FINITE ELEMENT ANALYSIS OF MOSO BAMBOO-REINFORCED SOUTHERN PINE OSB COMPOSITE BEAMS

Xuesong Bai†

Project Engineer

Henkel Engineering, Inc.
4324 North Belt Line Road, Suite C-106
Irving, TX 75038

Andy W. C. Lee

Professor

Department of Forest Resources

Lonny L. Thompson

Assistant Professor

Department of Mechanical Engineering

and

David V. Rosowsky

Associate Professor

Department of Civil Engineering
Clemson University
Clemson, South Carolina 29634

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ABSTRACT

A finite element (FE) analysis was performed to investigate the flexural properties of a structural composite lumber—Moso bamboo (*Phyllostachys pubescens*) reinforced southern pine oriented strandboard (OSB). Parametric analyses were conducted to investigate the stress and displacement distributions. Various beam configurations as affected by glue, web structure, flange composition, and bamboo–OSB combination were considered. The comparison of the numerical results from the selected models with those from bending tests was also performed. Finally, a rational design criterion for this type of composite beam was proposed based on the analytical and experimental studies. Bamboo is capable of improving the flexural properties of the OSB for use as a structural beam or joist. At a given cross section of about 30 × 140 mm, for instance, two-layer (6.4-mm thickness each) laminated bamboo flange can increase the OSB beam's maximum bending stress by 60 to 70% and double its stiffness. The total flange thickness, rather than the thickness of each layer, controls the beam deflection while the flange with a thinner layer (3.2 mm) resulted in higher bending, vertical, and transverse stresses but lower in-plane shear stress. More reinforcing material in the composite beam could reduce the maximum bending stress but would likely increase beam weight and processing cost. From this study, it is suggested that a two-layer flanged composite beam would be favorable from a material processing standpoint as well as superior in engineering performance over other configurations of bamboo-OSB composite beam product.

Keywords: Finite element analysis, experimental bending test, bamboo-OSB composite beam, flexural behavior, stress distributions.

† Member of SWST.

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INTRODUCTION

A significant change in engineering technology to utilize our renewable natural resources in the forest products industry has been taking place over the past forty years. More materials from commercially grown species, forest/mill residues, and by-products, as well as underutilized species are being used to produce various value-added engineered wood composite products. Oriented strandboard (OSB) is known as a cost-efficient, environmentally friendly, and material-saving structural product. However, it has relatively poor flexural performance when used as a beam member. Previous studies have been focused on increasing the strength of OSB by using steel, aluminum, fiber-glass plastics, or higher strength wood products as reinforcing materials (Davalos et al. 1993; Bulleit et al. 1989; Koenigshof 1986). However, these materials are costly, either in materials or in processing. With the continuously increasing demands for timber-based structural materials in the booming construction market, further research work is needed to develop new engineering products from available natural resources. Since bamboo possesses much higher tensile strength than common wood material along the longitudinal direction (Lee et al. 1994), this study attempts to analyze and demonstrate the characteristics of bamboo-reinforced southern pine OSB as a structural beam member.

Moso bamboo (*Phyllostachys pubescens*), a renewable and fast-growing natural resource, has been successfully grown in the southeastern United States for more than seventy years (Adamson et al. 1978). Native in Asia, Moso bamboo can reach over 20 m in height and 15 to 18 cm in diameter, and can tolerate temperature to −15°C. In the past decades, researchers in the United States have been studying the propagation, plantation, and fundamental characteristics of this species regarding processing and potential industrial applications (Lee et al. 1994; Adamson et al. 1978; Glenn 1956). It has been found that, compared to commercial wood species such as loblolly pine and yellow-poplar, Moso bamboo generally has the following specific charactristics:

- Faster growing and fully mature within 3–5 years
- More dimensionally stable in longitudinal direction
- Higher tensile strength along the culm direction
- Higher specific stiffness and specific strength.

The objectives of this paper are: (1) to simulate a bamboo-OSB composite beam and evaluate its flexural performance under a third-point loading pattern (ASTM 1994) using three-dimensional (3-D) finite element (FE) analysis; (2) to study the effect of several selected composite configurations in terms of glue, web structure, flange layer and thickness, and bamboo-OSB combinations on the stress and displacement distributions; (3) to verify the model with tests of full-size beams; and (4) to develop a rational design criterion for this type of wood/bamboo composite whose structural performance will meet the commercial and industrial standards for engineered wood composite products.

