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# Energy absorption characteristics of multi-frusta configurations under axial impact loading

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ABSTRACT

In this study, the behavior of multi-frusta configurations under axial loading was analyzed, the effect of column spacing, number of tubes, shells, and cone combinations investigated, and multi-objective optimization applied to obtain optimal multi-frusta configurations. The results obtained indicate that the interaction between multi-frusta configurations without shell improves the system's specific energy absorption (SEA), the SEA of multi-frusta tubes can be improved by the rigid outer shell, and the overall energy absorption of restricted size structures benefit from having an appropriate number of multi-frusta configurations. They also show that cross-arranged tapers offer better energy absorption characteristics than other arrangements.

## 1. Introduction

*Metallic thin-walled structures are widely used in vehicles, aircraft, and high-speed trains owing to their light weight and high-energy absorption efficiency* [1,2]. Economic pressure and manufacturing cost have forced manufacturers to decrease the weight of such structures; however, it is not always safe to reduce the weight of any structural component if it involves in sacrificing the crashworthiness [3,4]. Therefore, methods to improve the energy absorption characteristics of thin-walled structures have become essential [2,5,6]; consequently, several improvement methods have been proposed.

One of the proposed methods involves in dividing the cell section into multi-cell regions according to certain rules [2,6,7]. As multi-cell tubes have several advantages over single tubes, in recent years, various studies have investigated the energy absorption ability of multi-cell thin-walled structures. For instance, Chen and Wierzbicki [8] performed comparative analysis of a single-cell, two-cell, and triple-cell structure under axial impact loading. Zhang et al. [9] conducted quasi-static axial compression tests to study the energy absorption performance of multi-cell square tubes, and Hou et al. [10] carried out theoretical research via numerical simulation of single-cell, two-cell, triple-cell, and four-cell structures under longitudinal impact load. A new multi-cell profile has also been proposed and investigated by Kim [7]. The results obtained by Kim showed that the specific energy absorption of the new structure is 1.9 times larger than that of the conventional square box column form.

Several configurations of multi-cell tubes under axial loading have also been studied, both numerically and experimentally by Jusuf et al. [11]. Results obtained by Jusuf et al. showed that the energy absorption efficiency is significantly improved by introducing internal ribs to double-walled columns. Zou et al. [12] numerically investigated eight kinds of multi-cell square tubes to determine the effect of multi-cell configurations under axial and oblique loads. Their results showed that the collision resistance of multi-cell structures is superior to that of single-cell structures. Wu et al. [13] experimentally and numerically investigated the effect of the number of cells and topological configurations of multi-cell structures on their crashworthiness characteristics. Their results showed that the specific energy absorption (SEA) increased with increases in the number of cells in each multi-cell tube. To improve the efficiency of material utilization for multi-cell tubes, Zheng et al. [14] proposed a laterally variable thickness (LVT) multi-cell tube and investigated the crashworthiness characteristics of the LVT multi-cell tubes by means of experimental and numerical analyses. Fang et al. [15] presented functionally graded thickness multi-cell tubes with improved energy absorption capacity. *A modified artificial bee colony algorithm was proposed by Fang et al.* [16] *to systematically search for novel multi-cell sectional profile without predefining the topological configurations.*

The thin-walled structure can also be filled with cellular materials, such as honeycomb, foam, or sawdust, to improve their energy absorption: owing to the high absorption efficiency and low weight, many researchers have conducted theoretical and numerical analyses on thin-

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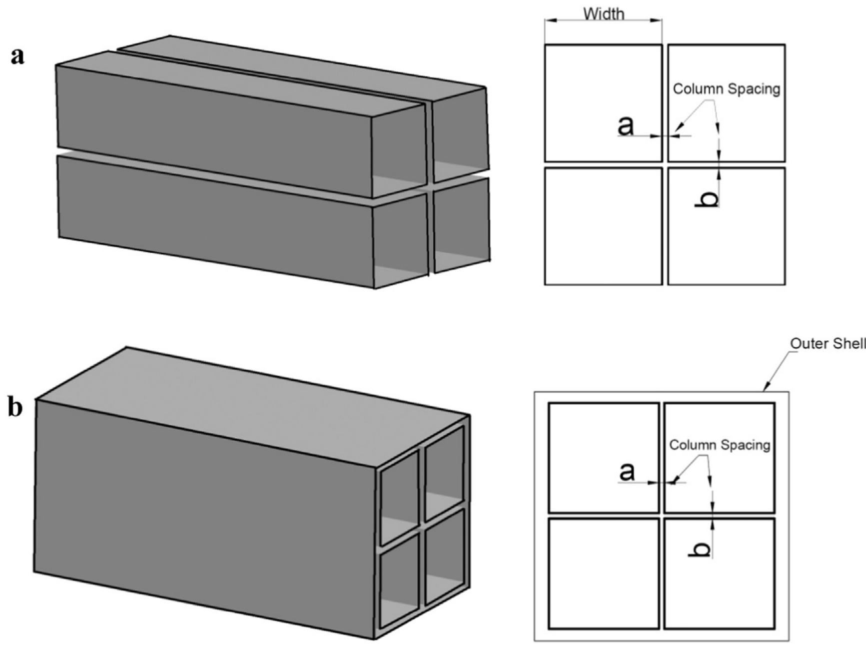


