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Crashworthiness optimal design of multi-cell triangular tubes under axial and oblique impact loading

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ABSTRACT

This paper addresses multi-objective optimisation design for multi-cell structures under multiple loading angles. Triangular tubes with three different cross-sectional shapes are considered in this study. Numerical simulations are constructed via LS-DYNA to analyse the crashworthiness responses of the tubes where the accuracy of the numerical model is verified using experimental and theoretical techniques. It was observed that the global bending deformation mode occurs for all tubes at large loading angle whereas the progressive deformation mode is developed in some tubes under axial and oblique loading with small loading angles. Also, it was revealed that the load angle and number of cells have a significant effect on mean crushing force (MCF) where the impact of the number of cell on MCF is less than that of the load angle. A new kind of multi-objective optimisation for multiple loading cases (MOMLC) employing metamodeling and linear weighted average methods is presented. This optimisation strategy considers all impact loading cases simultaneously and thus it is effective for designing the multi-cell tubes under the multiple-loading case. The results exhibit that the optimal designs of the multi-cell tubes show better crashworthiness performance for multiple load cases.

1. Introduction

Increasing energy-absorption, reducing the weight during a crash are demands of the structural optimization [1]. Achieving all objectives simultaneously may be done by choosing a material such as aluminium alloy. In the past few decades, lightweight energy-absorption structures such as thin-walled tube made of aluminium alloy are increasingly used to meet the crashworthiness requirements with a minimum weight increase. Plentiful researchers have carried out on the crush and energy absorption behaviour of thin-walled tubes under axial [2], lateral [3–6] and oblique [7] loading by employing experimental, theoretical or numerical methods. The cross-sections of such energy absorbers are usually formed in cylindrical or polygon sections, and used separately or filled with foams in works [8–17]. Furthermore, the multi-cell thin-walled tubes have been considered preferably to hollow tubes since they are more likely to provide desirable stable anti-crushing forces. Regarding multi-cell thin-walled tube, Chen and Wierzbicki [18] pointed out that an addition of interior walls increased the specific energy absorption SEA by approximately 15% bigger than single-cell model. They also developed a theoretical formula for calculating the mean crushing force of multi-cell columns, which agreed well with the simulation results.

The early research tried to investigate the mechanisms of structural collapse under axial crushing. The experimental and

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Nomenclature

a	Side length
t	Wall thickness
B	Length of all bending hinge lines
PCF	Peak crushing force
P_m, MCF	Mean crushing force
P(x)	Instantaneous crushing force
SEA	Specific energy absorption
E_A	Total strain energy
d	Crushing displacement of tube
FEA	Finite element analysis
λ	Dynamic impacting coefficient
ϕ	Load angle
$w_{\phi i}$	Weighting factor
α, θ, γ, ψ	Angle at tube's corner
σ_0	Flow stress of material
σ_y, σ_u	Yield strength and ultimate strength of material
MOMLC	Multiobjective optimisation for multiple loading cases
PRS	Polynomial response surface
RBF	Radial basis function
KRG	Kriging
SVR	Support vector regression

theoretical solutions of the axial crushing force of square and circular tubes under static and dynamic loading were firstly given by Wierzbicki and Abramowicz [19, 20]. Najafi and M. Rais-Rohani [21] extended simplified folding element (SFE) theory to investigate the crushing characteristics of multi-cell tubes with two different types of three-flange elements. The multi-cell tubal structures in their study had well exhibited their superior abilities in absorbing crash energy under axial loading. Hou et al. [9, 22, 23] performed the crashworthiness design for multi-cell tube. Tran et al. [24, 25] extended simplified super folding element (SSFE) theory to investigate the crushing characteristic of multi-cell tubes with different types of angle element. The crashworthiness optimization is also carried out in their work. Alavi Nia and Parsapour [26] studied the crashworthiness and the crushing behaviour of single cell and multi-cell tubes, and revealed that adding partitions at corners does help improve the crash behaviours. Khalkhali et al. [27] also carried out multi-objective optimization of perforated square tubes considering absorbed energy, peak crushing force and weight of the tube as three conflicting objective functions. Furthermore, multi-objective optimization design (MOD) method was widely employed for crashworthiness optimization design by [25, 28, 29].

However, thin-walled multi-cell tube as an energy-absorbing component will also experience oblique impact loadings during a crash event. Then, the energy-absorbing is subjected to both axial force and bending moment. When bending takes place, the energy-absorption would be smaller [30]. Han and Park [7] investigated the behaviour of mild steel tube under oblique impact loading. Their study revealed that the axial progressive wrinkle would be transferred to global bending under the critical load angle. Reyes et al. [31] studied the crashworthiness of square tubes under quasi-static oblique impact loading according to numerical and experimental analysis. Their works reveal that the energy absorption dropped sharply when load angle exceeded a critical value. Nagel and Thambiratnam [32] also studied the behaviour of square tubes under dynamic oblique impact, and their findings affirm that the critical load angle was ineffective by the impact velocity.

Although there have been numerous studies available on the analysis of multi-cell polygon tubes under axial impact or oblique impact, optimisation of multi-cell triangular tube under multiple loading angles is rare. The triangular structures have the smallest circumference among all other shapes and thus they can be considered of particular importance for applications that are restricted in terms of space and with a limited crush zone. Therefore, this article investigates the optimisation of multi-cell triangular tube under multi-impact loadings and considers what happens during multiple loading cases and also to identify the load angle affecting both MCF and SEA. The theoretical analyses are proposed for multi-cell thin-walled tubes under oblique loading conditions. Besides, modelling results are validated by comparing with the theoretical and experimental data.

2. Numerical simulation

2.1. Geometrical description and material properties

The different shapes of the structures studied in this paper are shown in Fig. 1. Internal ribs were used with a triangular cross-

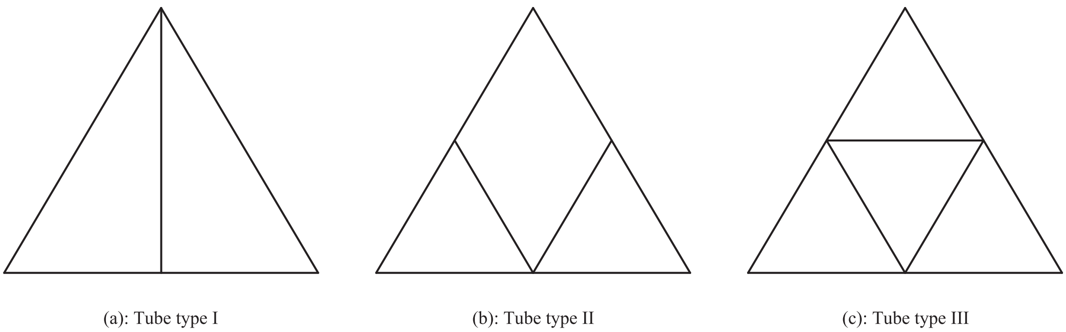

Fig. 1. Cross-sectional geometry of tubes: (a) type I; (b) type II; (c) type III;