Composites: Part B 67 (2014) 270–279

Contents lists available at ScienceDirect

Composites: Part B

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

Mechanical performance of foam-filled lattice composite panels in four-point bending: Experimental investigation and analytical modeling

Lu Wang [a], Weiqing Liu [a,*], Li Wan [a], Hai Fang [a], David Hui [b]

[a] College of Civil Engineering, Nanjing Tech University, Nanjing, China
[b] Department of Mechanical Engineering, University of New Orleans, New Orleans, USA

ARTICLE INFO

Article history:
Received 1 May 2014
Received in revised form 21 June 2014
Accepted 6 July 2014
Available online 23 July 2014

Keywords:
A. Foams
A. Glass fibers
B. Strength
C. Analytical modeling
D. Mechanical testing

ABSTRACT

This study focused on the bending behavior of an innovative sandwich panels with GFRP face sheets and a foam-web core (GFFW panels), manufactured by vacuum assisted resin infusion process. An experimental study was carried out to validate the effectiveness of this panel for increasing the ultimate bending strength. Compared to the control specimen, a maximum of an approximately 410% increase in the ultimate bending strength can be achieved. The influences of web thickness, web height and web spacing on failure mode, initial bending stiffness and mid-span deflection were also investigated. Test results demonstrated that the ultimate bending strength and initial bending stiffness can be enhanced by increasing web thickness and web height. In the meantime, the indentation failure and local wrinkling failure did not occur due to the presence of the GFRP webs. Furthermore, an analytical model was proposed to predict the mid-span deflection and initial bending stiffness of GFFW panels. A comparison of the analytical and experimental results showed that the analytical model accurately predicted the ultimate bending strengths and min-span deflections of the GFFW panels loaded in four-point bending.

1. Introduction

Recently, composite sandwich panels have been used increasingly in the structural engineering due to their advantages of low cost, high strength to weight ratios and convenient usage. In sandwich panels, low density materials, such as foam, paulownia wood and honeycombs, have been usually adopted to be the cores, which are combined with high stiffness face sheets to resist applied loading. The face sheets provide major contribution to the bending stiffness while the core provides the major of shear stiffness of sandwich structures.

A large number of experimental and analytical studies on sandwich members with different type of foam core have been conducted in the past three decades [1–12]. Steeves and Fleck [13,14] conducted the experimental, numerical and analytical studies on the collapse mechanisms for simply supported sandwich beams with GFRP face sheets and a PVC foam core. Twenty-nine sandwich beams were tested under three-point bending. The test results indicated that collapse was significantly influenced by the sandwich beam geometry and the density of the foam core. Tagarielli et al. [15] studied the initial collapse modes of sandwich beams with clamped and simply supports under three-point bending. Initial collapse was by three competing mechanisms: microbuckling of face sheet, core shear and indentation. The test results demonstrated that the simply supported beams displayed a softening post-yield response, but the clamped beams exhibited hardening behavior because of membrane stretching of the face sheets. An theoretical model to predict the deflection of clamped beams were also developed. Sharaf et al. [16] tested ten wall sandwich panels with a foam core under one-way bending. The test results showed that bending strength and stiffness of the panels improved significantly with the increase in foam density. However, the horizontal slip was measured between the top and bottom face sheets. The foam core with a smaller toughness can lead to a larger horizontal slip. Wang and Shen [17] studied the nonlinear bending of a sandwich panel with carbon nanotube-reinforced composite face sheets resting on an elastic foundation in thermal environments. The influences of nanotube volume fraction, core-to-skin thickness ratio, temperature change, foundation stiffness and in-plane boundary conditions on the nonlinear bending behaviors of sandwich plates were investigated. Dawood et al. [18] evaluated

* Corresponding author. Address: College of Civil Engineering, Nanjing Tech University, Pu Zhu South Road 30, Nanjing 211816, China. Tel.: +86 25 58139862; fax: +86 25 58139863.

E-mail address: wqliu@njtech.edu.cn (W. Liu).

http://dx.doi.org/10.1016/j.compositesb.2014.07.003
1359-8368/

the behavior of 3-D GFRP sandwich panels with fiber insertions subject to two-way bending. The test results showed that the behavior of the panels was determined by the panel thickness and the shear stiffness of the core. The dominant failure mode of the panels was buckling of the panel at the support locations. A corresponding finite element model was also developed to investigate the effects of face sheet thickness, face sheet modulus, fiber insertion density, panel thickness and aspect ratio on the bending strength of the panels. Reis [19] and Reis and Rizkalla [20] developed a new type of sandwich panels consisted of composite face sheets, foam core and through-thickness fiber insertions. The interface delamination of sandwich panels was prevented due to the use of the fiber insertions. The effects of fiber insertion density, face sheet thickness and panel thickness on the strength and stiffness of the panels were studied. However, although the interface delamination issue can be relieved, the initial bending stiffness of a sandwich panel was hardly improved. In practice, the common solutions to improve the initial bending stiffness are to use the higher density foam core and the thicker face sheets, which result in an sharply increase in engineering costs and dead loads. Hence, under the premise of keeping the minimum construction costs and the minimum weight, how to improve the ultimate bending strength and initial bending stiffness of sandwich panels is a critical issue. This is the motivation of this study.

