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An analytical model of stresses in adhesive bonded interface between steel and bamboo plywood

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ABSTRACT

Bamboo–steel composite structure is a newly developed type of structure. Structural adhesive is used to combine bamboo plywood with cold-formed thin-walled steel. Hence, the mechanical performance of the bonded interface between steel and bamboo plywood is crucial to the Bamboo–steel composite structure. To investigate the mechanical performance of the adhesive bonded interface, an analytical model for unbalanced adhesive bonded joint is proposed, and explicit closed-form expressions for the shear stress and peel stress in the adhesive layer, bamboo plywood, steel sheet and their interfaces are derived. The stresses distribution predicted by this model indicates that the initial debonding is caused by the shear stress and peel stress at the interface between bamboo plywood and adhesive layer, and is located in a tiny area close to the end of overlap. Analysis of the variables influencing the stresses distribution suggests increasing the section stiffness of bamboo plywood has a significant effect on reducing the concentration of stresses.

1. Introduction

Nowadays people are increasingly concerned about the influence of human activities on the environment. Major construction materials e.g. concrete, bricks, etc. are blamed to consume tons of natural resources and have extensive carbon emissions. Hence, searching and utilizing "green" construction materials is an important topic in the field of modern building structure.

Bamboo has great potential as a structural material as it is renewable, biodegradable and energy efficient. The specie "Phyllostachys pubescens", grows mainly in China, where it is known as "Maozhu" or "Moso" bamboo, is most used in construction. It has outstanding performance in term of strength to weight ratio compared to conventional materials such as concrete, timber and steel. And through engineered into plywood, Moso bamboo can be an excellent construction material (Donsheng et al., 2013).

Bamboo–steel composite structure is a newly developed type of structure to use the Moso bamboo plywood as structure construction material (Li et al., 2012). In Bamboo–steel composite structure, the bamboo plywood produced from Moso bamboo is bonded with cold-formed thin-walled steel using structural adhesive to be formed into composite structural members. And these composite members can be conveniently formed into different kinds of cross sections such as box and I-shaped. The composition of bamboo plywood and thin-walled steel can prevent the thin-walled steel from premature buckling, and take full advantage of the two materials. To understand the mechanical properties and the application potential of Bamboo–steel composite structure, lots of researches have been completed (Li et al., 2012; Shan et al., 2012; Shan and Li, 2008; Shen et al., 2009; Xie et al., 2012; Li et al., 2011, 2013).

The reliable bonding connection between bamboo plywood and thin-walled steel is the key to form the composite action. To deeper understand the mechanical properties of Bamboo–steel composite structure, investigations of the adhesive bonded interface between bamboo plywood and steel are needed. Adhesive bonding technology used in Bamboo–steel composite structure has been widely used in engineering, and a lot of researches have been performed. An extensive literature review on existing analytical models for adhesively bonded joints was performed by da Silva and co-workers (Silva and Öchsner, 2008; da Silva et al., 2009; Chaves et al., 2014) to assist designer in better understanding of the joint behavior. The first study of analytical model should date back to 1930s, Volkersen (1938) proposed a simple shear lag model assuming that the adherends are in tension and the adhesive only deforms in shear and the resulting stresses are constant across the thickness. But in the shear lag model, only the shear stress was analyzed and the peel stress was not taken into account. On the base of

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Nomenclature

A_i	coefficients defined in Eq. (29)	v^l	longitudinal displacement function at lower interface
B_i	coefficients defined in Eq. (29)	v^u	longitudinal displacement function at upper interface
E	Young's modulus	α_i	coefficients defined in Eq. (24)
F	tensile force acting at the end of joint	β_i	coefficients defined in Eq. (25)
G	shear modulus	γ	shear strain
k_i	coefficients relating A_i and B_i	σ_x	longitudinal normal stress in adherends
l	half-length of the overlap	σ_y	peel stress in adherends and adhesive
L	the adherends' length out of the overlap	σ_m	peel stress at the mid-plane of adhesive
$M^{\text{-}end}$	bending moment acting at the left end of adherend	σ_y^l	peel stress at lower interface
M^{end}	bending moment acting at the right end of adherend	σ_y^u	peel stress at upper interface
p	applied average tensile stress in the adherend	ε_x	linear strain in x direction
$Q^{\text{-}end}$	shear force acting at the left end of adherend	ε_y	linear strain in y direction
Q^{end}	shear force acting at the right end of adherend	μ	Poisson ratio
r_i	solution of Eq. (26)	ξ	non-dimensional coordinate through thickness
t	thickness	τ_0	applied average shear stress in the adhesive
u	longitudinal displacement function	τ^l	shear stress at lower interface
u^l	longitudinal displacement function at lower interface	τ^u	shear stress at upper interface
u^u	longitudinal displacement function at upper interface	τ_m	shear stress at the mid-plane of adhesive
v	transverse displacement function		

