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# Multi-objective robust optimization of foam-filled bionic thin-walled structures

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ABSTRACT

Bio-inspired design has drawn increased attention in recent years for the excellent structural properties of biological system. In our recent work, a bionic thin-walled structure (BTS), which was inspired from the structural characteristic of horsetail, was found to have excellent crashworthiness (Yin et al., 2015) [1]. In order to further improve the crashworthiness of the BTS, a foam-filled bionic thin-walled structure (FBTS) was investigated using the software LS-DYNA in this study. And, the FBTS was optimized by a multi-objective deterministic optimization (MDO) method. The MDO result indicates that the FBTS performed better than the corresponding traditional structure. However, the deterministic optimal design is likely to become unacceptable when considering the uncertainties of design parameters. To solve this problem, a multi-objective robust optimization (MRO) method which employs ensemble metamodel, NSGA-II, "3-sigma" robust design and Monte Carlo simulation (MCS) was developed. Then, the FBTS was optimized by this MRO method. The comparison of the Pareto fronts of the MDO and MRO shows that the robust optimal FBTS is more reliable than the deterministic optimal FBTS. The robust optimal FBTS not only has excellent crashworthiness but also has high reliability. Therefore, the robust optimal FBTS is a kind of excellent and reliable energy absorber in impact engineering.

## 1. Introduction

As energy absorbing devices of vehicle, thin-walled structures are widely used to protect the drivers and passengers in vehicular accident. Due to their excellent energy absorbing capacity and extraordinary light weight, a large number of investigations [2–11] were carried out on the crashworthiness of thin-walled structures. In the impact process, the thin-walled structures such as the bumper, side-door beam and B-pillar in a vehicle suffered a lateral impact loading. Therefore, some researchers had investigated the energy absorption characteristic of thin-walled structure under lateral impact condition by experimental, analytical and numerical methods [12–17]. Kim and Reid [12] studied the bending collapse of thin-walled rectangular section columns analytically. They presented an approximate method to predict the bending collapse and crumpling moment and the energy absorption for thin-walled rectangular sections. Kim and Wierzbicki [13] investigated the crush behavior of thin-walled prismatic columns under bending loading numerically and analytically. Through analyzing, they found the general characteristics of failure locus calculated analytically and numerically were quite similar. Zhang et al. [14] studied the bending collapse behavior of thin-walled square tubes with variable thickness in the cross section by experimental and numerical methods. They found that the characteristic of variable thickness in the cross section could improve the crashworthiness performance of structure under lateral impact.

To reinforce the energy absorption capacity of thin-walled structure and obtain light weight design, filling cellular materials like aluminum foam into thin-walled structures had proven to be an ideal method [18–22]. Santosa and Wierzbicki [18] studied the effect of ultralight metal filler on the bending collapse behavior of thin-walled prismatic columns. They found that the columns filled with low-density metallic such as foam or honeycomb could effectively increase the bending strength of the column. Chen [19] investigated bending collapse of foam-filled hat profiles by experiment and numerical simulation. It was found that foam-filled members provided a 30–40% increase, compared to traditional non-filled members, of the specific energy absorption. Guo and Yu [20] studied the dynamic bending behavior of foam-filled bitubular structures experimentally and numerically. Through analysis, they found that the foam-filled double cylindrical tubes had steadier load carrying capacity and much higher energy absorption

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efficiency than traditional foam-filled single tube under bending conditions. Based on previous investigations [23–29], the same phenomenon was also found when researchers studied the crash-worthiness of foam-filled thin-walled structures under axial impact loading. For instance, Seitzberger et al.. [23] investigated the square tube under axial impact through experiments and they found that square tubes filled with aluminum foam had better energy absorption efficiency than the empty square tubes. Ahmad and Thambiratnam [24] studied conical tubes under quasi-static axial loading. Based on the energy absorption performance of the foam-filled conical tube, they found that the foam-filled conical tube was superior to empty conical tube.

Although the foam filler can improve the energy absorption capacity of thin-walled structure, the energy absorption was found to be significantly dependent on the foam density and tube geometry [30]. Therefore, optimization techniques have been widely employed as useful methods to select the appropriate tube geometry and foam density. Zarei and Kröger [31] optimized both the empty and the foam-filled beams. From the optimization results, they found that the optimal foam-filled beam could absorb the same energy as the optimal empty beam but it had 28.1% lower weight than the empty one. To achieve maximum SEA and minimum collapse load, Baroutaji et al. [32] carried out multi-objective crashworthiness optimization for oblong tube and they found that the optimal design of unconstrained oblong tube (FIU) can be obtained when the tube diameter and tube width were set at their minimum limits and the maximum tube thickness was chosen. Fang et al. [33] conducted the multi-objective crashworthiness optimizations for the structures of uniform foam (UF) and functionally graded foam (FGF) filled beams. From optimization results, they found that the FGF filled beams performed better than the UF counterparts. Yin et al. [34] optimized the foam-filled multi-cell thin-walled structures (FMTSs) under lateral impacts. According to the comparison of Pareto fronts, they found that the FMTS with nine cells had the best crashworthiness in their considered cases.

