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Optimization of energy absorption properties of thin-walled tubes with combined deformation of folding and circumferential expansion under axial load

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ABSTRACT

Recently, the combined mechanism of energy absorption has been considered for increasing energy absorption efficiency. The combined deformation of circumferential expansion and folding in the cylindrical aluminum thin-walled tubes is one of these mechanisms that can be effective in improving energy absorption. In this paper, the effect of parameters of diameter, height and thickness of the tube, friction, and interference of the tube and punch, as well as the half-angle of the tip of the conical punch on the energy absorption have been investigated using LS_Dyna software. Taguchi method was used to design the experiments and response surface method was used for optimization. In the Taguchi method, the design limit has been significantly reduced and the effect of different parameters on energy absorption has been demonstrated. In optimization with response surface method, optimal states have been proposed that increased energy absorption compared to reference test. Finally, by providing a mathematical model for single-objective optimization, the specific energy absorption increased by 127%, but the maximum force in this case was increased by 130%. In multi-objective optimization, specific energy absorption and maximum force were considered as design parameters that optimized specific energy absorption increased by 77%, while the maximum force was only 37% higher. Thus, by combining suitable types of energy absorption mechanisms and optimizing them, absorbents with a higher specific energy absorption capacity and lower maximum force were designed.

1. Introduction

Formerly, collapse behavior of thin walled structures as energy absorbents has been considered by researchers. In recent years, a bulk of analytical, experimental and numerical analyses have been carried out on various energy absorption mechanisms, such as circumferential expansion and folding. However, such studies generally only included an examination of one of these mechanisms independently.

In this section, the research literature is presented in three sections, including research on circumferential expansion, axial collapse, and optimization.

Shakeri et al. [1] studied deformation in the circumferential expansion of cylindrical thin-walled tubes. In their research, they showed that the average collapse force can be affected by the tube thickness and tolerance between the rigid punch and the absorbent tube and the coefficient of friction. Yang et al. [2] both experimentally and numerically studied the effect of thickness and friction on the energy absorption and circumferential expansion of the tubes. In another study, Yan et al. [3] performed a theoretical and numerical study on the circumferential expansion of cylindrical thin-walled tubes as energy absorbers. They reported the most suitable angle for circumferential expansion from 10° to 20°. As for deformation in the form of axial collapse, Alexander [4] was the first to present a theoretical model for calculating average crushing forces with a cylindrical tube. Following him, Abramovicz and Wiersbicki promoted his model. Abramowicz and Jones [5] studied axial crushing of steel circular cylindrical shells loaded either statically or dynamically and compared the results with various theoretical predictions and empirical relations. Wierzbicki et al. [6] proposed an analytical method for determination the mean crushing force of tubes by introducing a two folding elements model.

In addition to theoretical studies, numerous experimental and numerical studies have been undertaken to improve energy absorption in axial collapse, including the use of foam [7] and tube multi-cellularization [8,9], the change in the tube-sectional geometry [10], the effect of impact velocity [11 and 12], the effect of the strain rate [13], the groove [14], the addition of internal and external stiffeners to the structure [15], the use of nested tubes as energy absorbers [16,17], and the construction of variable-thickness tubes [18].

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Symbols

α	Angle of semi-conical tip
β	Coefficient of problem
μ	Friction coefficient
D	Diameter
EA	Energy Absorption
Fa	Average force
Fp	Peak force
Int	Interference
L	Length
Mass	Mass
Moment	Moment
Response Surface Method	Response Surface Method
Specific Energy Absorption	Specific Energy Absorption
Stoke	Stoke
Thickness	Thickness
Variable of problem	Variable of problem
Cost function	Cost function
Yield	Yield

Tanaskovic et al. [19] carried out empirical studies on the tube energy absorption in a shrinking-splitting process of cylindrical tube. The results indicated that this combined process increased the energy absorption capacity by about 60% compared to shrinking only. Li et al. [20] conducted a study on the expanding-splitting energy absorption of tube with circular cross-section. Quasi-static pressure tests showed that the design of this type of energy absorber is possible, and this compound absorber increases the energy absorption about 95.34% compared to the expansion absorber.

Optimization has also applications in the investigation of energy absorption of structures. Using multi-objective optimization through genetic algorithm and neural network, Marzbanrad and Ebrahimi [21] improved the energy absorption of aluminum tubes for five effective factors. Tanlak et al. [22] designed an optimum section to increase the crashworthiness of thin-walled tubes. They presented a function to optimize the section using a combined genetic algorithm and Nelder and Mead algorithms. Taştan et al. [23] studied frusta energy absorbers with lateral holes by means of a surrogate-based optimization method; the studied parameters were to maximize specific energy absorption and crush force efficiency, the thickness and angle of the cone, diameter and number of holes. Olabi et al. [24,25] conducted a study on the optimization of energy absorption of nested tubes with an oval and circular cross section in lateral loading. Wu et al. [26] optimized the crashworthiness of tubes that were sinusoidally and circumferentially folded.

