holding the bumper beam of a vehicle. The behavior of the crash-box is simulated for the loading conditions in a standard high-speed crash test, European New Car Assessment Program (EuroNCAP). Because of the difficulty in modeling the whole car and the resulting long computational times, a lumped-parameter car model is developed that accounts for the structural behavior of the main body of the vehicle as well as the parts in front of the crash-box. Moreover, in this study, a hybrid of genetic algorithm (GA) and Nelder–Mead algorithm is developed to find the globally optimal design or a near global optimal design.

The goal of global design optimization is to find the design with the best possible performance. This requires a definition of the geometric design that allows significant changes in shape, i.e. the solution domain should be large so that it includes the designs leading to the highest possible levels of performance. This means the number of geometric parameters and the range of values that can be assigned to these parameters by the search algorithm should be large. Global shape optimization of a vehicle for maximum crashworthiness is infeasible considering the high number of interacting parts, the high number of parameters used to define their geometries, and complex interactions among them during crash. This is beyond the capabilities of the current state-of the-art computers and search algorithms. Considering the computational effort to simulate crushing of the whole vehicle, it is not possible to find the globally optimum design within such a large solution domain and with such a large number of design variables even if a powerful global search algorithm is used. If large changes are allowed in the values of the optimization variables during optimization, the accuracy of surrogate models will also be questionable even for a single part let alone the whole vehicle. Besides, if the individual parts are separately optimized, loading conditions on them will be different from that of a drop test. That means the shape of a part optimized for the loading conditions in a drop test will not be optimum for the loading conditions in a real crash test.

The procedure suggested in this study to surmount these problems is the following: individual parts of the vehicle are optimized via a reliable global search algorithm by using a high number of design variables and allowing large changes in the values of these variables. The remaining parts of the vehicle are modeled with a system of lumped masses, springs, and dampers using parametric system identification, therefore computational times will not be prohibitively long. At the last stage, the whole vehicle is optimized starting from the optimized shapes of the individual parts, but this time the ranges of values that can be assigned to the variables will be small and some of the parameters may be taken as constant. Then, it becomes feasible to develop a reliable surrogate model for the vehicle and perform optimization. In this study, modeling and design optimization of a single part, a crash-box, is considered.

2. Problem statement

The main objective of this study is to develop a methodology to obtain the optimum shape design of thin-walled tubes subjected to high-velocity axial impact loads. The specific structure considered in this study is the bracket that supports the bumper beam of a car. Two brackets hold the bumper beam at two sides. They are in turn fixed to the main frame of the car. The types of obstacles that bumper-beam-crash-box system endures during frontal impact are countless. However, they can be categorized into three major divisions: full frontal collision, offset frontal collision, and pole frontal collision. The harshest collision that a bracket endures is the offset frontal impact, where one of the brackets takes the impact energy. Accordingly, the crash-box is optimized for offset collision conditions in accordance with EuroNCAP, IIHS, ANCAP standard tests, where the vehicle hits a wall with 40% offset and 64 km/h speed (See Fig. 1). At such high speeds, a car incurs substantial damage, but it is crucial that the occupants do not