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Cross-sectional shape optimization of thin-walled columns enduring oblique impact loads

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ABSTRACT

This study aims to find the best cross-sectional shapes of thin-walled columns enduring an oblique impact loading for crashworthiness. For approximating to the shape, spline polynomials are used with four key-points benefiting from the double symmetry of the cross section. Crashworthiness is defined by using a multi-objective function. By using Latin hypercubes design of experiment methodology, the design space is sampled. Based on the finite elements analyses, the objective functions are approximated by adopting radial basis function network. The corresponding Pareto front is found by Non-dominated Sorting Genetic Algorithm II. It is found that plus-sign-like cross-sections have better performance than benchmarks for all objectives.

1. Introduction

Some engineering applications need high-performance thin-walled structures under an impact loading. Keeping the damage localized in these parts is usually the main objective in their design. One of the most important usages of these structures is to use them as passive safety measures in vehicles. Thus, protecting the occupants is expected by taking the collision energy if they are a structural member in a car experiencing a collision. During a crash, thin-walled columns suffer from not only pure axial or bending loads but also combinations of them. Cross-sectional shapes may play an important role in crashworthiness. Most investigations to date have focused on certain cross-sections such as circular, square, and hexagonal. Hence, there is a need for a comprehensive optimization study of the cross-sections of the columns sustaining an oblique impact loading.

The literature on the thin-walled columns is rich. However, many of them consider axial impact loads. One of the most important books in axial impact is Jone's book [1]. Yamazaki and Han [2] worked circular and square tubes to maximize total energy absorption (TEA) while restraining average crushing force by using the diameter as well as the thickness of tubes. Lee et al. [3] investigated circular tubes with design parameters of diameter, length, and thickness. Sheriff et al. [4] changed height, diameter, and taper angle as parameters for maximum TEA. Avalle and Chiandussi [5] studied circular tubes having tapered tip to make the reaction force uniform by varying the tip diameter and its length. Hou et al. [6,7] worked on single and multi-cell hexagonal and square tubes taking thickness and length of the cross-section as variables for minimum peak force (PF) and maximum specific energy absorption (SEA). With the purpose of maximizing both SEA and ratio of the average crushing force over the PF, Acar et al. [8] studied the tubes using a number of ribs and taper angle. Qi et al. [9] conducted a study about square single and multi-cell tubes for minimizing the PF and maximizing the SEA by varying wall thickness and taper angle under oblique impact. Side lengths and wall thicknesses of a box-shaped column, and straight and curved hexagonal, and octagonal columns were the variables of Liu's [10,11] studies for maximizing the SEA while restraining the PF.

Empty and filled square tubes enduring an axial or oblique impact were investigated by Yang and Qi [12] for increasing the SEA and decreasing the PF by changing the density of the filler material, the yield strength of the material used for the column, cross-section width, and the wall thickness. Empty cylindrical tubes were optimized by Zarei and Kröger [13] by assuming their length, radius, and thickness as parameters for maximal TEA and SEA. In addition, they studied honeycomb-filled [14] and foam-filled [15] tubes by varying their densities. Kim and Arora [16] worked on tapered columns to develop a single-degree-of-freedom model for simplified analysis. Santosa and Wierzbicki [17] examined resistance of honeycomb or foam-filled tubes with the square shape to axial crushing. Crash-boxes filled functionally graded foams were optimized by Sun et al. [18] to minimize PF and

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Nomenclature

AD	Axial displacement
DoE	Design of experiments
MOO	Multi objective optimization
PF	Peak force
RBF	Radial basis functions
RMSE	Root mean square error
RS	Response surface
SEA	Specific energy absorption
TEA	Total energy absorption
A	Area of the cross section
E	Young's modulus
$\bar{f}$	Mean value of f_i
f_i	Function value at the ith design point
$\hat{f}_i$	Function value calculated using the meta-model
F_{max}	Maximum force that occurs in the first 0.5 ms at the end of the column
$f(x, y)$	Function that defines the cross-sectional shape of the column
I_{ii}	Area moment of inertia with respect to i-axis
n_i	Normalization constants whose values are found using the finite element simulation of the circular tube of 50 mm-radius (See Table 3)
P	Penalty function
P_{an}	Penalty function for checking whether an FEA completed or not
P_g	Geometric constraints, which are switched on if $f(x, y)$ does not fit the specifications, $P_g = P_{bound} + P_{curvature} + P_{inter}$
p^i	ith key-point
R	The minimum allowed radius of curvature in $f(x, y)$
IR	Real numbers
SS_{res}	Sum of square errors
SS_{tot}	Total sum of squares
s, u	Parametrization variables of $f(x, y)$
t	Time
t_f	The total time of the simulation
V	Volume of the column
x_u,xl	Upper or lower limit of the design space, respectively
Δt	The time that the force reaches its maximum
ε	Equivalent strain
ε_{ij}	Strain tensor
$\bar{\varepsilon}$	Mean value of ε
ν	Poisson's ratio
ρ	Density of the material used in the column
σ_{ij}	Stress tensor
σ_y	Initial yield stress

