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A comparative study on empty and foam-filled hybrid material double-hat beams under lateral impact

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ABSTRACT

In previous research, an innovative hybrid material double-hat thin-walled beam has been proposed for vehicle bumper system, which has demonstrated great potentials for improved pedestrian safety and reduced weight. In this work, we have used aluminum foam to fill the hybrid double-hat beam to further its application in vehicle bodies with increased bending resistance and energy absorption efficiency. Bending behaviors of both empty and foam-filled hybrid beams were numerically investigated using the validated LS-DYNA models. Three representative loading positions including the mid-span, 50 mm and 100 mm offsets from the mid-span were simulated to reveal the effect of load position uncertainty. It was found that the foam filler could increase the specific energy absorption (*SEA*) by more than 30% and double the bending moment (*Mb*) of the empty hybrid beam by changing its deformation pattern. Moreover, the foam-filled beam shows more robust crashworthiness performance against load position variation. Using radial basis function (RBF) metamodels, the multi-objective design optimization (MDO) problems were formulated for both empty and filled hybrid beams to maximize *SEA* and *Mb* and minimize the initial peak force (F_{ip}). The multi-objective particle swarm optimization (MOPSO) was used to seek the Pareto fronts of the MDO problems. The MDO results show that the foam-filled beam has much broader performance space in terms of F_{ip}, *SEA* and *Mb* and has great potentials for high-energy crash applications. It was also found that the Pareto front varies for different loading positions for either empty or filled hybrid beam. Including multiple loading positions could achieve a more robust design against load uncertainty. Appropriate weighting factors should be chosen for different loading positions to yield realistic and more robust designs of the proposed hybrid beams.

1. Introduction

In recent years, research attention on the materials used for thin-walled vehicle body structures has shifted from conventional steels to advanced lightweight materials, such as aluminum alloys [1–3] because of their commendable energy absorbing abilities and lightweight characteristics. On the other hand, despite of the great potentials for weight reduction, higher cost and poorer impact intrusion performance of the aluminum alloys compared with steel counterparts restrained their wide applications on vehicle body structures. To utilize fully the advantages of both steel and aluminum alloys, some researchers have proposed hybrid material vehicular body structures and investigated their crashworthiness performances. For instance, Zhou et al. [4] proposed an S-shaped vehicle front rail made of steel-aluminum hybrid materials to reduce the peak impact force and the total weight when adopted in a vehicle's body frame. Gedikli and Meric investigated the crashworthiness of empty [5] and foam-filled [6,7] aluminum-steel tailor-welded tubular structures under axial impact. They found that both material type and tube configuration have significant effects on the axial crashworthiness of such tubes. Wang et al. [8] revealed that tapered tailor welded tubes made of aluminum-steel hybrid materials outperformed their homogeneous counterparts with more stable deformation and energy absorption processes when oblique impact is inevitable. Fang et al. [9] optimized the crashworthiness of a steel-aluminum hybrid S-shaped rail. Compared to the conventional monomaterial structure, the hybrid rail increased the energy absorption while maintaining the peak force and total weight at a lower level.

Filler materials including honeycombs [10], polyethylene foams [11] and metal foams [12–14], have been widely used to further increase the energy absorptions of thin-walled tubular structures without adding extra volume and too much weight. Researchers have carried out extensive studies to reveal the crashworthiness difference of the thin-walled structures with and without foam fillers [14–20]. Thambiratnam [16,17] highlighted the significant role of metal foam fillers

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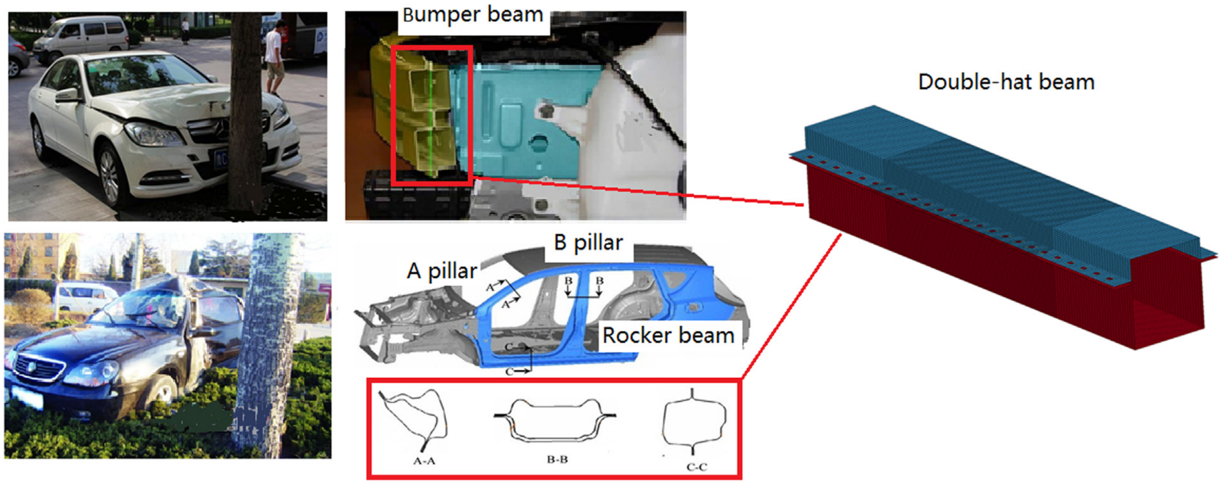

Fig. 1. Application of thin-walled double-hat beam on vehicle body for lateral impact.

for conical tube type energy absorbers in impact applications. Yang et al. [18] compared the crashworthiness of empty and foam-filled columns under both axial and oblique impacts. Based on the optimization results, they found that foam-filled columns have a better performance than empty columns under axial impact loading.

