Research paper

Simulation and Analysis of Hygroscopic Warping of Sawn Timber by a Finite Element Method

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【Summary】

Wood warps due to differential shrinkage or swelling when the moisture content (MC) of the wood changes. Anisotropy and non-homogeneity of solid wood are the main causes for this behavior of wood when it experiences variations in MCs. This warping phenomenon causes considerable reductions in product value, frustration for manufacturers, and loss of confidence by consumers. Therefore, the warping of wood is a leading technical problem and deserves further investigation. The objectives of this study were to propose an analytical method and develop a three-dimensional (3D) finite element model (FEM) to examine the warping behavior of solid wood.

A 3D FEM was developed to simulate and analyze the hygroscopic warping of sawn timber with the commercial software, ANSYS (vers. 5.3; ANSYS, Canonsburg, PA). Through this potent tool, the FEM and the deformed geometry were graphically demonstrated. This specially developed FEM was applied here to understand warping due to MC gradients in solid wood. Formulation of the governing equations, detailed model development, computer simulation results are presented in the text.

It appears that the simulation and analysis were successfully carried out in this study. These results suggest that this FEM adequately reflects hygroscopic deformations of flat-sawn and quarter-sawn plates and can help practitioners understand the complex warping behavior and generate ideas on how to reduce the magnitude of warping.

Key words: differential shrinkage, finite element method, hygroscopic warping, moisture content gradient.

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研究報告

有限元素法模擬與分析徑面與弦面板木材之濕翹曲

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摘 要

木材含水率改變時，木材會因材料各部分收縮或膨脹差異而發生翹曲。木材因含水率變異而引起翹曲現象之主要原因是實木異方性與非均質性。此翹曲現象會造成相當大產品價值降低、生產者沮喪與消費者失去信心。因此翹曲是使用實木最重要問題，值得進一步探究。本研究目的是提出分析方法與研發三維有限元素模型應用在實木翹曲行為。

使用ANSYS軟體開發三維有限元素模型來模擬與分析實木因含水率梯度而引起翹曲。透過功能強大ANSYS，實木有限元素模型與翹曲變形幾何能以圖示展現。文中詳盡說明公式化控制方程式、模型之研發與電腦模擬之結果。

本研究成功地模擬與分析實木翹曲。這些結果顯示有限元素模型足以反應出弦與徑面板之濕翹曲，有助於業者瞭解複雜翹曲與激發如何減少翹曲之想法。

關鍵詞：差異收縮、有限元素法、濕翹曲、含水率梯度。

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INTRODUCTION

To meet the requirements of the building industry, timber and timber products should have good shape and dimensional stability. However, wood warps when its moisture content (MC) changes due to its non-homogeneity, anisotropic shrinkage, and other defects such as knots, juvenile wood, annual ring curvature, spiral grain angle, and so on. Warping, defined as an out-of-plane deformation of an initially flat panel, is a critical problem associated with the shape stability of solid wood. The mechanism of wood warping is ascribed to imbalances in hygroscopic swelling or thermal stresses triggered by changes in the MC or temperature. A variety of wood warps, cups, bows, twists, diamonding, crooks, and kinks, are commonly seen during wood-drying processes and in service. All of these distortions can be traced to the differential shrinkage of wood.

The severe warping of finished products can cause considerable reductions in product value, frustration for manufacturers, and loss of confidence by consumers when wood products are used. Therefore, warping is of great concern and is a very significant factor in the use of solid wood. It was noted that anisotropy and non-homogeneity of solid wood causes more-complicated warping of solid wood subject to variations in MC. Wood warping is regarded as one of the leading technical problems and deserves further investigation.

The first paper with a 1-dimensional (1D) mathematical model of wood warping was reported by Heebink et al. (1964). Subsequently, many researchers (Suchsland and McNatt 1986, Suchsland 1990, Suchsland et al. 1995, Wu 1999) used 1D warping models to explore warping of wood-based materials including particle-board, laminated wood panels, veneered furniture panels, plywood, and medium-density fiberboard (MDF). Serial numerical studies on the shape stability of sawn timber subjected to moisture variations were reported by Ormarsson et al. (1998, 1999, 2000). With the advent of composite mechanics, the finite element analysis (FEA), and computer technology, a 2D warping model was developed by Tong and Suchsland (1993), and Cai and Dickens (2004). Ganev et al. (2005) used an FEA of a 2D warping model to simulate and analyze hygroscopic warping of MDF panels. Blanchet et al. (2005, 2006) used an FEA of a 2D warping model to predict wood flooring deformation and design engineered wood flooring.

The objectives of this study were to describe an analytical method and use a 3D FEM to simulate and analyze the warping behavior of solid wood, including flat-sawn and quarter-sawn plates. We hope that timber warping might be better understood, and ideas on how to reduce the magnitude of timber warping can be developed for practitioners from this study.

MATERIALS AND METHODS

Materials

A solid wood plate of yellow birch (*Betula alleghaniensis*) was used to simulate and analyze the warping of solid wood due to MC gradients. Its dimensions were 30 cm long, 30 cm wide, and 3 cm thick as shown in Fig. 1. The initial 12% MC was assumed for the entire plate.