Nowadays, bionic structures had gained researchers' attentions due to their excellent crashworthiness as well as extraordinary light weight. Liu et al. [35] proposed and studied the bionic non-convex multi-corner column (BI-NCMC), which was inspired from the bamboo. They found that the BI-NCMC had higher energy absorption than a similar column without the bulkheads. Yin et al. [1] designed and investigated a new energy absorbed structure named as bionic thin-walled structure (BTS) based on the structure characteristics of horsetails. They found that the crashworthiness of BTSs was better than that of traditional thin-walled structure, i.e., the circular and square tubes. However, this horsetail-based bionic structure is an empty structure. In order to further improve the energy absorption capacity of the horsetail-based bionic structure, the foam-filled bionic thin-walled structure (FBTS), which can be obtained by filling aluminum foam into the horsetail-based bionic structure, was proposed.

The punch used for structural bending in the above studies was in the mid-span without considering the practical position uncertainty.

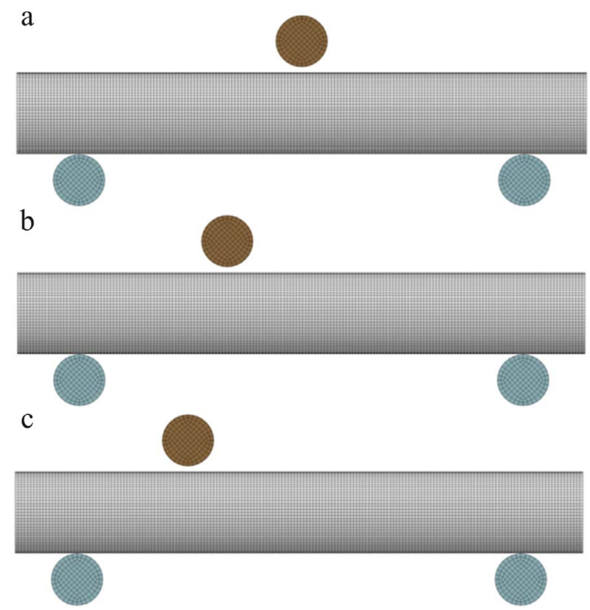


**Fig. 2.** Finite element models of FBTS with different punch positions: (a) $p$= L/2, (b) $p$= L/3 and (c) $p$= L/4.

And, the optimization studies on thin-walled structures were based on deterministic simulations without considering the uncertainty of design variables. In this study, the FBTS under lateral impact condition with different punch positions was investigated using nonlinear finite element method through LS-DYNA. In order to consider the uncertainty of the design variables, a multi-objective robust optimization method which employs ensemble metamodel, multi-objective non-dominated sorting genetic algorithm II (NSGA-II), "3-sigma" robust design and Monte Carlo simulation (MCS) was developed and used to optimize the FBTS.(Figs. 1 and 2).

## 2. Finite element modeling

### 2.1. The cross-section configuration of FBTS

According to the previous work [1], we proposed and investigated a new thin-walled structure named as bionic thin-walled structure (BTS). Based on the investigation results, we found that the BTS with twelve cell numbers (BTS12) was the best. In order to reinforce BTS12, we filled aluminum foam into it. In this study, the foam-filled BTS (FBTS) was subjected to lateral impact loading. The loading illustration and the cross section of the FBTS with twelve cell numbers are shown in Fig. 3. The FBTS lay on two cylindrical supports [1]. A cylindrical punch with a diameter of 50 mm and a mass of 1500 kg impacted onto the FBTS at an initial velocity of $v$=15 m/s. The span and diameter of the two cylindrical supports were 430 mm and 50 mm, respectively. The length, the outer diameter and the inner diameter of the FBTS were

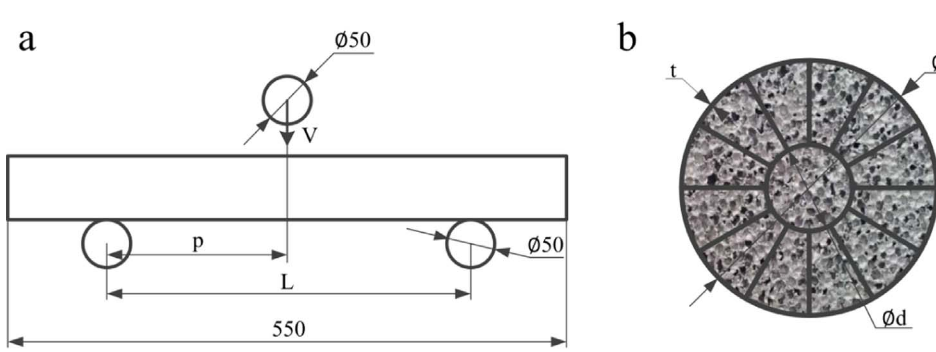


**Fig. 1.** Loading condition and cross section of FBTS: (a) Loading condition and (b) cross section.