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Dynamic bending responses of CFRP thin-walled square beams filled with aluminum honeycomb

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ABSTRACT

Aluminum honeycomb-filled Carbon Fibre Reinforced Plastic (CFRP) thin-walled square beams is a new outstanding energy absorption component. In this paper, dynamic impact tests for bending of aluminum honeycomb-filled CFRP beams with different configurations are carried out, and the failure mode and force responses are investigated. For the failure mode, modified Chang-Chang failure criteria are used to predict tensile and compressive fibre failure, as well as tensile and compressive matrix failure. Numerical simulation of the tests is also performed, and the accuracy is validated by the experimental results. The influences of some factors, including the wall thickness, fibre direction, stacking sequence, and impact velocity, on the bending resistance, are analyzed. The effect of aluminum honeycomb filler on the crashworthiness characteristics is also discussed. The results show that the energy absorption and specific energy absorption of filled composite tubes can significantly increase by 104.3% and 26.8% respectively compared with those of CFRP hollow beams. This study demonstrates the potential of CFRP beams filled with aluminum honeycomb to be used as energy absorbers.

1. Introduction

It has been proven that Carbon Fibre Reinforced Plastic (CFRP) is an effective energy-absorbing material [1,2]. CFRP thin-walled structures are considered exceptionally efficient energy-absorbing components for aerospace and automotive engineering applications [3–5]. However, the issue as to how to decide the best possible structural configuration still presents a challenge. Composite structures filled with lightweight materials have also attracted considerable interest due to their potential to enhance the energy-absorbing capability of composite structures. Moreover, honeycomb filling has been shown to be efficient in improving the energy absorption and specific energy absorption of composite structures [6–12]. It should be noted that aluminum honeycomb-filled CFRP thin-walled square beams have not been studied in depth. As such, understanding their mechanical behavior and crashworthiness would be of critical importance to more extensive and reliable application of such composites [13].

Extensive studies have been made on the crashworthiness characteristics of composite structures with lightweight filler. Aluminum honeycomb has attracted much attention as a typical cellular material due to its excellent mechanical and energy absorption property, and specific strength-to-weight ratio. Qiang Liu et al. [1] explored the crashworthiness of CFRP square tubes filled with aluminum honeycomb subjected to quasi-static axial crushing. By comparison, the peak load and absorbed energy of the filled tubes increased by more than 10% compared with those of hollow CFRP tubes, ranging from approximately 12.41–27.22% and from approximately 10.49–21.83% respectively. They [14] also investigated the lateral planar crushing and bending responses of CFRP square tubes filled with aluminum honeycomb. The results of a lateral three-point bending test showed that the peak load, energy absorption and specific energy absorption of honeycomb-filled CFRP tubes increased by 17%, 32% and 0.9% respectively compared with those of CFRP hollow tubes. Rafea Dakhil Hussein et al. [15] studied the axial crushing behavior of aluminum honeycomb-filled square CFRP tubes. The results showed that the energy absorption of aluminum honeycomb-filled CFRP tubes increased by 20–36% over that of hollow CFRP tubes at different crushing velocities. Nine kinds of foam-filled multi-cell thin-walled structure (FMTS) with different cross-sectional configurations under lateral crushing load conditions were investigated by Hanfeng Yin et al. [16]. The complex proportional assessment method was used to clarify which kind of FMTS has the best crashworthiness, and FMTS with 2, 3 and 9 cells were found to be the three best structures among the considered cases. They were optimized using a metamodel-based multiobjective optimization method which was developed by employing a polynomial regression metamodel and multiobjective particle swarm optimization algorithm. A new type of

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tube filler with good cost-effectiveness and easy availability was proposed by Xiong Zhang et al. [17]. Quasi-static and dynamic impact tests for the bending of tube-filled beams with different configurations were carried out, and the deformation mode and force responses were investigated. They also [18] tested Commercial aluminum honeycomb with various cell configurations in order to study the influence of the cell number and central angle on the out-of-plane crush resistance of such structures. The dynamic responses and blast resistance of innovative honeycomb sandwich structures with auxetic re-entrant cell honeycomb cores under blast loading were investigated numerically by Xiaochao Jin et al. [19]. The results showed that both graded honeycomb cores and cross-arranged honeycomb cores could significantly improve resistance ability. Guo Liuwei et al. [20] studied the dynamic three-point bending behavior of double cylindrical tubes with closed-cell aluminum foam-filled cores. The results showed that, compared with traditional foam-filled single tubes, the specific energy absorption of this new structure was much higher, and those of both foam-filled structures in a dynamic situation were higher than in a static situation. Shojaeifard et al. [21] studied the energy absorption characteristics of hollow and foam-filled aluminum tubes with different cross-sections (circular, square and elliptic) numerically, and the results showed that the energy absorption of the elliptic foam-filled tubes was 22.5% higher than that of the hollow aluminum tubes, while the energy absorption of the circular and square foam-filled tubes were 38.2% and 17.1% higher than that of the hollow aluminum tubes respectively. Zarei and Kroger [22] performed bending crash tests on hollow and foam-filled square aluminum beams, and the results showed that the energy absorption of the foam-filled square aluminum beams could be 31.5% higher than that of the hollow beams. Qiang Liu et al. [23] studied the impact responses and residual properties of thin-walled CFRP tubes and aluminum tubes subjected to multiple axial impacts, and the results showed that the CFRP tubes had much better performance in energy absorption capacity in comparison with the aluminum counterparts, weighting approximately 134.86~184.38% in the repeated impact tests and 185.83~204.32% in the residual crushing tests under the same condition. Zhonggang Wang et al. [24] studied the matching effect of honeycomb-filled thin-walled square by means of both experiments and numerical simulations. The results showed that, the geometric configuration, the material properties as well as the loading impact velocity have significant influence on the matching effect. Different HFST structures with different geometric configurations or different matrix material properties, or undergoing different impact velocities show different mechanical behaviors.

