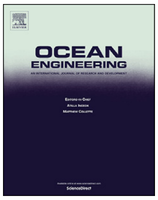
Ocean Engineering 144 (2017) 78–89

Contents lists available at ScienceDirect

Ocean Engineering

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



The mechanical behavior of sandwich composite joints for ship structures

Wei Shen [a,b,*], Bailu Luo [c,**], Renjun Yan [a], Haiyan Zeng [a], Lin Xu [a]

[a] *Key Laboratory of High Performance Ship Technology (Wuhan University of Technology), Ministry of Education, Wuhan 430063, China*
[b] *State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[c] *China Ship Development and Design Center, Wuhan 430064, China*

ARTICLE INFO

Keywords:
Sandwich L-joint
Ultimate strength
Fatigue test
Fatigue model

ABSTRACT

Low density foam core sandwich composites are recerving increasing attention and application in marine engineering. In order to solve the damage failure problem of sandwich L-joints for ship structures, the ultimate strength and fatigue properties of full scale L-joints were researched by experimental method. On the basis of the research on the static strength, the fatigue life and failure mode of this kind of connection were analyzed in different load amplitudes by a series of fatigue tests. The generation and development of cracks in the whole process were revealed and *S-N* curves were also drawn. The results show that fatigue life and stiffness of sandwich L-joints are decreased with the increase of load levels, and the major failure modes are in the form of sandwich debonding, sandwich face/core delamination, and gelcoat damage. Finally, a fatigue life model has been developed with stress level r and crack length a_i and validated with test results.

1. Introduction

The sandwich composites are multi-layered materials made by adhesive, high strength skins and core materials (Belouettar et al., 2009). Sandwich structures exhibit good characteristics such as high stiffness and low weight ratios in the reasonable proportion of materials. Therefore, sandwich materials are widely concerned and used in the aerospace, shipbuilding, construction and other fields. However, the anisotropic and brittle characteristics of composites make the stress distribution and fatigue failure modes of composite joints far more complex than metal structures (Kilic and Hajali, 2003; Herrmann et al., 2013). In fact, the failure of composite structures occurs widely in practical engineering, at the earlier stage, the weak part will be damaged first, which leads to local damage and stress redistribution. However, this kind of damage cannot be seen on the macro in the beginning. With the cycles increasing, the damage region will expand and the stiffness of structure will be degraded gradually until a stage closed to the final failure.

The strength of the sandwich is a integrated feature of the skin, core and adhesive. The static and fatigue behavior of honeycomb core composites were focused primarily in the past few years (Masters and Evans, 1996; Gibson and Ashby, 1997). The honeycomb structures are considered to provide a weight minimization by means of the reduction of secondary structures. They can be used on high-speed vessels as separating divisions, mezzanines and movable car decks (Ferraris and Volpone, 2005). As sandwich structures have become more widely used, the use of foam core as a sandwich structural element has increased continuously. Foam sandwiches exhibit good characteristics such as efficient capacity of energy dissipation, high impact strength, acoustic and thermal insulation, high damping, that made them very appropriate for applications in marine engineering (Ashby et al., 2000; Abdi et al., 2014). In addition, the collapse mechanisms are also presented different between honeycomb and foam sandwiches. Impact tests implied that the collapse of honeycomb sandwiches occurred for the buckling of the cells and was restricted by the cell size. However, the foam sandwiches damaged due to the foam crushing and their energy absorbing capacity affected by the foam quality (Akay and Hanna, 1990; Crupi et al., 2013).

Many approaches are proposed to predict the ultimate bearing capacity and fatigue performance of composites based on global response. Masters and Evans (1996) studied the in-plane stiffness of honeycomb cores based on the honeycomb elements. Meraghni et al. (1999) proposed a modified laminate theory to calculate the out-of-plane stiffness of honeycomb cores. As to the fatigue behavior of sandwich honeycomb composites, several methods in stiffness (Hwang and Han, 1986; Kuo et al., 2003), residual strength (Shenio et al., 1995) and experimental observation (Burman and Zenkert, 2000; Demelio et al., 2001) were presented to evaluate the fatigue damage. While residual stiffness and

---

* Corresponding author. Key Laboratory of High Performance Ship Technology (Wuhan University of Technology), Ministry of Education, Wuhan 430063, China.
** Corresponding author.
E-mail address: shenwei_abc@163.com (W. Shen).

http://dx.doi.org/10.1016/j.oceaneng.2017.08.039
Received 11 March 2017; Received in revised form 9 July 2017; Accepted 27 August 2017

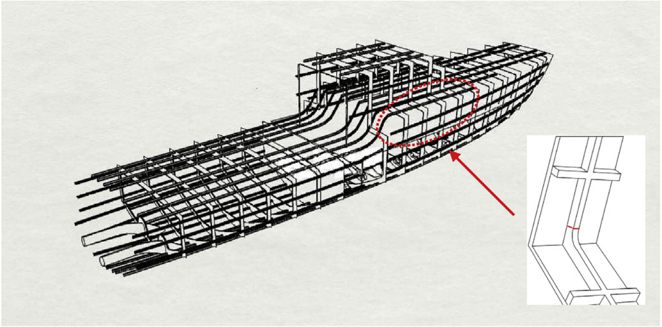


Fig. 1. Schematic of the framework for composite ships.

strength might reduce slightly with the increase of cycles until the final failure happened (Yang et al., 1990; Belingardi et al., 2007). Till now, the fatigue strength analysis of foam core sandwich structure is still in the stage of development. Kulkarni et al. (2003) analyzed the crack growth process under flexural fatigue and developed a model to predict the life of low-density foam core sandwich composites. Theotokoglou et al. (2008) calculated the stress intensity factors at the crack tips to explain the crack growth behavior of foam core sandwich beams. However, the crack initiation and propagation of core materials subjected to cyclic loads is still relatively unexplored and experimental investigations are to be developed for such material (Burman and Zenkert, 1997a,b). The experimental research on large scale sandwich structures is especially scarce. Meanwhile, due to the diversity of microscopic damages, the process of damage failure is lack of regularity. Therefore, it is necessary to have a comprehensive knowledge of the static and fatigue performance of foam core sandwich by experimental method.