Taguchi method and response surface method are used to design experiments and perform optimization. For example, Abbasi et al. [27] optimized a polygonal section using Taguchi method in terms of energy absorption and crashworthiness. They considered different shapes for the corners and eventually reached an ideal shape for this type of cross section, which had the most energy absorption. Lee et al. [28] used the response surface method based on the random process to increase the energy absorption of the cylindrical thin-walled tubes. Mohammad Sharif et al. [29], using response surface method, for designing the cone structure of the semi-cone as an energy absorbent, studied geometric parameters such as diameter, height and cone half angle to determine the design space with a three-level, second-order Box–Bhenken technique.

There are many studies on optimization of multi-cell tubes. Wu et al. [30] investigated mechanical behavior of multi-cell rectangular tubes under quasi- static loading and showed that these structures have better efficiency when have variable thickness. Zheng et al. [31] studied theoretically, numerically and experimentally energy absorption of multi-cell thin walled tubes and used an integer coded genetic algorithm for optimizing the loading angle and the cells arrangement. Sun et al. [32] optimized configuration of multi-cell topologies for multiple oblique load of thin walled tubes. Qiu et al. [33] analyzed crashworthiness and design of multi-cell hexagonal columns under normal and oblique loading cases and found that loading at angles greater than 30° results in general buckling. Axial and oblique impact loading of multi-cell tubes have studied by Fang et al. [34]. Results of the study showed that increasing the number of cells increases both the absorbed energy and the peak load; oblique load can cause general buckling; and finally using complex proportional assessment presented a 7 × 7 cells configuration for various loading angles. A novel multi-objective discrete robust optimization (MODRO) algorithm for design of engineering structures was investigated by Sun et al. [35]. In this procedure, grey relational analysis (GRA), coupled with principal component analysis (PCA), was used as a multi-criteria decision making model for converting multiple conflicting objectives into one unified cost function. A multi-objective reliability-based design optimization (MORBDO) procedure was proposed to explore the design of vehicle door by Fang et al. [36]. To improve the efficiency of optimization, response surface method (RSM) was used. The results showed that the proposed optimization procedure is capable of generating a well-distributed Pareto frontier of reliable solutions, and it is suggested to select an optimum from relative insensitive regions. Fang et al. [37] proposed a multi-objective optimization in order to simultaneously enhance the performance and robustness of the fatigue life of a truck cab. The multi-objective particle swarm optimization (MOPSO) algorithm was adopted to perform the optimization. Finally, to find a best compromise optimum from the Pareto set, a multi-criteria decision making (MCDM) model was implemented. Crashworthiness design of foam-filled bi-tubal structures with uncertainty was optimized by Fang et al. [38]. They used a multi-objective robust design optimization (MORDO) method, and adaptive Kriging models were employed in the optimization process to reduce the computational burden of highly-non-linear crash analysis. The results demonstrated that the proposed method is capable of improving the robustness of Pareto solutions within the prescribed minimum requirements of reliability. Axial loading of aluminum tubes in two cases of axial functionally graded thickness (AFGT) and lateral functionally graded thickness (LFGT) was studied by Fang, Su and their coworkers [39–41] and absorbed energy and peak load in these cases were compared with the constant thickness tubes.

A meta-model based multi-response objective-oriented sequential optimization was carried out to design of steel–aluminum hybrid structures for the highly nonlinear impact scenario in Refs. [42–44]. Sun et al. [45] used the non-dominated sorting genetic algorithm II (NSGA-II), coupled with Monte Carlo Simulation (MCS), to seek optimal reliability solutions and improve crashworthiness of tailor rolled blank (TRB) structures. Fang et al. [46] introduced a novel honeycomb structure with lower cell honeycombs stand for the walls, and showed that this structure can improve energy absorption characteristics along with buckling control. Fang et al. [47] carried out a comprehensive review about the important studies on design optimization for structural crashworthiness and energy absorption. They studied the design criteria used in crashworthiness and energy absorption, multi-objective optimization, optimization under uncertainties and topology optimization as well as the crashworthy structures in industrial applications.

The main objective of the present study was to investigate the effective factors in the energy absorption of aluminum cylindrical tubes under the combined deformation of circumferential- expansion and folding and optimization of this process. In existing resources, so far, this mechanism has not been used for energy absorption. To do this, an appropriate fixture was designed and built. The parametric study of this process was done using LS_Dyna software and its optimization was

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