Composites Part B 153 (2018) 295–305

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Energy absorption of foam-filled multi-cell composite panels under quasi-static compression

Jiye Chen[a], Hai Fang[a,*], Weiqing Liu[b,**], Lu Zhu[a], Yong Zhuang[c], Jian Wang[a], Juan Han[a]

[a] College of Civil Engineering, Nanjing Tech University, Nanjing, China
[b] Advanced Engineering Composites Research Center, Nanjing Tech University, Nanjing, China
[c] China Railway Major Bridge Reconnaissance & Design Institute Co., Ltd., Wuhan, China

ARTICLE INFO

Keywords:
Foam-filled multi-cell
FRP
Quasi-static compression
Energy absorption
Numerical simulation

ABSTRACT

This paper reports on the energy absorption characteristics of four types of innovative foam-filled multi-cell composite panels (FMCPs) composed of glass fiber reinforced polymer (GFRP) face sheets, GFRP lattice webs, and polyurethane (PU) foam. Quasi-static compression experiments on the FMCPs manufactured by a vacuum assisted resin infusion process (VARIP) were performed to demonstrate the feasibility of the proposed panels. Compared with the traditional FMCP with double-layer orthogonal foam cells, a maximum decrease in the peak crushing force (PCF) of approximately 148% was obtained for the FMCP with trapezoidal cells. Moreover, the enormous decrease in bearing load has been overcome by the proposed FMCPs. Among the four proposed FMCPs, the FMCP with double-layer dislocation cells exhibited the greatest specific energy absorption (SEA) capacity and the highest mean crushing load (MCL). Several numerical simulations using ANSYS/LS-DYNA were conducted on the FMCP with double-layer dislocation cells to parametrically investigate the effects of the face-sheet and lattice-web thickness, the foam-cell height, the foam-cell width, and the foam density. The effectiveness and feasibility of the numerical model were verified by the experimental results. The numerical results demonstrated that thicker face sheets and lattice webs, higher foam densities, and narrower foam cells can significantly increase the PCF and bearing load decrease. Moreover, the PCF and bearing load decrease were hardly affected by the foam-cell height.

1. Introduction

Extensive research has been conducted on the energy absorption performance of anti-collision facilities as a consequence of the increasing frequency of ship-bridge collisions. According to the principle of energy absorption and momentum buffering, several types of anti-collision devices have been developed, and each type has its own characteristics and operating conditions [1,2]. Steel fenders are more commonly used in China than other types of anti-collision devices [3], but this fender device exhibits major drawbacks, such as poor corrosion resistance, high initial costs, and high maintenance requirements [4].

Compared with traditional anti-collision devices, composite sandwich structures are particularly appealing to anti-collision structures (Fig. 1) owning to their high strength to weight ratios, good cushioning performance, excellent corrosion resistance, and enhanced stability [5–18]. Foam-filled sandwich panels composed of upper and lower face sheets and a polyurethane (PU) foam core were tested under quasi-static compression, and the results showed that the PU foam core plays an important role in energy absorption [19,20]. However, foam-filled sandwich panels have a low initial stiffness and a low ultimate strength, and they exhibit severe interfacial debonding. Thus, a foam-filled multi-cell composite panel (FMCP) with double-layer orthogonal foam cells (Fig. 2) was proposed to overcome these weaknesses, and such panel demonstrated a significant increase in the ultimate bearing capacity under both bending and compression because of the improved resistance to interfacial debonding between the face sheets and foam core [20–22]. Nevertheless, further investigations showed the FMCP with double-layer orthogonal foam cells has two major drawbacks, a great peak crushing force (PCF) and a sudden enormous bearing load decrease [Fig. 6(a)]. The enormous bearing load decrease is not conducive to energy absorption and the substantial drop in the bearing capacity over a very short time may cause secondary damage to people and impact objects. Based on existing research on the FMCP with double-layer orthogonal foam cells, four types of innovative FMCPs (Fig. 2)

---

[*] Corresponding author.
[**] Corresponding author.

E-mail addresses: fanghainjut@njtech.edu.cn (H. Fang), wqliu@njtech.edu.cn (W. Liu).

https://doi.org/10.1016/j.compositesb.2018.08.122
Received 8 August 2018; Received in revised form 24 August 2018; Accepted 26 August 2018

(a)

(b)

Fig. 1. Application of the orthogonal lattice-web reinforced composite sandwich panels as anti-collision devices: (a) Langqi Min River Bridge and (b) Oubei Bridge.

