Thin-Walled Structures 107 (2016) 543–553

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Optimum crashworthiness design of tapered thin-walled tubes with lateral circular cutouts

A. Taştan, E. Acar, M.A. Güler*, Ü. Kılınçkaya

Department of Mechanical Engineering, TOBB University of Economics and Technology, Söğütözü, Ankara 06560, Turkey

ARTICLE INFO

Article history:
Received 22 December 2015
Received in revised form
22 July 2016
Accepted 22 July 2016
Available online 25 August 2016

Keywords:
Crush force efficiency
Specific energy absorption
Finite element analysis
LS-DYNA
Surrogate models
Multi-objective optimization
Circular cutouts
Thin-walled tubes

ABSTRACT

In this paper, the effects of introducing lateral circular cutouts on crash performances of tapered thin-walled tubes are explored within a simulation-driven surrogate-based multi-objective optimization framework. The crash performances of the tubes are measured using the crush force efficiency (CFE) and the specific energy absorption (SEA) criteria, which are computed using the finite element analysis code LS-DYNA. Surrogate-based optimization approach is followed to find out that optimum values of the wall thickness, the taper angle, the cutout diameter and the numbers of cutouts in horizontal and vertical directions to maximize CFE and SEA. Four different surrogate models are used: polynomial response surfaces, radial basis functions, and Kriging models with zeroth- and first-order trend models. It is found that the optimum CFE of the tubes with lateral circular cutouts is 27.4% larger than the optimum CFE of the tubes without cutouts. It is also found that the optimum SEA of the tubes with lateral circular cutouts is 26.4% larger than the optimum SEA of the tubes without cutouts. It is observed that the optimum SEA design has slightly reduced wall thickness, significantly reduced taper angle, significantly increased cutout diameter, increased number of cutouts in horizontal direction and slightly reduced number of cutouts in vertical direction compared to the optimum CFE design. In addition, multi-objective optimization of the tubes is performed by maximizing a composite objective function that provides a compromise between CFE and SEA. It is found that the CFE dominates the behavior of composite objective function.

1. Introduction

In recent years, thin-walled structures have been increasingly used as crash absorbers which convert impact energy into internal energy through structural deformation. Tubular structures are the most common type due to their simple, efficient shape and also ease of manufacture and assembly in the industry. The main goal of these crash absorbers is to transfer minimum amount of crash energy to the occupants and the main parts of the vehicle in case of a collision. In a crash incident, crash absorber is deformed plastically and a great part of energy is absorbed during the collision. It becomes unusable (i.e., discarded) after a single crush. Light-weight design of these crushable parts are still studied by many researchers in order to have excellent crashworthiness and formability.

To predict and observe the crushing behavior of thin-walled tubes under axial impact loading, there have been numerous researches in the literature. These studies have mainly focused on circular [1–4] and square [1,5] types of tubes, while many different types of cross-sectional shapes exist such as hexagonal [1,6] or octagonal [7]. Tubular structures have a wide range of options including straight and tapered types. All side-walls are parallel to the longitudinal axis of the tube in the straight types. However, for tapered types, at least one side-wall is oblique with respect to the longitudinal axis. Tapered crash absorbers are more advantageous to the straight tubes since they are effective for both oblique and axial impact loads [8]. Energy absorption capability of different tapered tubes under axial impact loading was investigated by Nagel and Thambiratnam [9]. They varied the number of tapered sides and the wall thickness. Liu [10] performed a design optimization for the tapered tubes with square sections, where section's side length, wall thickness and tapering angle are design variables. Paralleling the strategy in tapering the tubes, there are many other suggestions which propose reducing the initial peak load or increasing the amount of absorbed energy. Applying imperfections and geometrical discontinuities, such as grooves [11], cutouts (or holes) [12,13], dents [14] and corrugations [1,15,16], is the prevalent one. In addition to these conventional modification methods, some studies propose a topological change of the tube side-walls including the form of circular cutouts [17] or rectangular

* Corresponding author.
E-mail address: mguler@etu.edu.tr (M.A. Güler).

http://dx.doi.org/10.1016/j.tws.2016.07.018
0263-8231/

windows [18]. The energy absorption characteristics of the tubes with laterally drilled cutouts under axial impact loading were investigated by Arnold and Altenhof [19]. They experimentally observed the effect of location and diameter of the cutouts on the energy absorption behavior. For the square form of cutouts, Han et al. [20] studied crushing behavior under axial loading by changing the location of cutout and tube length. Also, Bodlani et al. [21] varied number of cutouts and cutout diameters with different cutout spacing configurations for square tubes. Common among the aforementioned studies is to investigate the effect of tapering or geometrical discontinuities in the form of cutouts only. This paper aims to analyze both the effect of tapering and geometrical discontinuities in the form of cutouts.

