Composites Part B 93 (2016) 265–272

Contents lists available at ScienceDirect

Composites Part B

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

Mechanical behavior of the CFRP lattice core sandwich bolted splice joints

Shengxin Zhu [a], Guojian Shao [a], Yana Wang [b], Xiaolei Zhu [c, *], Qilin Zhao [d, **]

[a] Department of Engineering Mechanics, College of Mechanics and Materials, Hohai University, Nanjing, 210098, China
[b] College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing, 210098, China
[c] School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing, 211816, China
[d] College of Field Engineering, PLA University of Science and Technology, Nanjing, 210007, China

ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form
5 September 2015
Accepted 14 March 2016
Available online 19 March 2016

Keywords:
A. Polymer-matrix composites
B. Mechanical properties
C. Analytical modeling
D. Mechanical testing
E. Joints/joining

ABSTRACT

Composite lattice core sandwich structure is a novel type of effective load bearing structure. In this paper, one kind of bolted splice joint between two CFRP lattice core sandwich panels is proposed. The mechanical behavior of this joint structure is investigated through four-point bending. The main deformation pattern and failure mode of the lattice core sandwich bolted splice joint structure are demonstrated by both experimental test and FE simulation. The failure mode includes the successive events, namely yield of the lower metal plate and then debonding between the lattice core and sheets. A simplified theoretical model is also proposed for this joint which is capable of calculating the load−displacement curve before yield of the lower metal plate. By monitoring the stress in the lower metal plate not to exceed the yield strength, the present model can give a simple engineering design for this kind of joint structure.

1. Introduction

Sandwich structures are well-established system in lightweight design since the separation of two thin sheets by a cellular core, allowing an outstanding weight-specific bending stiffness in contrast with monolithic composite structures [1]. They have been widely used in aircraft, aerospace, marine and automotive industries. Recently, it was reported that the lattice core sandwich structure was more effective in load-bearing than many other sandwich structures and was of great application potential [2–4]. However, beside the difficulty in connection of composite materials, strong mechanical connection between two composite sandwich panels seems an even more challenging problem, which may become a bottleneck in the application of composite sandwich structures.

Generally speaking, there are two types of connection technologies for composites, e.g. adhesive connection and mechanical connection. In engineering application, bolted joint is the most widely used connection due to its advantage of easy installation, disassemble and maintain. However, the strength degradation due to bolted joints is always much more significant for the composite structures as compared with their metallic counterparts, since the opened holes in composites inevitably cause fiber breakage, resulting in more severe stress concentration and earlier crack initiation. To overcome these disadvantages, bolted joint of composite has been widely studied, including the influences of many factors, such as the bolted type [5,6], geometric parameters [7,8], bolt-hole clearance [9,10], stacking sequences [8,11] and so on. A comprehensive conclusion on the influencing factors has been reviewed by Thoppul [12].

On the other hand, researches on the mechanical connection between two composite sandwich structures were much less systematic. Cao [13] studied by four-points bending test the ultimate strength of two kinds of connection joint between a foam core composite sandwich structure and a steel hull, including bonded-bolted joint and co-infused perforated joint. The experimental results showed that both joints had sufficient strength, approaching 90% of the strength of the intact foam core composite sandwich specimens, and the co-infused perforated joint was indicated to be lighter and stronger than the bonded-bolted joint. Jung [14] investigated the fatigue load and fracture behavior of

---

* Corresponding author.
** Corresponding author.
E-mail addresses: zhuxiaolei856028@126.com (X. Zhu), zhaohsql919@163.com (Q. Zhao).

http://dx.doi.org/10.1016/j.compositesb.2016.03.036

hybrid sandwich/steel joints under static loads and cyclic loads. It was found that the static load led to shear deformation and fracture in the honeycomb core. Moreover, cyclic load caused degeneration in interface between the sheets and the cores. Weidner [15] adopted static in-plane tensile test to investigate failure modes and ultimate strength of bolted joints in discontinuous ceramic cored sandwich structures (DCCSS). It was indicated that the structure strength increased with the increase of the edge distance, and the efficient geometric ratios of e/D = 8 and w/D = 8 was suggested. Nanayakkara [16] employed tensile test to analysis the fracture resistance of PMI sandwich composite T-joints by Z-pinning. It was concluded that the ultimate fracture load increased with volume fraction of the Z-pinning. To our knowledge, there was rare work on the mechanical connection of composite lattice core sandwich structure.

