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Foam filling options for crashworthiness optimization of thin-walled multi-tubular circular columns

M. Altin[a], E. Acar[b], M.A. Güler[b,*]

[a] Department of Automative Engineering, Gazi University, Ankara 06590, Turkey
[b] Department of Mechanical Engineering, TOBB University of Economics and Technology, Ankara 06560, Turkey

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ABSTRACT

There is an increasing trend in using aluminum foam-filled columns in crash management systems due to their light weight in automotive industry. The main goal of this study is to optimize the crashworthiness of aluminum foam-filled thin-walled multi-tubular circular columns under quasi-static loading. The existing studies in the literature considered only lateral foam filling (the foam lateral dimension is variable and the foam height is equal to the column height). In the present study, we considered both lateral and axial foam filling and compared the performances of these two options. In optimization, the column thicknesses, taper angle, foam density, and foam height/diameter are considered as design variables. The quasi-static responses of the columns are determined through explicit dynamic Finite Element Analysis (FEA) using LS-DYNA software, and validated with quasi-static tests conducted in our facilities. Response surface based crashworthiness optimization of the columns for maximum Crush Force Efficiency (CFE) and maximum Specific Energy Absorption (SEA) is performed. It is found that lateral foam filling is superior to axial foam filling in terms of both CFE and SEA maximization. The maximum CFE obtained through lateral foam filling is 19% larger than the maximum CFE obtained through axial foam filling. Similarly, the maximum SEA obtained through lateral foam filling is 6% larger than the maximum SEA obtained through axial foam filling. For both CFE and SEA maximization, the columns should be tri-tubular type and have a large thickness and a taper angle. To attain the maximum CFE, foam should be designed with large density and medium foam diameter. However, foam plays an adverse role in maximization of SEA because of its weight. The increase in energy absorption obtained by using foam does not compensate the additional weight introduced by the foam.

1. Introduction

Thin-walled columns located behind the bumper of vehicles exhibit the capability of absorbing energy by deforming plastically in case of a frontal collision accident (see Fig. 1). If the impact force exerted on the columns cannot be sufficiently absorbed, it is transferred directly to the passenger cabin during collision. This may cause fatal injury to the passengers and damage to the vehicle. Thin-walled columns of different geometries such as circular [20], square [35], frusta [32], honeycomb [11,34], and foam-filled [24,9] are efficient energy absorbers owing to their capability to crush and fold in a progressive and stable manner.

Crashworthiness of foam-filled columns is the focus of research for the last two decades due to the development of metallic foam materials. Mirfendereski et al. [27] considered the experimental and numerical analysis of the crashworthiness characteristics of foam-filled straight, double-tapered, triple-tapered and frusta geometries for static and dynamic impact loads. They found that the initial peak load was decreased as the number of oblique sides increased. Ahmad and Thambiratnam [2] determined that a foam-filled conical column absorbs significantly more energy and have a higher mean crush load than an empty one. Goel [12] compared the energy absorption capability of empty and foam-filled columns with different cross-sections under impact loading, and determined that foam-filled bi-tubular and tri-tubular structures absorb more energy than mono-tubular foam-filled columns. The axial crushing tests of empty and partially foam-filled thin-walled circular and square columns were performed by Altin et al. [4]. They determined that foam-filled square columns displayed the highest crash performance. The common main observation of these studies was that the energy absorption capacity can be increased by using metallic foams.

In order to improve the crashworthiness performance of foam-filled structures, the effects of cross-sectional geometry and foam densities

* Corresponding author.
E-mail addresses: maltin@gazi.edu.tr (M. Altin), acar@etu.edu.tr (E. Acar), mguler@etu.edu.tr, prof.guler@gmail.com (M.A. Güler).

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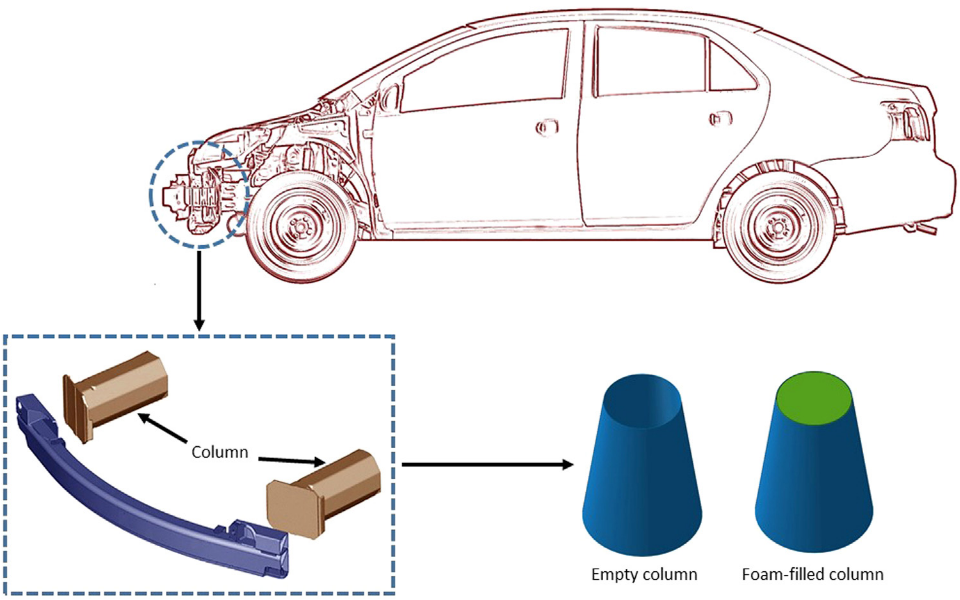