During the axial crushing process of thin-walled tubes, crushing forces are generated to overcome the resistance of the tube. For a crashworthy energy absorber design, the tubes under axial impact loading are expected to provide both high energy absorption and stable reaction force. In other words, they should have a fairly uniform response to impact load after the initial peak. At the start of axial crushing process, initial peak force should be as low as possible to minimize the injury and damage, while the ability of energy absorption of the tube is being improved. Accordingly, both peak crush force and energy absorption values should be taken into consideration in determining the optimal design of a crush absorber. One of the common way to determine the optimal design is the calculation of crush force efficiency (CFE) and specific energy absorption (SEA). CFE and SEA can be described as the ratio of mean crush force to the peak crush force and the energy absorption per unit mass, respectively. For example, Arnold and Altenhof [19] studied the effect of circular cutouts centrally located into the two opposing walls of the square tubes by comparing the CFE and SEA values. Han et al. [20] characterized the crushing behavior of tubes with a cutout by evaluation of SEA values. On the other hand, weight of the structure is another remarkable factor for a commercial design. Song et al. [18] aimed to reduce weight by introducing patterned windows to the thin-walled square tubes. They performed a parametric study in terms of SEA. SEA parameter do not only provide a great information about the efficiency of crash absorber but also it may lead to a light-weight design of energy absorbing component, which the weight and the material cost of the structure are also crucial.

The main objective of this study is to analyze tapered tubes with geometrical discontinuities in the form of lateral circular cutouts, where the wall thickness, the tapering angle, the cutout diameter, and the numbers of cutouts in horizontal and vertical directions are considered as design variables. Such an analysis can be conducted using either experimental or numerical methods (e.g., finite element method (FEM)). Since experiments are expensive and time demanding, and FEM has become a widely accepted technique in engineering applications, FEM is used in this paper to analyze several designs without the need of building an testing them. The commercially available explicit dynamic finite element (FE) analysis code LS-DYNA [22] is used in this study to simulate the crash behavior of thin-walled tubes under axial impact loading. The simulations of the thin-walled tubes are performed based on the loading conditions in a standard high-speed crash test, European New Car Assessment Program (Euro NCAP) [23].

In this study, the global geometrical properties (the wall thickness and the taper angle) as well as the local geometrical properties (the cutout diameter and the numbers of cutouts in horizontal and vertical directions) are optimized to maximize the CFE and the SEA. The main challenge in solving this optimization problem is related to the very large computational costs of performing FE simulations, and the use of surrogate models is a common and practical approach. Several researchers performed structural optimization of the vehicles or their components by using surrogate models (e.g., [24–30]). In particular, some researchers focused on energy absorption capabilities of the thin-walled tubes, and used surrogate models to perform crashworthiness optimization of these tubes [10,31–36]. In this study, multi-objective surrogate-based optimization of the tubes are performed to determine the global and local geometrical properties of tapered thin-walled tubes with lateral circular cutouts for maximum CFE and SEA.

The remainder of the paper is organized as follows: The next section provides the description of the optimization problem. Section 3 presents the details of the finite element analysis of the tapered thin-walled tubes with lateral circular cutouts. Section 4 discusses the construction and accuracy evaluation of the surrogate models. Section 5 presents and discusses the results of the optimization problem. Finally, the concluding remarks are given in Section 6.

2. Problem description

Differently from previous conventional modification methods [14–16], the thin-walled tubes having circular cross sections have

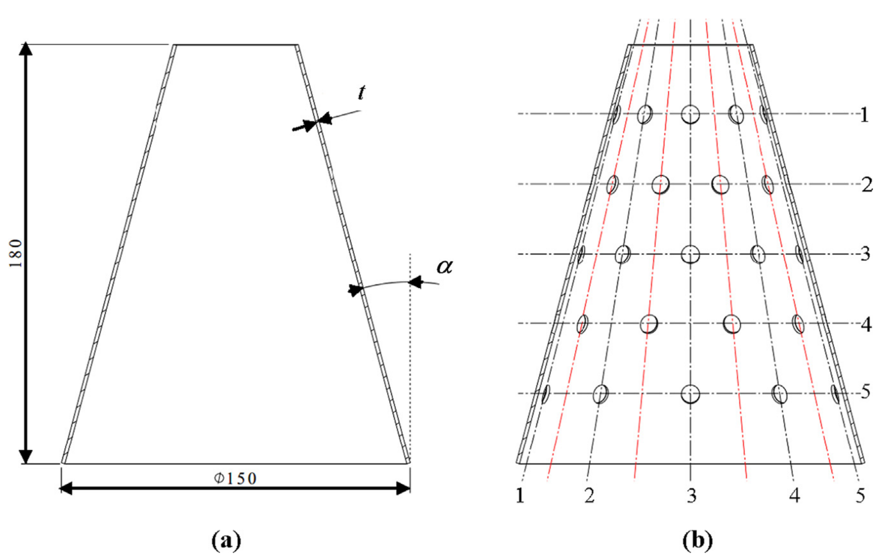

Fig. 1. The geometry of the thin-walled tube (a) without, and (b) with circular cutouts. *The dimensions are in millimeters.*