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Theoretical and experimental study of foam-filled lattice composite panels under quasi-static compression loading

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ABSTRACT

In this paper, a simple and innovative foam-filled lattice composite panel is proposed to upgrade the peak load and energy absorption capacity. Unlike other foam core sandwich panels, this kind of panels is manufactured through vacuum assisted resin infusion process rather than adhesive bonding. An experimental study was conducted to validate the effectiveness of this panel for increasing the peak strength. The effects of lattice web thickness, lattice web spacing and foam density on initial stiffness, deformability and energy absorbing capacity were also investigated. Test results show that compared to the foam-core composite panels, a maximum of an approximately 1600% increase in the peak strength can be achieved due to the use of lattice webs. Meanwhile, the energy absorption can be enhanced by increasing lattice web thickness and foam density. Furthermore, by using lattice webs, the specimens had higher initial stiffness. A theoretical model was also developed to predict the ultimate peak strength of panels.

1. Introduction

Sandwich panels have been widely used for constructing bridge decks, temporary landing mats and thermal insulation wall boards due to better performance in comparison to other structural materials in terms of enhanced stability, higher strength to weight ratios, better energy absorbing capacity and ease of manufacture and repair. In sandwich panels, low density material, known as core, is usually adopted in combination with high stiffness face sheets to resist high loads [1]. The most common types of core materials include polyvinyl chloride (PVC) foam, polyurethane (PU) foam, balsa wood, honeycombs, polyester foam coremat etc. The main functions of core materials are to absorb energy and provide resistance to face sheets to avoid local buckling.

Extensive experimental studies of composite sandwich panels with balsa wood core have been conducted in the past two decades [2–5]. Osei-Antwi et al. [6] investigated the shear mechanical characterization of composite sandwich panels with balsa wood core. Six specimens, cut from the panels in accordance with the three principal shear planes, were tested. The test results indicated that shear stiffness and strength increased with increasing density of the balsa wood, but they did not change with the use of different adhesive joints in the balsa panels between the lumber blocks. Bekisli and Grenestedt [7] developed a new manufacturing method for the balsa sandwich cores by vacuum assisted resin infusion, and conducted the experimental study on these cores under shear force. The test results revealed that the new manufacturing method can increase stiffness and strength of the balsa sandwich cores. However, the compressive and shear stiffness and strength of balsa wood have very large variations due to the natural and anisotropic characteristics of the material. Hence, a lot of material tests have to be carried out to obtain reliable values for practical design. Furthermore, appropriate fire and corrosion protections should be provided due to the use of wood.

Up to now, many investigations of geometric configurations have been conducted to find more effective lightweight energy absorbing structures [8–21]. Cartié and Fleck [22] studied the compressive strength of foam-cored sandwich panels with pin-reinforcements. The test results showed the compressive strength and energy absorption capacity of the sandwich panels were increased. In the buckling analysis of pin-reinforcements, the foam core was considered as an elastic Winkler foundation in supporting the pins. The compressive strength was governed by elastic buckling of the pins. Furthermore, the relationship between the compressive strength and loading rate was studied. Fan et al. [23] tested a series of multi-layered glass fiber reinforced composite woven textile sandwich panels under quasi-static compression loading. Their test results revealed that energy absorption of the multi-layered panel was greatly improved and far exceeded that

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of the monolayer panel of the same thickness, and the failure mode was progressively monolayer collapses. The authors also conducted the bending tests of multi-layered glass fiber reinforced composite woven textile sandwich panels [24]. The failure mode was associated with the crippling and shear failure within the face sheets, and the load capacity was dictated by the fracture strength of the face sheets. Meanwhile, the authors pointed that the plastic hinge mechanism made the panels to possess a long deflection plateau after the peak strength. As an effectively kind of energy absorbing structures, the egg-box shape has also extensively been investigated [25–27]. Yoo et al. [28] carried out the compressive tests on foam-filled composite egg-box panels to evaluate the energy absorbing capacity. The crack initiation and propagation of composite egg-box cores without foam were observed and analyzed. Furthermore, the possible use of foam-filled composite egg-box panels as a thermal insulation wall board for membrane type liquefied natural gas ships was also evaluated. Although a lot of geometric configurations for energy absorbing structures have been developed in recent years, the majority of them have been applied to various protective packaging and crashworthiness structures for automobiles, ships and aero planes rather than civil engineering structures, because the compressive, shear and bending stiffness of these composite panels are low, the manufacturing process of these geometric configurations is complicated, and the cost of production may stay at a relative high level. Choy et al. [29] developed two types of sandwich panels, namely the fiber inserted foam panels and the aluminum foil covered panels. Their test results proved that the bending stiffness of these panels was increased. However, these panels were used to reduce the noise and isolate the vibration in the air conditioning. Hence, the composite panels with these geometric configurations are hardly extended to civil engineering field.

