Thin-Walled Structures 127 (2018) 540–555

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Optimization of hole height and wall thickness in perforated capped-end conical absorbers under axial quasi-static loading (using NSGA-III and MOEA/D algorithms)

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ARTICLE INFO

Keywords:
Conical absorbers
Optimization
Perforated energy absorber
NSGA-III
MOEA/D

ABSTRACT

In this study, a perforated capped-end conical steel absorber was investigated to optimize its wall thickness and hole height. The holes were worked out on the perimeter of the absorber to lower peak force at collapse. For this purpose, once finished with simulating the absorber utilizing LS-Dyna software and verifying the simulated model using experimental data, hole height and wall thickness of the absorber were optimized to achieve maximum energy absorption along with minimum peak force. A total of 96 different cases were simulated, of which 7 cases were subjected to experimental tests. The optimization was performed using NSGA-III and MOEA/D algorithms implemented in MATLAB software. Response surface methodology was used to determine input functions for these algorithms. Finally, optimal position for the holes in conical absorbers was found to be the nearest point to the upper base of the truncated cone. A relatively good agreement was observed between the results of NSGA-III and MOEA/D algorithms, and the algorithms could predict optimal wall thickness and hole position at an acceptable accuracy in some cases.

1. Introduction

In many phenomena, kinetic energy imposes dangerous effects, so that it is required to be reduced or neutralized. Mechanical absorbers are used for this purpose. Mechanical absorbers are of two types, namely reversible and irreversible energy absorbers. Today, thin-walled metallic energy absorbers (as an example for irreversible energy absorbers), which dissipate destructive energy of accidents through plastic deformation, have found numerous applications. In the scope of energy absorbers, there are two important factors to be studied by researchers: specific energy absorption (*SEA* or ratio of absorbed energy to mass) and maximum force or *Fm* (first peak load) developed when an absorber is collapsed. The larger the absorber deformation, the higher will be the amount of absorbed energy. Numerous studies have been performed on the collapse force and energy absorption by thin-walled absorbers [1–4]. Other than these two parameters, stability and constant rate of energy absorption are other important and effective factors in this regard [5]. Considering the studies performed on different cross-section geometries, circular cross-section has exhibited the highest energy absorption potential and represents the most appropriate cross-section geometry; moreover, among various circular cross-section geometries, conical form has been associated with the highest energy absorption [5]. In the following, firstly, primitive studies on conical absorbers are reviewed followed by an introduction on research works where the maximum force at collapse is lowered using buckling initiator. Then, a review is presented on the works on optimization of energy absorbers.

Postlethwaite and Mills [6] were the first to investigate conical absorbers in 1970. Using Alexander's method [7] for axial deformation patterns, they calculated average axial force for collapsing steel cones in symmetric deformations. Conducting tests on square-sectioned PVC-made cones and presenting a theoretical model, Mamalis et al. [8] considered deformation patterns and absorbed energy. Mamalis et al. [9] presented a new theoretical model for axial folding of this type of cone under quasi-static and dynamic loadings by studying square-sectioned cones of composite and fiberglass materials. Gupta and Abbas [10] presented a theoretical model for folding of the cones under axial loading. In another research, Gupta et al. [11] investigated axial collapse of cone under axial loading. In this study, they presented their theoretical model considering fixed and rotating plastic hinges as wells radius of the rotating plastic hinge. Hosseini et al. [12] investigated symmetric axial collapse of metallic cone using a folding model with internal and external folds. Mamalis and Johnson [13] examined

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https://doi.org/10.1016/j.tws.2018.03.006
Received 6 November 2017; Received in revised form 26 January 2018; Accepted 6 March 2018
0263-8231/

aluminum-made tube and cones and compared their deformation patterns and energy absorption properties. Undertaking experiments on low-carbon steel cone and tube with similar outer diameter and initial length, Mamalis et al. [14] investigated deformation patterns and average collapse force. El-Sobky et al. [15] studied energy absorption performance and deformation patterns of a circular cone between two flat surfaces under quasi-static and dynamic axial loading at 2–5 m/s. Alghamdi et al. [16] tested tens of aluminum-made cone samples with half-angles in the range of 15–60° and wall thicknesses of 1–3 mm between two parallel plates under quasi-static axial loading. Gupta and Venkatesh [17] performed tests on aluminum cones with half-angles of 6–65° and different average diameter-to-thickness ratios ($2R/t$) in the range of 22–79 under dynamic loading. Ahmad and Thambiratnam [18] tested a hollow cone filled with polyurethane foam under quasi-static and dynamic loading. They found that, filling the cone with foam results in more stable deformation and higher energy absorption capacity. Ahmad et al. [19] tested a hollow cone filled with polyurethane foam under transverse loading. The results showed that, filling the cone increases energy absorption capacity against transverse loads. Furthermore, it was revealed that, one can adopt either of three solutions for increasing energy absorption capacity of cone under transverse loading: increasing half-angle of the cone, increasing wall thickness of the cone, and filling the cone to prevent further buckling under transverse loads. Ghamarian et al. [20] compared the process of axial folding between a hollow cone and a cone filled with polyurethane foam, both experimentally and numerically. The results showed higher peak force and energy absorption for the filled cone rather than the hollow one, with the superiority increased at higher foam densities. In 2000, Aljawi and Alghamdi [21] introduced inversion process as a new deformation pattern for cones for the first time. Conducting experiments on cone, Alghamdi [22] studied effects of the angle α and wall thickness of cone on its multiple inversion capability. Aljawi et al. [23] studied cone inversion using experimental and numerical methods. They used cones with different angles and thicknesses and compared the results of quasi-static and dynamic loading with those of FEM analysis. Accordingly, the experimental results were in good agreement with the numerical analysis.