A significant advantage of the composite lattice core sandwich structure is its insensitivity to local defects. Sebaey [17] studied numerically the strength of CFRP pyramidal lattice core sandwich structures with circular holes in the sheets and showed that the biaxial compression strength was not sensitive to defect in composite sheets. Therefore, the bolted splice joints are supposed to be an efficient connection type for composite lattice core sandwich structures. In this paper, the bolted splice joint structure between two CFRP lattice core sandwich panels is proposed, as shown in Fig. 1, which consists of two metal plates bolted together with the CFRP lattice core sandwich panels by eight metallic bolts. The mechanical behavior under four-point bending was investigated by experimental test, theoretical model and finite element (FE) simulation. The main deformation pattern and failure mode of the bolted splice joint structure were demonstrated by both experiment and FE simulation. From the perspective of engineering application, a simplified theoretical model was proposed. The bearing capacity of the joint structure was determined by coupling the strength of metal joints and the theoretical model.

2. Theoretical model

A simplified theoretical model for the four-point bending of the bolted splice joint structure between two CFRP lattice core sandwich panels is illustrated in Fig. 2. The dimensions in Fig. 2 correspond with the four-point bending test in this study. In our one dimensional model, the two bolted sites, between which the distance is 100 mm, are regarded as rigid points, which means the rotation angle on two sides of this kind of point should be the same.

Based on the experimental observation, deformation only occurs in the sandwich panel and the lower metal plate, and no obvious deformation occurs in the upper metal plate. Since there are intervals between the bolts and bolted holes, the two rigid points are in fact instantaneous hinges at the beginning. When the deformation of the lower metal plate happens continuously, the instantaneous hinges change into rigid joints due to deformation compatibility. The total deflection of the lattice core sandwich panel on the loading point consists of the bending deflection of the sandwich panel and the vertical displacement caused by the rotation of the sandwich panel. It can be expressed as Eqs. (1) and (2).

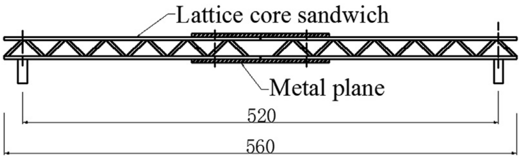

Fig. 1. The bolted splice joint structure between two lattice core sandwich panels.

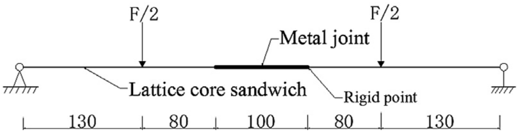

Fig. 2. A simplified model for the bolted splice joint structure.

$$\omega = \omega_1 + \omega_2 \tag{1}$$

$$\omega_2 = \theta \cdot l_1 \tag{2}$$

where ω_1 is the bending deflection of the lattice core sandwich panel, ω_2 is the vertical displacement caused by rotation, and θ is the rotation angle as shown Fig. 3.

Composite bolted joints are designed based on the bearing strength of bolted hole, and thus the deformation of the sandwich panel can be regard as small deformation. As shown in Fig. 3a, the bending deflection of the lattice core sandwich panel under a concentrated force loading of $F/2$ can be calculated as Eq. (3).

$$\omega_1 = \frac{0.5Fl_2^2(3l_1 + 2l_2)}{6(EI)_c} - \frac{0.095Fl_2^3}{6(EI)_c} \tag{3}$$

where $(EI)_c$ is flexural stiffness of the lattice core sandwich panel.

As shown in Fig. 3b, the metal plate between the two bolts can be regarded as a simply supported beam. Both ends of the beam suffering bending moment M, which is expressed as Eq. (4).

$$M = 0.5Fl_2 - 0.095F(l_1 + l_2) \tag{4}$$

The rotation angle θ of the beam can be expressed as Eq. (5).

$$\theta = \frac{Ml_3}{3(EI)_s} + \frac{Ml_3}{6(EI)_s} = \frac{Ml_3}{2(EI)_s} \tag{5}$$

where $(EI)_s$ is the flexural stiffness of the lower metal plate.

The deflection of the loading point due to rotation is then expressed as Eq. (6).

$$\omega_2 = \theta \cdot l_1 = \frac{Ml_1l_3}{2(EI)_s} \tag{6}$$

Based on the experimental phenomena, the lower metal plate experiences an obvious plastic deformation. Therefore, the yield stress of the lower steel plate can be regard as a key factor in deciding the ultimate strength of the whole joint structure. According to Eq. (4), when plastic deformation occurs in the overall rectangular cross-section of the lower metal plate, the load can be expressed as Eq. (7).

$$F = \frac{\sigma_s bh_s^2}{2(l_2 - 0.19(l_1 + l_2))} \tag{7}$$

where σ_s is the steel yield stress, h_s is the thickness of the steel. Eq. (7) is taken as the formula for design load of the bolted splice joint between two lattice core sandwich panels.