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Theoretical prediction and crashworthiness optimization of multi-cell square tubes under oblique impact loading

TrongNhan Tran [a,c], Shujuan Hou [a,b,*], Xu Han [a,b,*], NhatTan Nguyen [b,d], MinhQuang Chau [c]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, PR China
[b] College of Mechanical and Vehicle Engineering, Hunan University, Changsha, Hunan 410082, PR China
[c] Faculty of Mechanical Engineering, Industrial University of Ho Chi Minh City, Go Vap District, HCM City, Vietnam
[d] Center for Mechanical Engineering, Hanoi University of Industry, Tu Liem District, Hanoi, Vietnam

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ABSTRACT

Multi-cell square tubes under dynamic oblique impact loading were studied in our work. The theoretical predictions of mean crushing force, mean horizontal force, and mean bending moment were proposed by dividing the profile into basic angle elements based on a Simplified Super Folding Element (SSFE) theory. The formulas of an oblique impacting coefficient (λ) with a load angle of 15° were proposed based on the geometric parameters, the inertia effect and the oblique loading angle by taking the effect of oblique loading and dynamic crushing into account for aluminum alloy tubes. A new method was proposed to find out a "knee point" from Pareto set with maximizing the reflex angle. The optimal configurations of multi-cell tubes were analyzed under axial and more than one oblique impact loadings. The results showed that the FE numerical results agreed well with the theoretical predictions.

1. Introduction

Thin-walled tubes were widely used as energy absorber during the past two decades. Extensive efforts by Wierzbicki and Abramowicz [1], Abramowicz and Jones [2,3], Guillow et al. [4], DiPaolo et al. [5], Krolak et al. [6], were conducted to investigate the crushing and energy absorption characteristics of the thin-walled tubes subjected to axial impact loading by using experimental, theoretical and numerical methods. For multi-cell tube, Wierzbicki and Abramowicz [1] concluded that the number of "angle" elements on cross-section of tube, to a certain extent, decided the effectiveness of the energy absorption. The quasi-static axial crushing of single-cell, double-cell and triple-cell hollow tubes and corresponding foam-filled tubes were examined by Chen and Wierzbicki [7]. The work of Chen and Wierzbicki [7] showed that the multi-cell tube increased the specific energy absorption SEA by approximately 15%, compared to hollow tube. Therefore, it is necessary to design multi-cell thin-walled tubes as weight-efficient energy absorption components. In order to get a simplification to replace the kinematical admissible model of Super Folding Element (SFE) theory, the Simplified Super Folding Element (SSFE) theory was proposed by comprising three extensional triangular elements and three stationary hinge lines [1]. Assuming that each panel and angle element has the same role, the theoretical prediction of the mean crush force was deduced by dividing the cross-sectional tube into distinct panel section and basic angle element. Kim [8], Jensen et al. [9], Karagiozova and Jone [10], Zhang et al. [11–15], Najafi and Rais-Rohani [16] and other authors have investigated the multi-cell thin-walled tubes under axial impact loadings and made many valuable conclusions. The progressive collapse of tubes under axial loadings was summarized by Karagiozova and Alves [17]. Otherwise, the global bending was an undesirable energy-dissipating mechanism. Alternatively, the desirable energy-dissipating mechanism was the stable and progressive wrinkle deformation. Kim and Reid [18] also proposed an approximate method to predict the bending collapse, the crumpling moment and the energy absorption for tubes subjected to pure bending. Recently, Tran et al. [19] utilized the Simplified Super Folding Element (SSFE) theory to estimate the energy dissipation of angle elements in the theoretical predictions and crashworthiness optimization of multi-cell triangular tubes.

Nevertheless, multi-cell thin-walled tubes as an energy absorber normally bear the oblique impact loading. At that time, the tubes are subjected to both axial force and bending moment. In case the tube experiences a global bending, the energy absorption would be smaller [20]. Therefore, it is necessary to study the mechanical

* Corresponding authors at: College of Mechanical and Vehicle Engineering, Hunan University, Changsha, Hunan 410082, PR China.
E-mail addresses: shujuanhou@hnu.edu.cn (S. Hou), hanxu@hnu.edu.cn (X. Han).

