International Journal of Mechanical Sciences 103 (2015) 63–73

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

# Dynamic crashing behavior of new extrudable multi-cell tubes with a functionally graded thickness

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ARTICLE INFO

*Article history:*
Received 5 January 2015
Received in revised form
14 August 2015
Accepted 25 August 2015
Available online 14 September 2015

*Keywords:*
Functionally graded thickness
Extruded multi-cell tube
Crashworthiness
Multiobjective optimization

ABSTRACT

Multi-cell structures have been extensively studied for their outstanding performance as potential energy absorbers. Unlike existing multi-cell tubes with a uniform thickness (UT), this paper introduces a functionally graded thickness (FGT) to multi-cell tubes under dynamic impact, which can be fabricated by an extrusion process. A numerical model is first established using the nonlinear finite element analysis code LS-DYNA and validated with experimental data. Based on a numerical study, the thickness gradient parameters in different regions have considerable effects on the crashworthiness of the FGT multi-cell tubes. Moreover, the FGT multi-cell tubes are able to absorb more energy while yielding a similar level of peak impact force to the UT multi-cell tubes. Finally, multiobjective optimizations of the UT and FGT multi-cell tubes are then performed to determine the optimal gradient parameters that simultaneously improve the specific energy absorption (SEA) and reduce the maximum impact force. In these optimizations, the multiobjective particle optimization (MOPSO) algorithm and response surface (RS) surrogate modeling technique are adopted. The optimization results demonstrate that the FGT multi-cell tubes produce more competent Pareto solutions than the conventional UT counterparts; similar gradients in the outer walls and stronger internal ribs are recommended for the FGT multi-cell tubes because of their improved interactions.



## 1. Introduction

In automotive engineering, thin-walled structures have been extensively used because of their exceptional performance in energy absorption and their light weight. Fig. 1 displays a typical front longitudinal rail [1], which is responsible for absorbing approximately 50% of the kinetic energy of the vehicle during a full frontal collision [2]. The forward part of the rail structure is generally straight to induce progressive folding collapse in the axial direction; this is regarded as the most efficient deformation mode for energy absorption. Because the crashing process determines the acceleration pulse of the occupant compartment, which is closely associated with occupant injuries, a crash analysis of the thin-walled structure is considered critically important. In this regard, the earliest research traces back to the 1960s, when Alexander [3] studied axial crushing of cylindrical tubes and developed a closed-form analytical solution for evaluating the average crushing force. Since then, a series of experimental and theoretical studies [4–9] have been performed in this attractive field to investigate square and circular tubes subjected to static and dynamic loads.

Typically, severe deformation with combined bending and membrane deformation occurs near the corners of the tubes [10]. Thus, the number of corner elements on a tube's cross-section largely influences the energy absorption and crashing behaviors [4,11]. One way to enhance the crashworthiness of a frame is to devise sophisticated multi-cells and internal webs [10,12–14]. Another way is to place more material and increase the wall thickness in the corners because these regions undergo more severe deformation; this solution allows for more energy to be absorbed. With this concept in mind, the European Aluminum Association [15] found that a square tube with reinforced corners offered a significantly higher specific energy absorption than a tube with constant wall thickness (as shown in Fig. 2). Zhang et al. [16] investigated square tubes with graded thicknesses and found a 30–35% increase in energy absorption efficiency. The possibility for tailoring wall thickness variations offers a new opportunity for

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http://dx.doi.org/10.1016/j.ijmecsci.2015.08.029
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optimization. In other words, this novel configuration enables a more flexible design to achieve better performance.

It is noted that the concept of varying the wall thickness in the longitudinal direction has recently been proposed for enhancing crashworthiness. Sun and his co-workers first explored the tubes with functionally graded thickness (FGT) and found such a FGT tube does outperform the uniform counterpart in crashworthiness subjected to axial crushing [17] and lateral bending [18]. Zhang et al. [19] also investigated the axial crushing of tapered circular tubes with graded thickness that were successfully fabricated using a tube tapering machine. While the FGT structures in the longitudinal direction have demonstrated advantages in crashworthiness, the fabrication process could necessitate some specially dedicated equipment.