In the aforementioned studies, most of the thin-walled components were under pure axial and/or oblique loads. In reality, lateral and bending loads exert more frequently on vehicle bodies in car accidents, and the vehicular components such as the bumper beam and the B-pillar commonly undergo bending or lateral deformation modes to absorb the impact energy (see Fig. 1). Many researchers have studied the lateral impact behaviors of thin-walled structures [21–29]. Among them, Zarei and Kröger [22] investigated the bending behaviors of empty and foam-filled aluminum square columns using experimental and numerical methods. According to their results, the optimal foam-filled beam could absorb the same amount of energy as the optimal empty beam with 28.1% weight reduction. Xiao et al. [28] proposed a novel bumper beam filled with functionally graded foam (FGF) and demonstrated that the FGF-filled bumper beam has much better crashworthiness than the uniform foam filled and hollow bumper beams. Compared with the baseline empty bumper beam, the FGF-filled beam ensures the crashworthiness of a passenger car while reducing the weight by about 14.4%. Considering the complicated situations in real-life accidents, several recent work have been devoted to the lateral impact of thin-walled structures with load position uncertainties [23,24,27], and found that the lateral crashworthiness is very sensitive to the loading position. Sun et al. [23] showed that functionally graded tubes outperform uniform tube in bending resistance under different loading positions. Wang et al. [24] investigated the transverse bending behaviors of multi-cell square tubes under different loading positions, and revealed the significant effect of the partition plates on the lateral impact behaviors of such tubes considering different loading positions.

Meanwhile, researchers have applied structural optimization techniques extensively to the crashworthiness design of thin-walled structures over the past two decades [30]. In contrast to the substantial optimization work focused on axial and oblique loads, a limited number of studies have considered lateral and bending loads, which actually may occur more frequently on vehicle bodies as previously mentioned. Noticing this, Sun et al. [31] performed multi-objective crashworthiness optimizations of the functionally graded and the uniform thickness tubes under lateral impacts. Based on the bionic-inspired design concept, Yin et al. [32] and Zou et al. [33] developed a type of thin-walled structure. They also conducted multi-objective optimizations of such structures under lateral impact to seek optimal configurations with maximum specific energy absorption (*SEA*, i.e., energy absorption per unit structural mass), and minimum initial peak force.

This research aim at developing innovative hybrid material lightweight energy absorption structures for automotive crashworthiness applications. In the previous work [34], the authors proposed a new type of double-hat thin-walled beam comprising an aluminum alloy upper hat and a steel lower hat. The hybrid material beam showed a well-balanced and better bending performance under lateral impact loading compared with its homogeneous counterparts. In this work, we have used aluminum foam to fill the hybrid double-hat beam for further increased bending stiffness, such that it can adapt to a wider range for energy dissipation and load transfer of auto bodies. By using LS-DYNA, we numerically analyzed the lateral impact response of the foam-filled hybrid double-hat beam. The numerical modeling methods were validated using the experimental test data. We have considered three representative impact positions to account for loading uncertainty. The bending behavior of the foam-filled hybrid beam was compared with that of the empty beam in terms of the initial peak force (F_{ip}), the specific energy absorption (*SEA*) and the bending moment (*Mb*). In addition, we formulated the multi-objective design optimization (MDO) problems for both the empty and the foam-filled hybrid beams with and without load uncertainty. By means of radial basis function (RBF) metamodels, we employed the multi-objective particle swarm optimization (MOPSO) algorithm to reveal the Pareto fronts of the MDO problems. The outcome of the current work could provide useful information for the application of such hybrid beams on automotive body structures.

2. Materials and methods

2.1. Empty and foam-filled hybrid double-hat beams

Fig. 2 illustrates the geometric configurations of the empty and the foam-filled hybrid double-hat beams under lateral impact loading. The empty beam consists of three parts: an upper hat made of aluminum alloy, a lower hat made of high strength steel and 48 steel rivets. The foam-filled beam has identical configuration as the empty beam except the addition of the aluminum foam filler between the two hats. Both specimens have a length of 500 mm and a cross section width of 80 mm. The upper and lower hats have fixed heights of 20 mm and 60 mm, respectively. The flanges have a width of 20 mm, and the rivets with a diameter of 5.2 mm were located on the flanges with a pitch of 20 mm. Both beams have an upper hat thickness t_{Al} = 1.2 mm and a lower hat thickness t_{Steel} = 1.2 mm. Besides, the foam-filled beam has an aluminum foam filler with uniform density ρ_f = 240 kg/m^3.

The empty and foam-filled profiles rest on two 30 mm-diameter cylindrical supports with 400 mm span. To simulate the realistic loading condition of the double-hat profiles used as automotive bumper