Chen and Davalos have investigated the strength and stiffness properties of composite sandwich deck panels with sinusoidal core geometry in the past few years. The compressive and shear tests of FRP sandwich deck panels with sinusoidal core geometry have been conducted [30]. Chopped strand mat, composed of E-glass fibers and polyester resin, was used for the core material. The test results showed that the typical shear failure mode was delamination at the core-face sheet bonding interface, and the maximum strength of these panels was determined by the number of bonding layers and core thickness. An analytical model for the buckling capacity of FRP panels with two loaded edges partially constrained was proposed by Davalos and Chen [31]. By considering the skin effect, Chen and Davalos [32] obtained an accurate solution of the transverse shear modulus and the interfacial stress distribution for sandwich structures with sinusoidal core. However, in their studies, the critical buckling stress of sinusoidal core is usually low, which is obviously caused by the absence of restriction from foam core. Hence the compressive strength of panels cannot be improved. Meanwhile, the energy absorbing capacity of panels was not evaluated.

To address the aforementioned shortcoming, a simple and innovative foam-filled lattice composite panel, manufactured through vacuum assisted resin infusion process [33], is developed in this study, as shown in Fig. 1. The face sheets, lattice webs and foam cores are combined by vacuum infusing resin, which can enhance the peel resistance between face sheets and foam cores. Unlike other foam-core sandwich composite panels, the compressive strength of foam is improved due to the confinement effects provided by lattice webs, and the foam cores can also restrict the local buckling of the lattice webs. Hence, the compressive strength of foam-filled lattice composite panels can be improved significantly. An experimental study was conducted to validate the effectiveness of this new type of panel. The peak strength, initial stiffness, deformability and energy absorbing capacity were investigated. A theoretical model was also developed to predict the ultimate peak strength of panels.

2. Manufacture process

The manufacture process can be divided into the following six steps: (i) four GFRP mats are placed on a large flat board as shown in Fig. 2(a), and the fiber orientation angle is 0/90° to the panel horizontal axis; (ii) the foams are cut into cubes according to the design dimensions, and then wrapped using GFRP with ±45° fiber orientation angle see Fig. 2(b); (iii) to place four GFRP mats on the foam cores, and the fiber orientation angle is also 0/90° to the panel horizontal axis; (iv) before vacuum infusing UPR, the stripping cloth, diversion cloth and a thicker cover plate which is used to make the face board flat are installed, respectively, as shown in Fig. 2(d); (v) the unsaturated polyester resin is infused into the vacuum bag due to the effect of atmospheric pressure (see Fig. 2(e)); (vi) After UPR curing, the manufacture of foam-filled lattice composite panels is completed, and then the panels are cut in accordance with special requirements, as shown in Fig. 2(f).

3. Theoretical model

3.1. Local buckling of the GFRP web

The local buckling of the GFRP web can be analyzed using elastic foundation model, as shown in Fig. 3(a). The foam is represented by the spring with a stiffness of k (per unit width and length). In accordance with classical theory of elastic stability [34], the governing differential equation for the stability analysis of web is expressed as

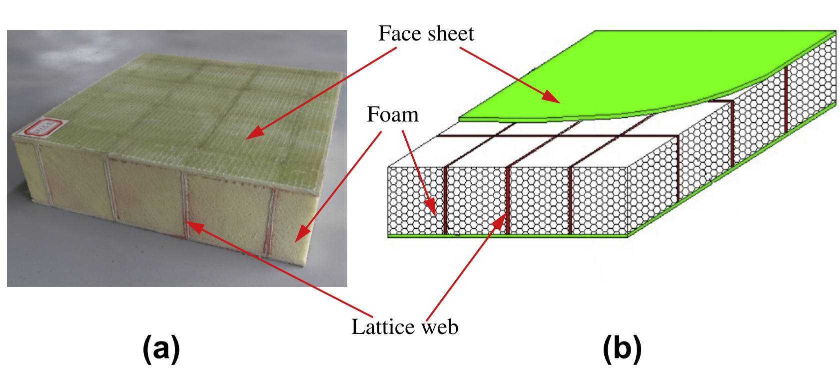

Fig. 1. The foam-filled lattice composite panels (a) photo of Specimen H5T2S5D6 and (b) schematic diagram.