Although material properties and proposed dimensions are for bamboo-OSB composites, the modeling techniques and results are generally applicable to other systems of orthotropic materials as well as to other geometric configurations of composite products, such as an I-beam and a structural wood component or system. The long-term goals of this effort are to provide additional material supply for the forest products industry and to make more productive use of diverse natural resources.

FINITE ELEMENT MODELING

Since physically testing enough samples to define material behavior for various structural sizes and configurations may be practically and economically infeasible, a mathematical model is often used. However, exact solutions, accounting for all material properties, the behavior of joints or overlaps, and interactive performance among the composite compo-

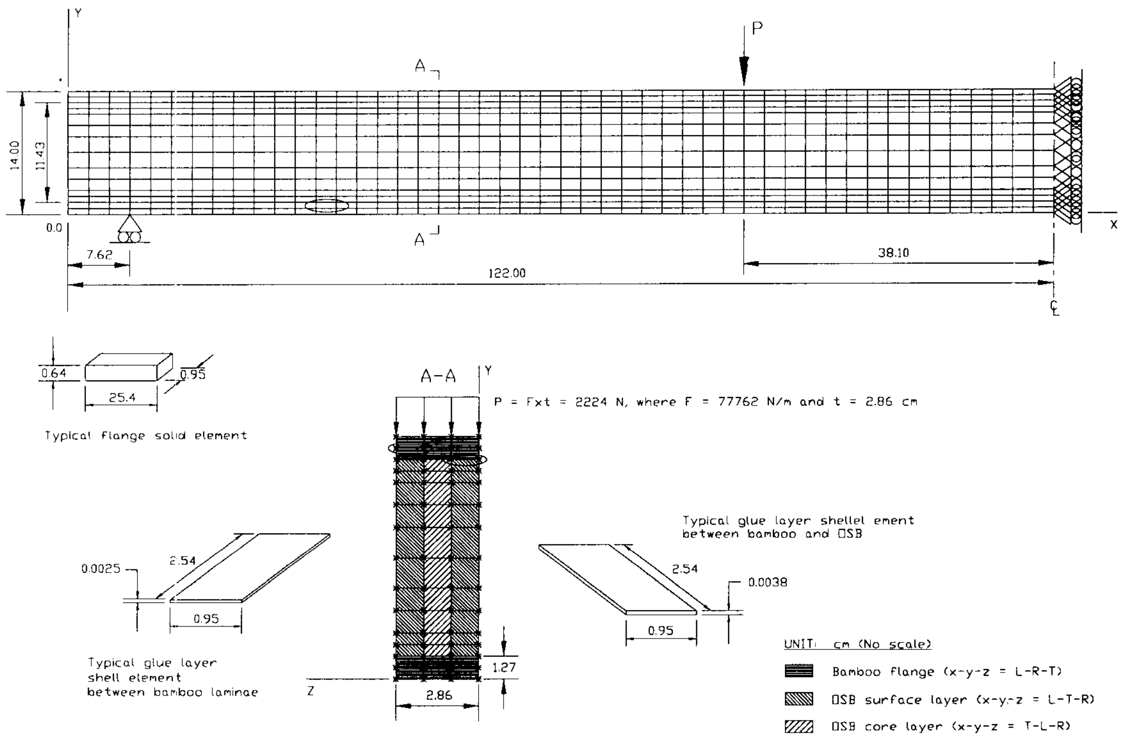

FIG. 1. Finite element mesh, boundary conditions, and element properties for bamboo-OSB composite beam.

nents, would be very difficult to formulate. Therefore, a numerical approach is a choice for complementing the experimental results (Lee et al. 1997). In this study, the I-DEAS simulation software (SDRC 1994) is used to perform the 3-D finite element analysis of bamboo-reinforced OSB composite beams.