Authors have developed a kind of foam-filled lattice composite sandwich panel consisted of GFRP face sheets and a foam-web core. The connection details and manufacture process were introduced in our companion paper [21]. As shown in Fig. 1, the face sheets, webs and foam cores are combined by vacuum infusing resin. The axial compression tests have been carried out by the authors. The test results indicated that the ultimate compressive strength, initial stiffness and energy absorbing of GFFW panels were improved significantly. The reason was that the compressive strength of foam was improved due to the confinement effects provided by GFRP lattice webs, and the foam cores can also restrict the local buckling of the lattice webs.

In order to thoroughly understand the bending behavior of the GFFW panels, the four-point bending test was conducted to investigate the ultimate bending strength, initial bending stiffness and failure mode of this type of panels in this study. An analytical model was developed to predict the mid-span deflection of GFFW panels under four-point bending. The accuracy of the model was verified through a comparison of the model with experimental results. Meanwhile, a comprehensive conclusion of four-point bending behavior was summarized, which can be used to aid engineers in designing GFFW panels and to ensure proper panel detailing for desirable performance.

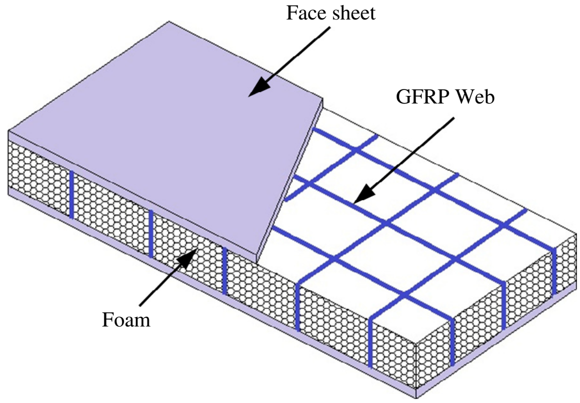

Fig. 1. The sandwich panel with GFRP face sheets and a foam-web core.

2. Experimental program

2.1. Description of test specimens and parameters

In this study, ten panels were manufactured by means of vacuum assisted resin infusion process in the Advanced Composite Structures Research Center at Nanjing Tech University. The GFRP and HS-2101-G100 unsaturated polyester resin were used for face sheets and webs. The polyurethane foam (PU foam) with 60 kg/m^3 density was used for filled core. Table 1 shows a summary of the test matrix and details of specimens. All the specimens had the identical length (L = 1000 mm), width (d = 225 mm) and face sheet thickness (t_s = 3.2 mm). Specimen FPB50-CON was a controlled sandwich panel with GFRP face sheets and a foam core, which was used to investigate the bending performance of normal sandwich panels. Specimens FPB50-16, FPB50-32 and FPB50-48 and Specimens FPB75-16, FPB75-32 and FPB75-48 were fabricated with 50-mm-web height and 75-mm-web height, respectively, which were used to investigate the influence of web thickness (t_w). Specimens FPB50-16, FPB75-16 and FPB100-16 and Specimens FPB50-32, FPB75-32 and FPB100-32 were fabricated with 1.6-mm-web thickness and 3.2-mm-web thickness, respectively, which were used to investigate the influence of web height (h). Specimens FPB100-32 and FPB100-32-II were fabricated with 3.2-mm-web thickness and 100-mm-web height, which were used to investigate the influence of web spacing (s).

2.2. Material properties

The face sheet were fabricated using E-glass mat, and HS-2101-G100 unsaturated polyester resin, and had an average thickness of 3.2 mm of the cured GFRP laminate. Five tension coupons were tested by the authors according to ASTM D3039/D 3039M-08 [22]. The tensile strength ranged from 290.9 MPa to 351.3 MPa, with an average of 322.9 MPa, and the tensile modulus ranged from 19.9 GPa to 23.3 GPa, with an average of 20.9 GPa. Meanwhile, five compression coupons were tested by the authors according to ASTM D695-10 [23]. The compressive strength ranged from 50.2 MPa to 59.4 MPa, with an average of 55.3 MPa, and the compressive modulus ranged from 5.6 GPa to 7.1 GPa, with an average of 6.7 GPa. Table 2 summarizes the material properties of the GFRP face sheet.

Totally fifteen cubic foam coupons of 50 mm thick were tested by the authors in tension according to ASTM C297/C297M-04 [24], in compression according to ASTM C365-03 [25], and in shear according to ASTM C273/273M-07 [26], using five cubes for each case. The measured ultimate tensile strength and tensile modulus of foam were 150 and 340 kPa, respectively. The measured ultimate compressive strength and compressive modulus were 0.36 MPa and 17 MPa, respectively. Also, the measured ultimate shear strength and shear modulus were 0.36 MPa and 50 MPa, respectively. The material properties are summarized in Table 3.

Table 1
Details of specimens.

Specimen	L (mm)	d (mm)	h (mm)	s (mm)	t_w (mm)	t_s (mm)
FPB50-CON	1000	225	50	–	–	3.2
FPB50-16	1000	225	50	75	1.6	3.2
FPB50-32	1000	225	50	75	3.2	3.2
FPB50-48	1000	225	50	75	4.8	3.2
FPB75-16	1000	225	75	75	1.6	3.2
FPB75-32	1000	225	75	75	3.2	3.2
FPB75-48	1000	225	75	75	4.8	3.2
FPB100-16	1000	225	100	75	1.6	3.2
FPB100-32	1000	225	100	75	3.2	3.2
FPB100-32-II	1000	225	100	100	3.2	3.2