By inducing geometrical discontinuities such as grooves [24], cracks [25], curvatures and holes into the structure, some researchers studied the reduction of maximum force in energy absorbers. Yuen and Nurick [26] investigated the effect of inducing geometrical discontinuities like holes or curvature on the body of absorber. In another study, Alavi Nia et al. [27] examined the effect of introducing buckling initiators on mechanical behavior of square-sectioned shells under transverse loading. The buckling initiators were developed by cutting small windows at the corners of the square shell. Rouzegar et al. [28] studied the effect of geometrical discontinuities on lateral crushing and energy absorption of tubular structures in both experimental and numerical methods. Three groups of specimens were investigated: square and rectangular aluminum columns, circular brazen tubes and circular composite tubes where some notches of different lengths were created on various positions of them. Experimental results showed that numbers of notches on walls of the structures may increase or decrease their energy absorption capability, depending on the notches positions. Nasir Hussaina et al. [29] studied the trigger configuration for enhancement of crashworthiness of automobile crash under axial impact loading. In their paper the effect of various types of triggers was investigated for GFRP composite crash boxes.

In some research works, energy absorption properties of thin-walled absorbers were optimized. Ebrahimi and Vahdatazad [30] multi-objectively optimized energy absorption parameters of circular sandwich columns with hexagonal core. In another study by Abbasi et al. [31] on polygonal-sectioned columns, corners number were optimized vial multi-objective optimization to increase specific energy while decreasing the maximum force. Via multi-objective optimization, Gao et al. [32] optimized oval-sectioned columns filled with foam under transverse impact loading. Taştan et al. [33] studied and optimized an energy absorber of truncated conical geometry with lateral holes under impact loading. Substitution-based optimization was performed to find optimal thickness and cone angle for maximizing specific energy absorption and impact force efficiency.

In recent years some researches have been done about energy absorbers. These researches provide useful information to readers, some of which are listed below.

In 2016 Adil Baykasoglu and Cengiz Baykasoglu [34] investigated the crashworthiness of circular tubes with functionally graded thickness and optimized them by a new multi-objective optimization procedure. They used gene-expression programming (GEP) for generating algebraic equations and multi-objective genetic algorithms for determining optimal cases. Also in ref. [35] they used neural networks and genetic algorithms for crashworthiness parameter optimization of circular tubes with functionally graded thickness. They have shown that the proposed approach can generate Pareto optimal designs which are in a very good agreement with the finite element results.

Mahmoodi et al. [36] investigated the crashworthiness behavior of the tapered multi-cell tubes theoretically and numerically. They extracted an analytical formula using the combination of the previous theories for the mean crush load prediction of the simple multi-cell tube and tapered single-cell tube.

In a paper by Azimi and Asgari [37], crushing characteristics of small-sized conical tubes under axial loading have been studied. Based on the crushing parameters of numerous examples, a simplified analytical model as a meta-model for the mean crushing force of miniature frusta was presented using a Genetic Algorithm optimization for finding the meta-model coefficients. Obtained results from the developed meta-model showed good concurrency with finite elements method (FEM) model.

In a review paper by Baroutaji et al. [38], brief and beneficial information about absorbers which have been investigated by researchers up to now is reflected. This paper is a good source for research about energy absorbers.

According to the investigated references, the maximum force in the collapse curve of energy absorbers is a serious and undesirable problem in the process of energy absorption. This undesirable maximum force can be reduced by creating buckling triggers such as holes in the body of the capped-end conical absorbers; but the creation of hole, in addition to lowering the maximum force, reduces the energy absorption. Therefore, it has been decided to use optimization algorithms for optimizing the position of holes and the thickness of the capped-end conical tubes, so as low maximum force and high energy absorption be achieved, as far as possible. Among the optimization algorithms, no paper was found which had investigated perforated capped-end conical absorbers using NSGA-III and MOEA/D algorithms. Therefore, it had been decided to investigate the ability of these two algorithms for optimization of the capped-end conical absorbers, and to compare their compatibility and their power with together. So far no research has provided a precise place for creating of holes in capped-end conical tubes; in this paper, this goal is pursued.

2. Materials and tests

In order to perform experimental tests, commercially available pre-manufactured cones were used. A simple example of these cones is presented in Fig. 1. The cones were produced through deep drawing method. Height, upper diameter, lower diameter, and thickness of the cones were 70, 60, 34, and 0.2 mm, respectively.

In order to determine composition of the alloy used to prepare test specimens, quantometry test was used, with the results presented in Table 1. Based on the table and Ref. [39], the metallic alloy of which the specimens were made was steel 430. According to Ref. [39], the alloy density is 7800 kg/m^3. Mechanical properties of steel 430 were determined via tensile testing; for this purpose, as shown in Fig. 2,