Mesh generation

A finite element mesh is schematically shown in Fig. 1. This bamboo-OSB composite beam contains two-layer (6.4-mm thickness each) bamboo laminates as the flanges and a three-layered OSB as the web (Lee et al. 1997). The beam has a dimension of 2.44 m (length) by 14.00 cm (depth) by 2.86 cm (width). Because of the symmetry about the midspan of the beam, only one-half of the beam is modeled. There are a total of 2,940 nodes, and of 2,016 solid elements and 576 thin shell elements for this particular mesh. The modeling considerations for each individual component in the structure are described as follows.

Bamboo flange.—Each layer in the laminated bamboo flange is assumed to be a 3-D orthotropic material and its engineering elastic properties are presented in Table 1. The flange is modeled using a linear 8-node hexahedral solid element, which has a dimension of 25.4 (length) by 9.5 (width) by 6.4 (depth) mm (Fig. 1). The elements are assumed to be continuous with constant material properties throughout the flange. The upper and lower flanges are identical for the beam, and each includes 288 such solid elements uniformly distributed over the beam.

OSB web.—The OSB is assumed to be a three-layered orthotropic material. Variations of material properties among the layers are associated with different principal directions of the beam as indicated in Fig. 1. For instance, as its longitudinal (L), tangential (T), and radial (R) directions are respectively parallel to

TABLE 1. *Material properties for bamboo-OSB components*[1].

Moso bamboo[2] (Orthotropic)	Southern pine OSB[2] (Orthotropic)	Resorcinol-phenol-formaldehyde[3] (Isotropic)
E_L = 10,350 Mpa	E_L = 4,000 Mpa	E = 6,900 Mpa
E_T = 690 Mpa	E_T = 2,400 Mpa	
E_R = 500 Mpa	E_R = 690 Mpa	
G_{LT} = 900 Mpa	G_{LT} = 690 Mpa	G = 2,650 Mpa
G_{LR} = 830 Mpa	G_{LR} = 170 Mpa	
G_{RT} = 290 Mpa	G_{RT} = 207 Mpa	
ν_{LT} = 0.341	ν_{LT} = 0.150	ν = 0.300
ν_{LR} = 0.390	ν_{LR} = 0.300	
ν_{RT} = 0.308	ν_{RT} = 0.300	

[1] L and T denote the longitudinal and transverse dimensions in plane of bamboo strip and OSB, respectively, while R is dimension perpendicular to that plane.
[2] Data are from Bai (1996).
[3] Data are from Triche (1988).

the x-, y-, and z-axis, the surface layer of OSB is represented by an x-y-z = L-T-R mode. Similarly, the core layer of OSB is denoted as an x-y-z = T-L-R mode, because its T, L, and R directions are coincided with x-, y-, and z-axis, respectively. The material properties for OSB are given in Table 1. The OSB is modeled using the same type of solid elements as the bamboo flange. However, because a stress gradient is expected through the depth of the web, large elements are used in the central zone of the web, while small elements are distributed close to the flange–web interfaces as shown in Fig. 1. As a result, the total number of elements is reduced from 2,592 for uniform mesh to 1,140 for gradient mesh without influencing the accuracy of the result.

Glue layer and bamboo/OSB-adhesive interphase zone.—Compared to other FE analyses of structural wood composite beams (Leitchi and Yoo 1992; Wang et al. 1992; Fawcett and Sack 1977), the model developed here is unique in that it tries to simulate the glue effect on the elastic performance of proposed composite beam. Theoretically, there may exist two kinds of action between the adhesive and porous substrate, such as wood. One is the interphase region including a mixture of adhesive and cell-wall material and the other is the interface adhesive layer between the substrates.

As a mixed structure, the interphase zone can be assumed to have a similar orthotropic behavior to wood. There are nine independent elastic properties to be determined. Generally, a numerical analysis such as a sensitivity study of finite element modeling may help to estimate some of major properties, for instance, longitudinal modulus of elasticity (E_L) in terms of approximate global characteristics of an adhesive-wood interaction zone. First, an initial E_L is assigned to the interphase in finite element model while assuming other properties of the substrates and mixture as constants. After simulation, the comparison between the predicted global E_L and the average experimental value is made. The modification of assumed value is needed if the two values do not closely match each other. However, because of the lack of experimental data, those minor properties must be assumed based upon the given wood and adhesive properties. To understand the real interaction mechanism and the properties of wood–adhesive interphase zone, further studies will be needed.