maximize SEA. They varied the density of the foam in layers. Langseth and Hopperstad with other coauthors [19–23] derived formulas from experimental data associating variables to stroke efficiency, average and maximum force to get optimal shapes for maximum TEA and minimum reaction force. Empty and foam-filled tubes were the subject of a study by Ahmad and Thambiratnam [24]. They changed impact velocity, and mass, foam density, taper angle, and thickness. Ahmad et al. [25] studied empty and foam-filled circular tubes suffering from an oblique impact loading by changing load angle, taper angle, wall thickness and initial length to quantify energy absorption. Bi et al. [26] worked on single and multi-cell hexagonal tubes filled with foam. SEA maximization was their objective while constraining the mean crushing force. Single and bitubular polygonal tubes filled by honeycomb were examined by Yin et al. [27]. The wall thickness and the side length of the columns were taken as the variables to maximize SEA and to minimize PF. Nia et al. [28] investigated the effect of tube corner cut-outs on the behavior of square tubes under quasi-static oblique loading by changing the locations of the initiators. Tarlochan et al. [29] compared circular, elliptic, square, hexagonal, octagonal foam-filled tubes with the same circumference using crush force efficiency and TEA. Song [30] studied rectangular-windowed empty squared tube under an oblique impact loading by parametrization loading angle, impact velocity, and rectangular window dimension. Song et al. [31] optimized the taper angle of thin-walled tubes having square cross-section under axial impact loads for SEA with constraints of PF and average force. Sun et al. [32] conducted a robust optimization of hexagonal foam filled tubes under axial loading by changing foam density and wall thickness. Tanlak and Sonmez [33] studied empty tubes under axial loading while they are mounted on a car. They investigated the cross-sectional shape as well as the longitudinal profile of the tubes by inserting taper angle and three indentations. They optimized the shape of the tubes directly, without using a meta-model, through a hybrid search algorithm. Qureshi et al. [34] studied the columns with sinusoidal, notch and progressive triggers having square cross-section under varied oblique loading. Li et al. [35] studied functionally graded thickness tubes under axial as well as oblique impact loading with various loading angle. They defined the thickness gradient by means of a power-law equation. Djamaluddin et al. [36] optimized empty or foam-filled two concentric circular tubes under oblique impact loadings. They used radial basis functions to fit the PF and SEA of columns.

One can divide the studies as axial impact loads [1–8,10,11,13–29,31,32,35–39], and oblique loading [9,12,25,28–30,34–36,38–42]. The shapes of the cross-sections investigated in the literature were square or rectangle [1,2,6,9,10,12,14,15,18,20,24,28,30,31,34,37,40,42], circular [1–5,8,13,25,35,36,41], hexagonal [7,11,26,27,29,32], octagonal [11,27], changing cross-sections [33]. In those studies, tubes are considered either as empty [1–13,16,24,25,28,30,33–37,40,41] or filled [12,14,15,17–27,29,31,32,36,39,41,42]. According to their longitudinal profile, the tubes can also be classified as straight [1–3,10,14,15,17,20,24,25,27,35,36,38,40,42], tapered [4,5,8,16,31,39–41] and with indentations [28,30,33,34].

Until now, usually approximate functions have been used for the objective functions like response surface methodology [2–11,13–15,18,26,27,31], Kriging [12,31,32,39,41], radial basis functions [8,31,36], artificial neural network [37], moving least-squares approximation [16], and support vector regression [31]. After building meta-models, particle swarm optimization [9,12,18,27,31,41], genetic algorithms [4,14,15,33,36], leapfrog [37], sequential quadratic programming [31,32], non-linear programming [6–8], Nelder and Mead [33] or multi-first order method [5] have been used as searching algorithms.

To the best of the author's knowledge, there is not any study investigating optimal cross-sectional shapes of the columns under oblique loading. So far, the previous works on the topic have considered one base shape (circle, rectangle, etc) and have tried to tune that shape for an oblique impact loading. But those studies could be considered as a local optimization in some sense. On the other hand, here in this study, a global search for the shape of tubes withstanding an oblique impact is implemented. The primary purpose of this article is to create a new dimension to the topic by enabling the columns to take any shape within the configuration space. This shows the importance of the current study.