Fig. 1. Schematic of column structures.

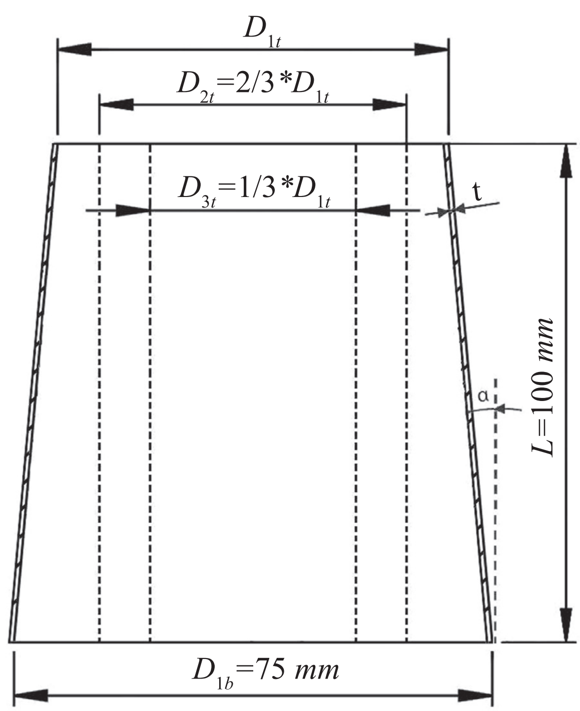

Fig. 2. A generic geometry of tri-tubular thin-walled column.

have been widely investigated. Langseth and Hopperstad [22] reported that increasing the wall thickness and foam density increased the SEA values of the columns under axial loading conditions. Hanssen et al. [15,16,14] investigated the crushing behavior of circular and square columns filled with aluminum foam under static and dynamic loads. They developed theoretical formulations to predict the average force, the maximum force, and the effective crushing distance. Sun et al. [33] compared the energy absorption capacity of functionally graded foam-filled column structures and the uniform foam-filled column structures. They found that the crashworthiness performance of functionally graded foam-filled column is better than that of the uniform foam-filled column. They also found that the energy absorption capacity was dependent on the foam density. Santosa and Wierzbicki [30] studied the effect of low-density filler material on the axial crushing resistance of square columns under quasi-static loading condition. They determined that the energy absorption of an aluminum honeycomb-filled square column was significantly larger than that of an empty square box column. The crashworthiness performance is highly dependent on the foam density and geometrical properties.

The most commonly used metrics to define crashworthiness of an energy absorber are SEA and CFE. A high value of CFE indicates a low peak crushing force, so that the force transferred to the passenger side will be low, which is desired for crashworthiness. A high value of SEA indicates a high value of energy absorbed per unit mass, so that the kinetic energy transferred to the passenger will be low. Recently, optimization studies to maximize the SEA and CFE of foam-filled thin-walled structures have drawn increasing attention. It has been demonstrated that the foam density [31,19,3,36] and the wall thickness [25,10,8] exert substantial effect on the energy absorption capacity of foam-filled columns. Thus, it is necessary to determine the optimal values of foam density and wall thickness for an efficient design. The remarkably large computational cost of crash simulations is a major challenge in crashworthiness optimization studies. To address the computational challenge, response surface models (or metamodels) that approximate the simulation model results are generally used. By concentrating mainly on the energy absorption capabilities of thin-walled structures, response surface models were employed in optimization studies in order to investigate the crashworthiness of these structures [23,40,26,5,38,37,18]. There are several studies on optimization of foam density and wall thickness to improve the crashworthiness capability of foam-filled columns. Hou et al. [17] optimized square mono-tubular foam-filled crash absorbers by using multi-objective optimization methods. They determined that the presence of foam filler increases SEA and improves crashworthiness performance; however, the peak crush force is also increased. Bi et al. [6] conducted design and optimization study for foam-filled mono- and tri-tubular columns. They optimized these structures for maximum SEA with the constraint of mean crush force (MCF) and determined that the maximum SEA tended to favor slender and thick columns having average foam density for both mono-tubular and tri-tubular columns.