In case of bamboo–bamboo bonding, the inspection of some failed specimens indicated that a clear interphase zone was not found between bamboo and adhesive because the resin could not easily penetrate into the highly densified structure of Moso bamboo (Bai 1996). Like bonding metal, a thin film of the adhesive is formed and may dominate bamboo bonding. In the bamboo-OSB bonding, a much more complicated situation is created. There is limited access to the cell walls, most of which are either crushed or already filled by the resin during OSB manufacturing. However, there are a lot of voids and gaps existing on the rough edge of OSB. Some of the resin may easily fill in these discontinuous voids, leading to developing some uneven gluelines under pressing.

Many studies have contributed to determining the characteristics of adhesive behavior. It has been reported that the resin for wood naturally is an isotropic material. The resin properties defined in Table 1 are based upon Triche's study (1988) of aligned wood strand composite, in which the modulus of elasticity of phenol-formaldehyde resin is estimated to be 6,900 MPa and Poisson's ratio is simply assumed 0.300.

As a result, this study assumes that the interface adhesive layer will make significant contributions to the beam properties and therefore ignores the effect from the undefined interphase zone. Using the given material properties in Table 1, a sensitivity study of finite element analysis based on a 2-ply laminated bamboo specimen approximately gives a glue layer thickness of 0.0025 mm between the bamboo. It is expected that more glue will be needed at the interface between the flange and web in order to take account for the losses of adhesive into the edge voids of OSB as well as to avoid shear delamination. Then, a thickness of 0.0038 mm, 50% more than 0.0025 mm, is assigned to the adhesive layer between the flange and web. The linear 4-node thin shell elements are used to model these adhesive layers (Fig. 1). There are a total of 288 such elements for each type of glue element.

Loading and boundary conditions.—A load resultant of 2,224 N is applied as a uniformly distributed load across the beam width. This load is about one-half of the average load at proportional limit obtained from a preliminary test on bamboo-OSB composite beam (Lee et al. 1997), and is placed at the one-third point along the longitudinal dimension of the beam.

At the support located 7.62 cm from the end of the beam, the vertical deflection along the y-axis is completely prevented as shown in Fig. 1. Due to the symmetry about midspan, only one half of the beam is modeled, and the longitudinal displacement along the x-axis is constrained at the center of the beam.

RESULTS AND DISCUSSIONS

Analysis of flexural behavior

A linear static analysis of this FE model is performed to estimate the flexural and shear behavior of the composite beam. It is indicated that the reinforcing flanges support a part of the stress concentrations around both the support and the load zones. For instance, in Fig. 2, normal stress σ_{xx} and in-plane shear stress τ_{xy} are significantly high at these critical locations as expected, but the general distributions of σ_{xx} and τ_{xy} along the span obey beam theory under a third-point loading. The transverse stress σ_{zz}, however, only exists inside the flanges with a maximum value located at the middle of flanges for a given cross section (C-S) plane, while extreme high values of vertical stress σ_{yy} can be found at the supporting and loading points. Interlaminar shear stresses τ_{xz} and τ_{yz} would be ignored due to their relatively small value across the beam domain.

The detailed distributions of stress components within the C-S plane at the one-sixth span of the beam are presented in Fig. 3 for several composite configurations. As illustrated, the component σ_{xx}, having an antisymmetrically distributed stress about the neutral axis, increases from zero at the neutral plane of the beam to the interfaces of the web and flange and then, due to discontinuity of material, jumps up to maximum value at the surface of the beam. The vertical stress σ_{yy} distribution is also antisymmetric about the neutral axis with larger magnitude existing at the top of the flanges. The τ_{xy} component, however, has a parabolic distribution with a maximum shear stress at the neutral axis of the beam.