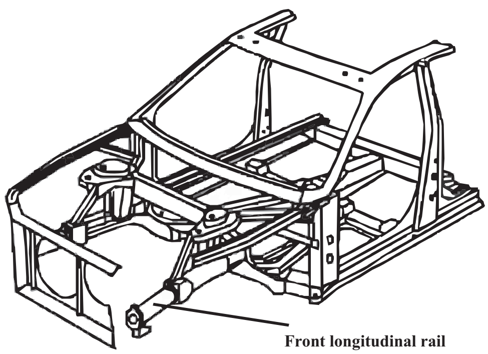


**Fig. 1.** Front longitudinal rails of the body structure [1].

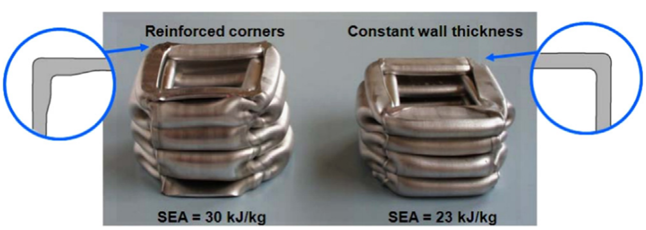


**Fig. 2.** Corner-reinforced tube vs. uniform wall tube [25].

From a manufacturing perspective, the extrusion process makes it possible to fabricate various prismatic tubes with almost any cross-sections in a cost-efficient manner, not to mention multi-cell and thickness variation configurations. The question is what is the crashworthiness of tubes if these two configurational features are integrated together? Therefore, this study aims to explore the crashworthiness of FGT based multi-cell tubes.

For the crashworthiness problems that involve highly nonlinear contact-impact and large deformation mechanics, analytical objective functions of *SEA* and $F_{max}$ are difficult to derive mathematically. Alternatively, metamodels or surrogate models have been widely utilized to approximate responses during optimization [17,20–25]. Of the various metamodels, the response surface model (RSM) with different orders of polynomial basis functions is the simplest and most commonly used formula and has been successfully used for some crashworthiness optimization problems [26–30]. In this study, the finite element (FE) model of this novel structure is first constructed in LS-DYNA for bearing a dynamic impact loading. The crashworthiness of the FGT multi-cell tubes is then analyzed and compared with that of uniform counterparts based on the RSM. Finally, the multiobjective particle swarm optimization (MOPSO) algorithm is used to optimize the sectional parameters to simultaneously enhance the specific energy absorption (*SEA*) and decrease the maximum crushing force ($F_{max}$).

## 2. Numerical modeling

### 2.1. Geometric description

The structure analyzed is a five-cell tube with a functionally graded wall thickness (Fig. 3a). The length of this tube is $H=200$ mm,

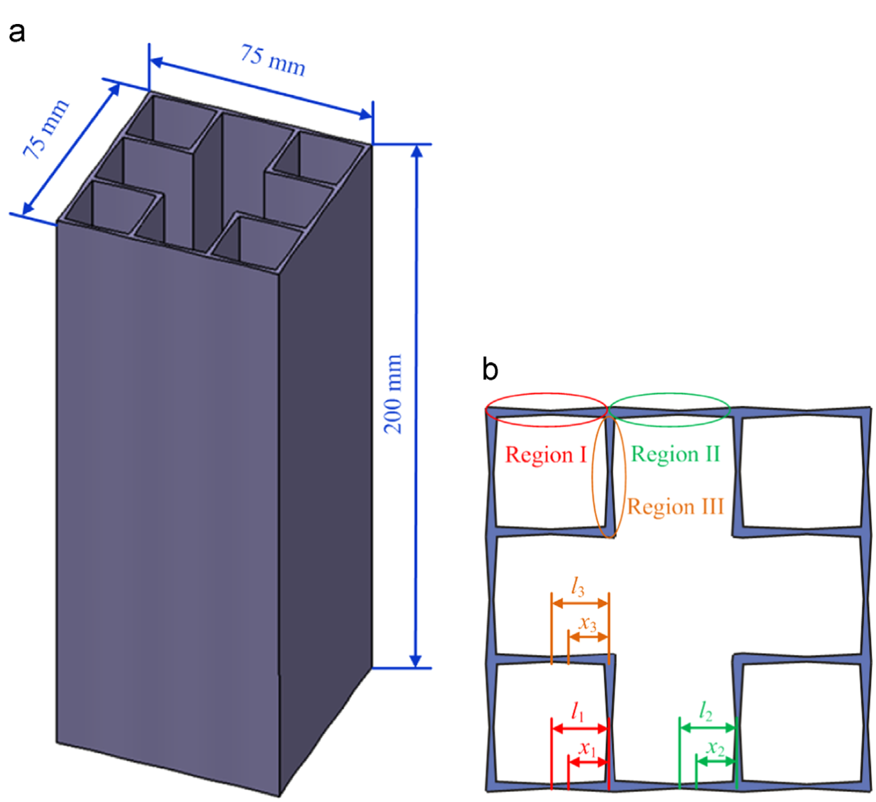


**Fig. 3.** Configuration of the FGT multi-cell tube: (a) 3D view and (b) 2D cross-sectional view.