**Fig. 1.** Schematic diagram of multi-frusta structures (a) without shell (b)shell.

walled structures filled with such materials [17,18]. For example, Reddy et al. [19] performed quasi-static and dynamic tests to investigate the crushing behavior of foam-filled circular tubes. They found that interaction between the tube wall and the foam filler caused the deformation mode to change from irregular diamond crumpling to axisymmetric folding. Hanssen et al. [20,21] proposed closed-form equations for predicting the energy absorption in foam-filled aluminum tubes under both quasi-static and dynamic loading conditions. Their results showed that the total energy absorption of a foam-filled tube exceeds the sum of the energy absorbed individually by an empty column and the foam filler. At similar foam-filler densities, the multi-tube design was found to have higher energy absorption than the single tube [22]. Aluminum foam filling in thin-walled structures has been shown to improve the energy absorption characteristics [23,24].

Sun et al. [25] presented a functionally graded foam-filled thin-walled structure that improves crashworthiness. Their results showed that the functionally graded foam-filled material is superior to its uniform counterparts in overall crashworthiness terms. Fang et al. [26] presented a novel dual functionally graded structure with the changing foam density and wall thickness along the transverse direction. *The single, double, multi-wall squares and circular tubes with aluminum foam core under the identical test conditions were carried out to assessing its crashworthiness characteristics by Goel* [27]. *Several multi-cell configurations, including multilayer, multi-cell and multi-tube specimens, were confined in four rigid walls to study the energy absorption characteristics of the structures* [28].

From previous studies, it can be inferred that the higher energy absorption of filled structures arises not only because of the structural characteristics of such cellular materials, but also because of interaction effects between the cellular materials and the thin-walled structures. The existing multi-cell configurations rarely considered interactive effects and the parameters governing the interaction effects have not been widely studied. Moreover, only a few studies of multi-frusta configurations or similar structures have been reported to date. This paper reports on a detailed study conducted on the dynamic crushing behavior of multi-frusta configurations. Newly proposed multi-frusta configurations will combine the corner effect and wall-interactive effects to enhance energy absorption. The focus of this paper is mainly on the interaction effects between the proposed multi-frusta thin-walled structures.

Multi-objective particle swarm optimization (MOPSO) was first used for multi-objective optimization design of foam-filled multi-cell thin-walled structures by Sun et al. [29]. Nariman-Zadeh et al. [30] used a multi-objective genetic algorithm to solve the problem of structural optimization design with two conflicting objectives. The obtained Pareto front provided more choices for optimal design of energy absorption for square aluminum columns under multiple constraints. Zarei and Kroger [31,32] also explored multi-design optimization to study the geometric parameters of foam-filled tubes and the accuracy of their finite element simulation was verified via experiments. Qiu [33] employed different multi-cell hexagonal cross-sectional columns and optimized the dimensions under axial and oblique loads. Their results showed that an optimized multi-cell sectional tube is more competent with regard to crashworthiness for multiple load cases. Fang et al. [6] undertook a comprehensive review of the studies on design optimization for structural crashworthiness and energy absorption and offered several recommendations for future crashworthiness optimization. Acar et al. [34] investigated the effects of tapering and introduction of axisymmetric indentations on the crashworthiness characteristics of thin-walled tubes were investigated. In their study, the optimum values for number of axisymmetric indentations, radius of the indentations, taper angle, and tube thickness were selected to maximize the crushing force efficiency and SEA.

In this study, numerical simulation of multi-frusta configurations under axial impact was performed and the effects of column spacing, shell properties, number of tubes, and different combinations of cones investigated. Further, multi-objective optimization functions were formulated for optimal design of a multi-frusta configuration under axial impact. In this paper, suggestions are also presented for the crashworthiness design of multi-frusta structures under axial impact.

## 2. Finite element model

Nonlinear finite element analysis software LS-DYNA was used to simulate the energy absorption characteristics of thin-walled tubes under impact loading. Belytschko-Tsay shell elements with four nodes (suitable for large deformation analysis), with a shear factor of 0.83 [35], were adopted as the basic unit for thin-walled multi-frusta structures. Five Gaussian integration points were selected along the direction of their thickness. Because of the collapse of the thin-walled tube, the contact coefficient of static and dynamic friction was taken as 0.15 [36,37].