Volkersen, Goland and Reissner (1944) considered the bending moment at the overlap ends, and proposed an analytical model including the shear stress and peel stress. Based on Goland and Reissner, Hart-Smith (1973) obtained the adhesive stress distributions by considering the adherends as individual parts to analyze the deformation. Oplinger (1994) proposed an analytical model by decoupling the two halves of the joint in the bending deflection analysis. Tsai et al. (1998) proposed an improvement on the classic solutions by taking the shear strain of adherends into account in the calculation of adhesive stress distributions. These studies are for the balanced bonded joint, in which the adherends have the same geometry and material parameters. However, adhesive bonding technology can also be used to connect two dissimilar adherends. Bigwood and Crocombe (1989), and Cheng et al. (1991) developed analytical solutions for the unbalanced joint respectively. Wang and Zhang (2009) proposed a three-parameter, elastic foundation model to analyze the unbalanced joint and obtained analytic expressions of interface stresses. Langella et al. (2012) proposed an analytical model by extending a known model to composite adherends using the laminated anisotropic plate theory, and obtained the explicit closed-form solutions of the peel stress and shear stress distributions in the mid-plane of adhesive. Liu et al. (2014) proposed an analytical model to determine the stresses in balanced and unbalanced adhesively bonded joints. By assuming three individual parts of adherends and adhesive with mixed force loading, the authors obtained the analytical expressions for the peel stress and shear stresses of the mid-plane of adhesive and adherends. Shishesaz et al. (2014a,b) presented an analytical model of stress distribution with a crack in the adherend. The papers mainly focus on the influence of crack in the adherend on stress distribution, and the model of the adherends is specific to laminated materials.

In Bamboo–steel composite structure, bamboo plywood is an orthotropic material, and the steel is isotropic, and these two components have different geometry. The adhesive bonding between bamboo plywood and steel is a typical unbalanced adhesive joint. To investigate the mechanical properties, this paper attempts to establish an analytical model for stress analysis in unbalanced adhesive joint with orthotropic adherends. The specific composition of adhesive bonded component is simplified to three individual parts of adherends and adhesive. The adherends are modeled as flexible beams, and the adhesive are modeled as elastic continuum. And the explicit closed-form solutions are derived, which can predict the two-dimensional distributions of the peel stress and shear stress in adherends, adhesive and their interfaces. Considering the assumptions are more common beyond Bamboo–steel composite structure, this analytical model may be also applicable to multiple geometries, materials and load combinations of adhesive bonded components.

2. Analytical model and solution

2.1. Simplified model of bamboo–steel adhesive bonded joint

The adhesive bonding between bamboo plywood and steel sheet in Bamboo-steel composite structure can be simplified to an adhesive bonded joint with a unit width (Fig. 1). A global coordinate system Oxy is introduced, and the state of plane stress is assumed. The bamboo plywood, steel sheet and adhesive layer of the joint are denoted as 1, 2 and 3 for convenience, respectively. The length of bonded region is $2l$, and the length of bamboo plywood and steel sheet out of the bonded region are L_1 and L_2. Because the x direction is parallel to the grain of bamboo plywood, it can be considered to be orthotropic material. And the steel sheet and adhesive are isotropic. Considering the existence of adhesive bonding between bamboo plywood in Bamboo-steel composite structure, the adherends 1 and 2 are assumed to be orthotropic in the derivation. So let E_{ix}, E_{iy}, G_{ixy}, μ_{ixy} $(i = 1,2)$ be the Young's modulus, shear modulus and Poisson's ratio of bamboo plywood and steel sheet, and E_3, G_3, μ_3 be the Young's modulus, shear modulus and Poisson's ratio of adhesive.

Free body diagrams of the overlap region and infinitesimal element are shown in Figs. 2 and 3. The bamboo plywood, steel sheet and adhesive in the bonded region are considered to be three individual components, and local coordinate systems Oxy_1, Oxy_2 and Oxy_3 are introduced, where the origins of y_1 and y_2 are at the upper surfaces, and the origin of y_3 is at the mid-plane of adhesive. Let F,

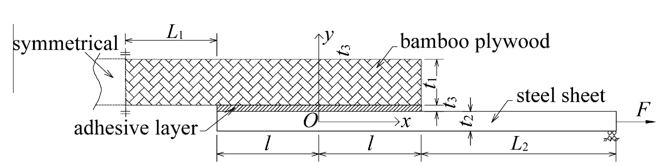

Fig. 1. Geometry of the simplified model of bamboo–steel adhesive bonded joint.