2. Experimental procedure

Currently there is a wide range of naval structures being developed using composite materials (Mouritz et al., 2001). As shown in Fig. 1, the simplest type of plate girder structure consists of plates, stiffeners and brackets. Stress concentrations at these corners cause cracks initiate and propagate under cyclic loadings, due to the elongated shape (Shen et al., 2015). Therefore, several full scale sandwich L-joints were used in this paper to analyze the ultimate strength and fatigue strength in the corner under cyclic loadings.

2.1. *Specimen and fixture*

As shown in Fig. 2a, several full scale sandwich L-joints were used in the experiment. Two sandwich plates were joined at 105°, the longitudinal reinforcement was joined by circular arc transition bracket along the corner, and the ends of L-joint were fixed with the vertical actuator and the base (see Fig. 2b). The sandwich panels and reinforcing ribs consist of GFRP skins and PVC foam core where top and bottom face sheets are bonded together as shown in Fig. 2c. The top and bottom GFRP face sheets are formed by the stitch-bonded fabrics layed-up in a 0/90° fiber orientation. The sandwich panel is fabricated in pultrusion process. Tables 1 and 2 summarize the physical and mechanical properties of the GFRP skins and PVC foam core, respectively.

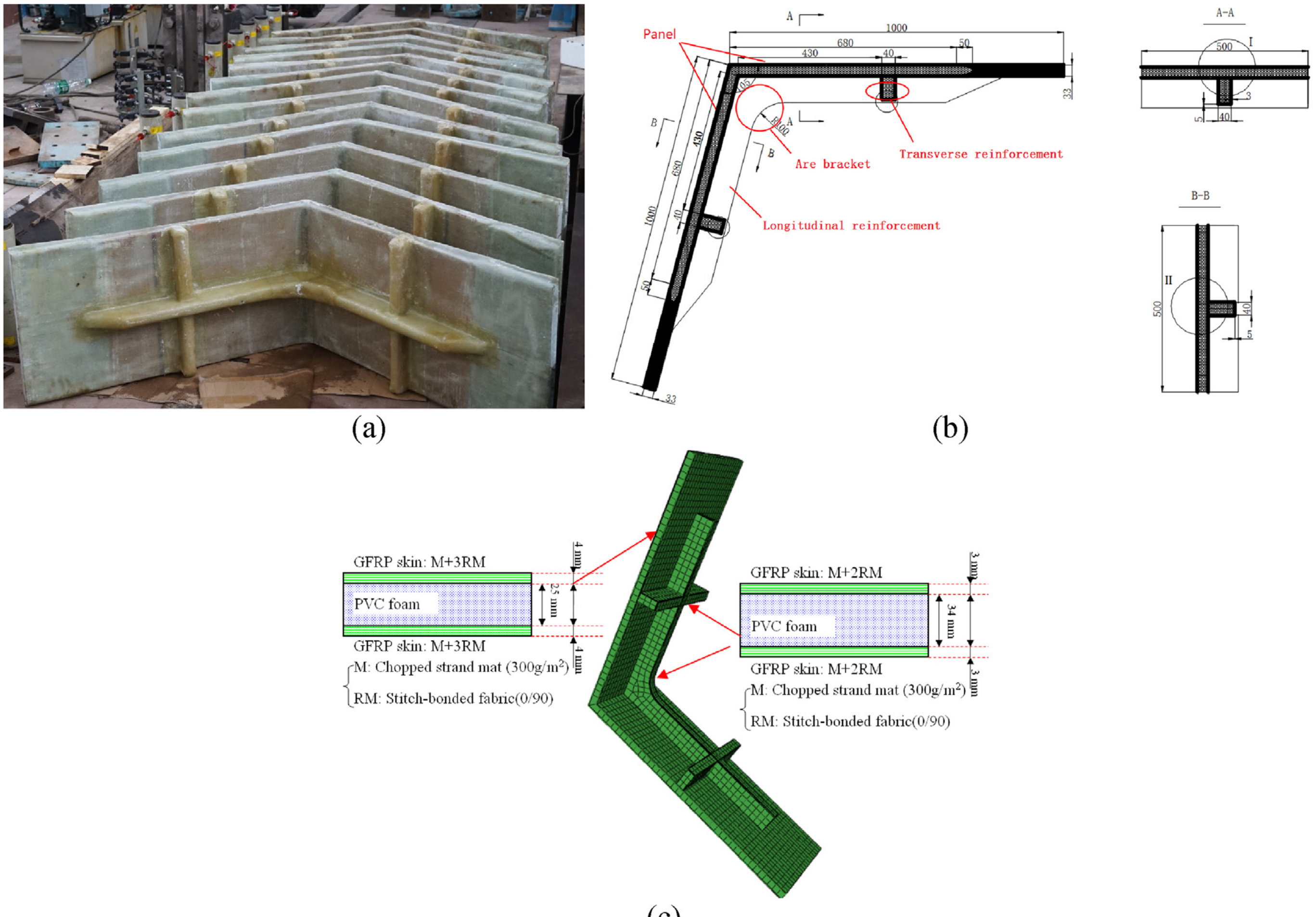


Fig. 2. Sandwich specimen: (a) test specimens; (b) schematic diagram, mm; (c) dimensions, mm.