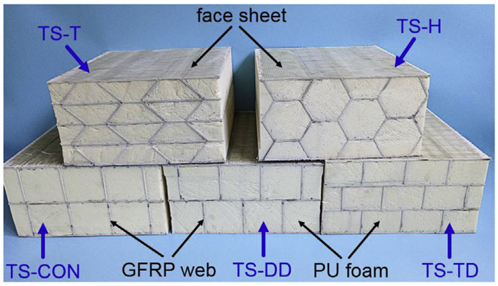

Fig. 2. Photo of the five FMCPs (TS-CON: traditional FMCP; TS-DD: FMCP with double-layer dislocation cells; TS-TD: FMCP with three-layer dislocation cells; TS-H: FMCP with hexagonal cells; TS-H: FMCP with trapezoidal cells).

were proposed to overcome these two major drawbacks. The FMCP, which uses PU foam as the cell and glass fiber-reinforced polymer (GFRP) as the face sheets and lattice webs, was manufactured through the vacuum-assisted resin infusion process (VARIP) method. The energy absorption characteristics of such FMCP draw our research attention.

In this paper, the quasi-static compression properties and energy absorption characteristics of the traditional FMCP with double-layer orthogonal foam cells and four proposed innovative FMCPs were investigated through experimental and numerical methods. All panels were manufactured through the VARIP and loaded by pressing two rigid plates on the upper and lower face of each panel. The failure modes, load-deflection curves and energy absorption characteristics of the FMCPs were reported and discussed. Parametric studies on the effects of the face-sheet and lattice-web thicknesses, the foam-cell height, the foam-cell width, and the foam density were conducted on the FMCP with double-layer dislocation cells.

2. Experimental program

2.1. Specimen description

In this study, five types of FMCPs were manufactured using the VARIP, and three identical testing panels were created for each type. These panels were constructed from face sheets and cells wrapped by lattice webs. The face sheets and webs were made of bi-axial [0/90] glass fiber laminates (800 g/m^2) and HS-2101-G100 unsaturated polyester resin. A variety of PU foam blocks with a nominal density of 60 kg/m^3 were used to form the cells, which were bonded to the face sheets and webs with the HS-2101-G100 unsaturated polyester resin. All panels had identical lengths (L = 300 mm), widths (W = 300 mm), heights (H = 150 mm), face-sheet thicknesses (t_s = 2.4 mm) and lattice-web thicknesses (t_w = 2.4 mm), as listed in Table 1. Specimen TS-CON, which was a controlled composite panel with GFRP face sheets, GFRP lattice webs and double-layer orthogonal foam cells, was used to investigate the energy absorption performance of normal composite panels. Specimens TS-DD, TS-TD, TS-H and TS-T, which were fabricated with double-layer dislocation cells, three-layer dislocation cells, hexagonal cells and trapezoidal cells, respectively, were used to investigate the influence of the cell type. Table 1 gives the details of each type of specimen.

2.2. Manufacturing procedures

Fig. 3 presents a detailed illustration of the manufacturing procedures of specimen TS-T, the manufacturing of which can be divided into the following four steps:

(i) As shown in Fig. 3(a), the manufacturing procedure began with the preparation of PU foam cells, which were cut into trapezoidal cross-sections according to the design dimensions. Many grooves of approximately 2 mm in width and 3 mm in depth were predrilled on all side faces for resin infusion during the VARIP.
(ii) As shown in Fig. 3(b), the foam cells were wrapped by E-glass fiber mats with 2 layers of bi-axial [0/90] glass fiber (with each layer weighing 800 g/m^2) to create the GFRP lattice webs.
(iii) The face sheets, which were also composed of 2 layers of bi-axial [0/90] E-glass fiber mats, were placed on the foam cells. Then, the foam cells covered with face sheets were sealed by a diversion cloth and a vacuum bag for the resin infusion, as shown in Fig. 3(c) and (d), respectively. The HS-2101-G100 unsaturated polyester resin was infused through the foam cells and face sheets by vacuum pressure using a series of predrilled grooves.
(iv) After curing the resin for 8 h, the manufacturing process was completed [Fig. 3(e)]. Then the panels were cut according to the design requirements [Fig. 3(f)].

2.3. Material properties

The tensile properties of the GFRP face sheets and lattice webs were evaluated under tension tests according to ASTM D3039/D3039M − 14 [23]. Five tension coupons with dimensions of 250 × 25 × 5 mm^3 were tested at a displacement rate of 2 mm/min until failure. The resulting tensile strength ranged from 303.1 MPa to 339.5 MPa, with an average of 321.5 MPa, and the resulting tensile modulus ranged from 20.3 GPa to 21.1 GPa, with an average of 20.7 GPa. Meanwhile, the flatwise compression properties of the GFRP face sheets and lattice webs were measured by compression tests based on ASTM D695-10 [24]. Five cubic compression coupons of 100 × 100 × 50 mm^3 were tested at a displacement rate of 1 mm/min. The resulting compressive strength ranged from 162.8 MPa to 168.3 MPa, with an average of 165.4 MPa, and the resulting compressive modulus ranged from 19.3 GPa to 20.6 GPa, with an average of 19.9 GPa. Table 2 gives an overview of the results.

The mechanical properties of the PU foam core were assessed under compression tests according to ASTM C365/C365M − 16 [25] by testing five coupons of 60 × 60 × 50 mm^3, under tension tests according to ASTM C297/C297M − 16 [26] by testing five coupons of 60 × 60 × 50 mm^3, and under shear tests according to ASTM C273/