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Nomenclature

$2H$	wavelength
a	side length
t	wall thickness
L_0	tube lengths
b	panel width
B	sum of side-length and internal web lengths
d	crushing displacement
SEA	specific energy absorption
E_b, E_m	bending and membrane energy
E_A	total strain energy
η	effective collapse coefficient
μ	rotation angle at bending hinge line
PCF	initial peak crushing force
$P(x)$	instantaneous crushing force
P	mean crushing force at load angle α
P_a	axial crushing force
P_m	mean crushing force
P_h	horizontal force
M	bending moment
M_0	fully plastic bending moment
λ	oblique impacting coefficient
ψ	reflex angle
β, ϕ	angle formed by internal panels
α	load angle
σ_0	flow stress of material
σ_y, σ_u	yield strength and ultimate strength of material

property of tubes under oblique impact loadings. According to the aspects of numerical simulation, Han and Park [21] studied the oblique behavior of thin-walled square mild steel tube. Their study showed that the axial progressive collapse should be transferred to global bending collapse at the critical load angle. Reyes et al. [22,23] carried out extensive numerical and experimental analyses on the square tubes under quasi-static oblique loading. Their researches concluded that the energy absorption dropped sharply when load angle exceeded the critical value. Nagel and Thambiratnam [24] also investigated square tubes under dynamic oblique impact loading. Their results made a conclusion that the impact velocity had no significant effect on the critical load angle. Qi et al. [25] investigated the crash behavior of the single-cell straight, the single-cell tapered, the multi-cell straight, and the multi-cell tapered tubes by the numerical method. Their work showed that the MCT tube had the best crashworthiness performance under oblique loading. Yang and Qi [26] optimized the crashworthiness of the empty and foam-filled thin-walled square tubes under oblique impact loading. Song [27] also studied the windowed square tubes subjected to oblique impact loading by the numerical method. Song utilized the variables for the sake of the load angle, the geometrical parameters of window, and the impact velocity. In addition, a multi-objective optimization design (MOD) method was employed for the crashworthiness design of multi-cell thin-walled tubes [28–30].

Most of the above studies just emphasized independently numerical simulations, theoretical analysis or experiments. In this paper, theoretical predictions, numerical analysis and optimization design were combined together for multi-cell square tubes under oblique collapses. Based on the SSFE theory [19], theoretical expressions for mean crushing force of tubes under oblique loading were derived by dividing the profile of tubes into the basic angle elements (the right corner, 3-, T-shape, criss-cross, 4-, 5- and 6-panel angle elements). The theoretical solutions for tube I, II and III were proposed for the calculation of the bending resulted by the mean horizontal force and the mean bending moment. Dynamic finite element analyses were performed by ANSYS/LS-DYNA. A new method was proposed to get a “knee point” from a Pareto set with maximizing the reflex angle ψ.

2. Theoretics

2.1. Theoretical prediction of multi-cell square tubes

For the predictions of collapse of thin-walled multi-cell square tubes, the SSFE theory was applied to calculate the mean crushing force [31]. In this theory, the variation of wavelength $2H$ and wall thickness for different lobes was ignored, which was assumed to be constant respectively. Each panel (flange) and angle element had the same role during the collapse. The profiles of tubes were divided into seven basic elements (right-corner, 3-, T-shape, Criss-cross, 4-, 5- and 6-panel angle element) to evaluate dissipated bending and membrane energy during the collapse of a fold, as shown in Fig. 1.

Regarding tubes under an oblique impact loading, the equilibrium of the element is expressed via the principle of virtual work,

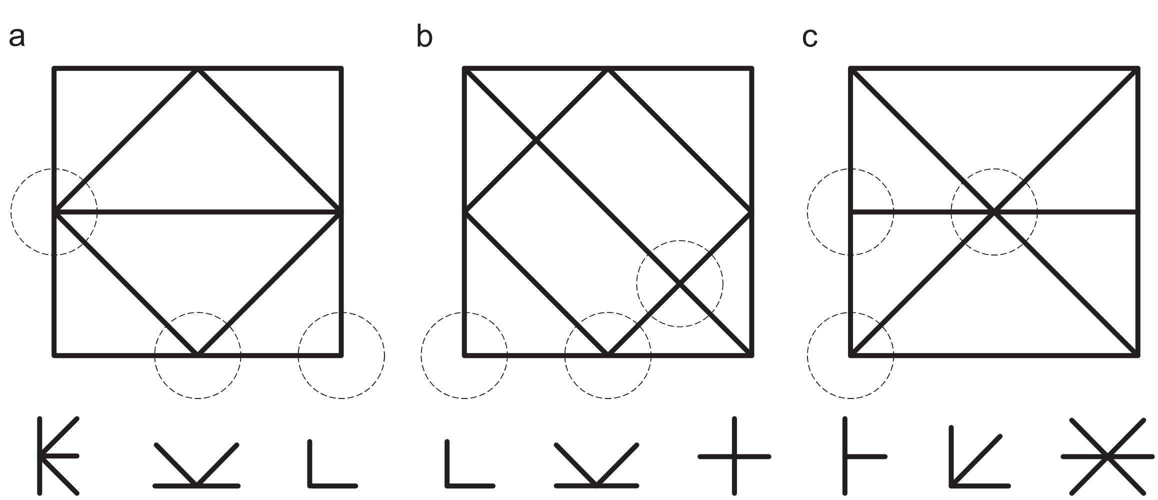

Fig. 1. Cross-sectional geometry of multi-cell square tubes and typical angle elements.