Results from this study indicate that bamboo flanges can improve OSB's flexural performance by significantly increasing the maximum bending stress σ_{xx} of the beam (Fig. 3a),

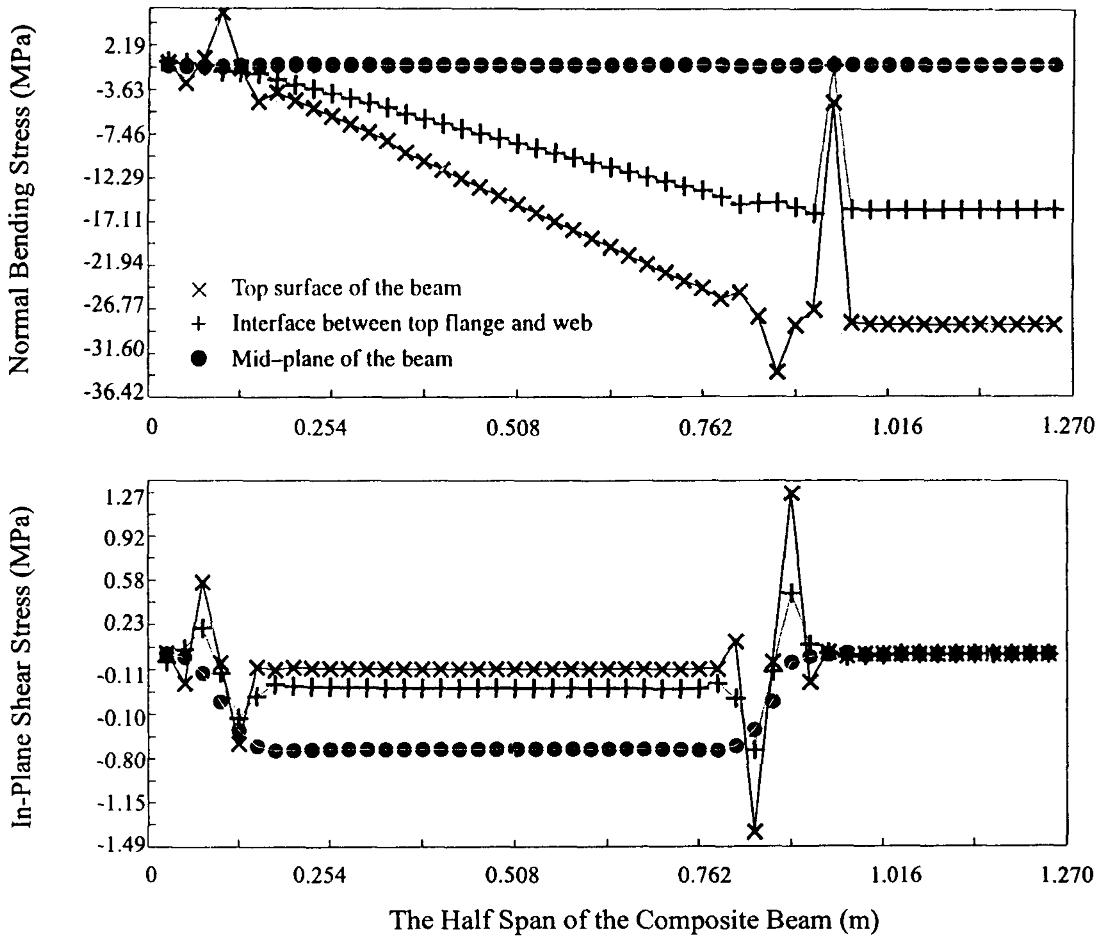

FIG. 2. Stress distributions along the length of bamboo-OSB composite beam: (a) Bending stress; (b) In-plane shear stress.

but they also reduce the maximum in-phase shear stress τ_{xy} of the structure (Fig. 3b). The maximum magnitudes of other stress components are summarized in Table 2.

Effects of the components

The effects of adhesive, OSB's web structure, and layer number and thickness of bamboo flanges on stress components are evaluated based on a C-S plane at the one-sixth span, or the middle of the C-S plane between the support and load.

The adhesive considerably contributes to reducing the potential delamination between the flange and web as well as between the two layers of the flanges. Based on the assumptions, Fig. 4 illustrates that a model with consideration of a glue layer in the structure results in reducing σ_{xx} and τ_{xy} by increasing σ_{zz} within the flanges of the beam. However, the glue element does not influence the beam's maximum values of major stress components, σ_{xx} and τ_{xy}. A slight effect of glue element on the other stress components exists. Figure 5 indicates that the distributions of the σ_{xx} within the flanges are different between a uniform OSB web and a layered one. As shown in Fig. 6, for a given thickness of the flange, increasing the number of the layers does not significantly influence any stress components. This