Although composite structures filled with lightweight materials have been extensively studied, there have been limited studies on CFRP thin-walled square beams filled with aluminum honeycomb. Furthermore, most of the experiments have been conducted under quasi-static conditions and few studies have paid attention to the dynamic crashing response. In this work, a investigation of their mechanical behavior is attempted, including failure modes and key factors affecting energy absorption, whose knowledge is believed to be necessary for designing a highly effective energy absorption devices.

Table 2
The material properties of aluminum honeycomb core.

E(GPa)	ν	ρ(kg/m3)	σ_s(Pa)
70	0.33	2.70E+ 03	2.76E+ 07

E: elastic modulus, ν: Poisson's ratio; ρ: density, σ_s: yield strength.

2. Materials and methods

2.1. Materials and lay-up schemes

CFRP thin-walled square beams are made of T700/FAW100 carbon fibre. Table 1 lists the material properties of CFRP T700/FAW100. Nine material constants in Table 1 will be used in the finite element analysis (FEA).

Consisting of 3003 aluminum alloy, the filled aluminum honeycomb cores have isotropic material properties. The specific material properties are listed in Table 2.

For the CFRP thin-walled square beams, three groups of different lay-up schemes are designed which consider the influence of wall thickness, fibre direction ($\pm 15^{\circ}$, $\pm 30^{\circ}$, $\pm 60^{\circ}$ and $\pm 75^{\circ}$) and stacking sequence respectively. The single-ply thickness of the fibre is 0.2 mm. The final lay-up scheme is shown in Table 3.

2.2. Specimen preparation

The CFRP thin-walled square beam specimens studied in this paper have cross-sectional dimensions of 40 × 40 mm and lengths of 300 mm, and their wall thickness is determined by the number of layers. The CFRP tubes are bonded to the aluminum honeycomb cores with DG-4 epoxy adhesive which can be set at room temperature and withstand temperatures of − 60 °C to + 120 °C. Moreover, the bonding process is simple, convenient and fast. The specimens are respectively numbered a-1, a-2, a-3, a-4, b-1, b-2, b-3, b-4, b-5, c-1, c-2, c-3, c-4, c-5, d-1, d-2, d-3, d-4, d-5, d-6 and a3-H, with two specimens for the same lay-up scheme (for example a-1-N1 and a-1-N2). The CFRP thin-walled beam test specimens are shown in Fig. 1.

2.3. Testing procedure

Dynamic drop hammer impact tests are carried out for the specimens on a 5000 J drop-hammer test machine at Structural Impact Laboratory at Huazhong University of Science and Technology. The geometry of the test is given in Fig. 2. In the impact loading, the head of the punch and supports are cylindrical with a diameter of D = 24 mm, and the span of the CFRP square beams is set at 240 mm. The dynamic experiment setup for the three-point bending test is shown in Fig. 3. It is mainly composed of a drop hammer testing machine, a data acquisition system and an experimental operating device. The impact hammer has a mass of 78.1 kg and is released at a height of 1.35 m. The fall of the impact hammer is controlled by the experimental operating device. The velocity of the hammer before impact on the specimen is measured as 5.1 m/s due to the influence of friction. Since the kinetic energy of the drop hammer is much larger than the energy that the specimens can absorb, the average velocity is about 5 m/s in the whole process [15]. As shown in Fig. 4, in order to prevent a second impact, a buffer device

Table 1
The material properties of CFRP T700/FAW100.

E_1(GPa)	E_2(GPa)	E_3(GPa)	ν_{21}	ν_{32}	ν_{31}	G_{12}(GPa)	G_{23}(GPa)	G_{13}(GPa)
150	9	9	0.24	0.24	0.28	5.12	5.12	3.34

E_1: longitudinal modulus, E_2, E_3: transverse modulus; ν_{21}: 21-direction Poisson's ratio, ν_{31}: 31-direction Poisson's ratio, ν_{32}: 32-direction Poisson's ratio; G_{12}, G_{13}: 12-direction, 13-direction shear modulus, G_{23}: 23-direction shear modulus.