Optik 130 (2017) 106–113

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Real-time bonded area in-situ shear stress measurement of double butt strap joints based on FBG center wavelength analyses

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ARTICLE INFO

Article history:
Received 13 September 2016
Accepted 7 November 2016

Keywords:
Shear stress
Double butt strap joint
Fiber bragg grating
Center wavelength analysis

ABSTRACT

One novel method which can achieve real-time bonded area in-situ shear stress measurement of double butt strap joints based on fiber Bragg grating (FBG) center wavelength analyses is proposed in this paper. Theory calculation model of this novel method is established to explain its feasibility. To verify the feasibility, testing experiment on one prototype is carried out. In the fabrication of the testing prototype of the double butt strap joint, four fiber Bragg gratings (FBGi, i = 1, 2, 3, 4) are embedded in the bonded area. After data analyses, shear stress measurement sensitivity coefficients of FBGi (i = 1, 2, 3, 4) show the same trend as theory calculation, and their values are 21.33 pm/MPa, 21.95 pm/MPa, 23.5pm/MPa and 21.2 pm/MPa, respectively. All these data confirm the feasibility and correctness of the novel bonded area in-situ shear stress measurement method.

1. Introduction

Double butt strap joint is one of most commonly used adhesive bonding types. Due to its unique advantages, such as lightweight, suitable mechanical and physical properties, double butt strap joints have been widely used in multiple engineering applications, especially in modern transportation (aircraft, trains and cars), building services and electronic devices [1,2]. For most of engineering applications, real-time bonded area internal shear stress measurement of double butt strap joints is one of the most important requirements in engineering structure health diagnostic system.

In order to understand adhesively bonded joint behavior and influencing parameters of bonded strength, theoretical analysis, numerical simulation and experimental approaches have been studied [3–7]. H. K. Lee, et al. [8] proposed an experimental investigation which is conducted to characterize the joint strengths modes in adhesively bonded joints and the experiment results showed that the joint strength was almost independent of adhesive type, decreased with the adhesive layer thickness and increased with overlap length. S. W. Park, et al. [9] calculated the stress distribution and energy release rate of the co-cured joint by using finite analysis with respect to design parameters such as fiber stacking sequence et al. Stress measurement method in references [8] [9] is load-displacement curve which has been studied by L. Tong, et al. [10] through theory calculation and finite element method ten years ago. Vallee, et al. [11,12] proposed a probabilistic method for the strength method of adhesively bonded lap joints based on the experimentally determined material strength of joint materials and its statistical distribution. However, this probabilistic method can not be used to predict joint strength of

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http://dx.doi.org/10.1016/j.ijleo.2016.11.023
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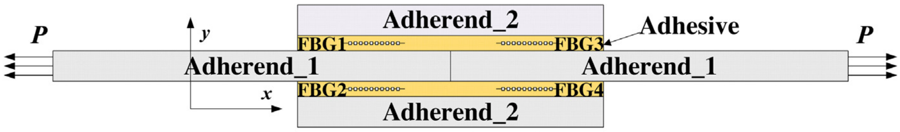
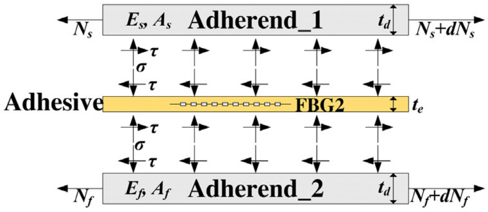


(a) The double butt strap joint diagram



(b) Micro unit force diagram of prototype under axial force

Fig. 1. Theory calculation model of double butt strap joint bonded area shear stress distribution.

quasi-brittle or pseudo-ductile. U.A. Khashaba, et al. [13] used strain gauge to measure surface strain of bonded area, and the detection results were used to improve the performance of bonded joints in carbon fiber composite with different scarf angles. All these strain detection methods, such as theory calculation, finite element simulation and strain gauge, can not detect bonded area in-situ shear stress/strain distribution. So, real-time bonded area in-situ shear stress distribution measurement of double butt strap joints is still a challenge which needs to be solved.

Due to its unique advantages such as immunity to electromagnetic interference, light weight, compact size, resistance to corrosion, high sensitivity and so on, FBG has been widely used [14–17] and proposes an ideal method to achieve bonded area in-situ shear stress measurement of double butt strap joints. Theory calculation model of the bonded area shear stress measurement method which is focus on the relationship between bonded area shear stress, center wavelength shift of FBG and external stress is established. To verify the feasibility of the bonded area shear stress measurement method, testing experiment on one prototype is carried out. According to reference standard ASTM D1002-01 [18], the prototype of double butt strap joints is fabricated and four fiber Bragg gratings are embedded in the bonded area during the manufacturing operation. Testing experiment results confirm that this real-time bonded area in-situ shear stress measurement method of double butt strap joints can be used with high detection accuracy.

2. Theory calculation model

2.1. Bonded area shear stress distribution

Fig. 1 shows theory calculation model of the bonded area shear stress distribution of double butt strap joints under external press P. To obtain the relationship between bonded area shear stress and external press, and simplify the theory calculation model analysis process, these following assumptions are made.

1) All materials are linear elastic and external loads are all in the material elastic range;
2) Shear stress of adhesive is evenly distributed at the thickness and cross section width direction.

According to Fig. 1(b), strain of adhesive γ_e can be expressed as:

$$\gamma_e = (u_s\text{-}u_f)/t_e \tag{1}$$

Further, we can obtain that:

$$t_e \cdot d\gamma_e/dx = \varepsilon_s\text{-}\varepsilon_f \tag{2}$$

with,

$$\varepsilon_s = \alpha_s \Delta T + N_s/(E_s A_s) \text{and} \varepsilon_f = \alpha_f \Delta T + N_f/(E_f A_f), \tag{3}$$

where, α_s and α_f are thermal expansivity of adherend, ΔT represents the environment temperature changes of specimen, E_s and A_s are elastic modulus and cross-section area of adherend_1 (Fig. 1), E_f and A_f are elastic modulus and cross-section area of adherend_2 (Fig. 1).

As shown in Fig. 1(a), the force balance formula at x direction can be expressed as

$$N_s = P\text{-}2N_f. \tag{4}$$