The assumed imbalance of MC gradients was based on +8% from the bottom surface to 1/4 thickness, +6% from 1/4 thickness to 1/2 thickness based on the bottom surface, +4% from 1/2 thickness to 3/4 thickness based on the bottom surface, and +2% from 3/4 thickness to the top surface based on the bottom surface.

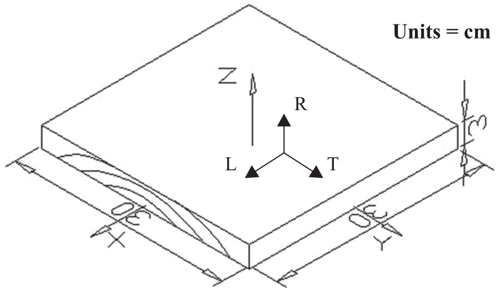

Fig. 1. Yellow birch plate used for the finite element modeling.

The mechanical properties of yellow birch at a 12% MC, used in this study, are described below (Blanchet et al. 2006).

Poisson's ratios (ν) of ν_{LT}, ν_{TR}, and ν_{LR}, were 0.45, 0.36, and 0.43, respectively. The hygroscopic expansions (α) of α_T, α_L, and α_R, were 0.0023, 0.00015, and 0.0015, respectively. The elastic moduli of E_L, E_R, and E_T, were 15.251, 1.251, and 0.641 GPa, respectively. The shear moduli of G_{LR}, G_{RT}, and G_{LT}, were 0.971, 0.242, and 0.721, respectively.

The subscripts L, R and T, indicate the longitudinal, radial, and tangential directions, respectively.

Poisson's ratios and hygroscopic expansions were assumed to remain unchanged with MC changes. However, elastic and shear moduli were affected by the MC. The appropriate adjustments were made according to the following equation:

$$E = E_{12}*(E_{12}/E_{GR})^{-[(M-12)/(Mp-12)]}; \quad (1)$$

where E is the modulus of elasticity (MOE) at an MC of M, E_{12} is the MOE at an MC of 12%, E_{GR} is the minimum MOE at an MC of Mp, which is somewhat less than the fiber saturation point (FSP), and Mp is the MC at which the modulus reaches its minimum value.

Formulation of governing equations

Wood, regarded as an orthotropic elastic body in the domain Ω, was subjected to the

MC change, ΔM. The governing equations are formulated as follows (Tong and Suchsland 1993).

The general stress-strain relation caused by a MC change in the expression of tensor form is:

$$\sigma_{ij} = E_{ijkl} (\varepsilon_{kl} - \alpha_{kl} \Delta M); \quad (2)$$

where σ_{ij} is the component of the stress tensor, ε_{kl} is the component of the strain tensor, E_{ijkl} is the stiffness tensor, α_{kl} is the hygroscopic expansion coefficient, ΔM is the MC change, and i, j, k, l are coordinate indices, each of which can independently attain values of 1, 2, or 3.

The general strain-displacement relation in the expression of tensor form is:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right); \quad (3)$$

where ε_{ij} is the component of the strain tensor, ∂u_i is additional displacement in the X_i direction, ∂u_j is additional displacement in the X_j direction, ∂x_i is the original length in the X_i direction, and ∂x_j is the original length in the X_j direction.

The stress equilibrium in the absence of body forces in the expression of tensor form is:

$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0. \quad (4)$$

The boundary conditions in the expression of the tensor form are:

$$u_i = 0 \text{ on } \Gamma_{i1} \text{ and} \quad (5)$$

$$\sigma_{ij} n_j = 0 \text{ on } \Gamma_{i2}; \quad (6)$$

where u_i is displacement in the i direction, n_j is the unit normal in the j direction, Γ_{i1} is the symmetric plane, Γ_{i2} is the traction-free boundary, and $\Gamma = \Gamma_{i1} + \Gamma_{i2}$ is the total boundary, Ω.

FEM for hygroscopic warping of yellow birch sawn timber

Modeling of hygroscopic warping of solid wood was conducted with the commercial software, ANSYS. A 3D orthotropic solid element (solid element 46) was used to model and simulate the warping of solid wood due to MC gradients. The effects of panel type, i.e., flat-sawn and quarter-sawn plates, on the warping of wood were also investigated. The principal material directions of wood were assumed perfectly oriented with the Cartesian coordinate system, and wood growth rings were assumed to be perfectly flat. The element mesh of the model is displayed in Fig. 2, using ANSYS preprocessing. This model included 100 elements and 605 nodes. This method can be applied to layered as well as homogenous materials. The commercial software, ANSYS, was implemented in this study so that the FEM and deformed geometry could be graphically displayed.

RESULTS AND DISCUSSION

Effects of the MC on mechanical properties

Wood was assumed to be an orthotropic material with significant differences in physical and mechanical properties among the longitudinal, radial, and tangential directions. These wood properties were required to run the ANSYS software. However, the elastic modulus, E, and shear modulus, G, of wood were affected by MCs below the FSP,

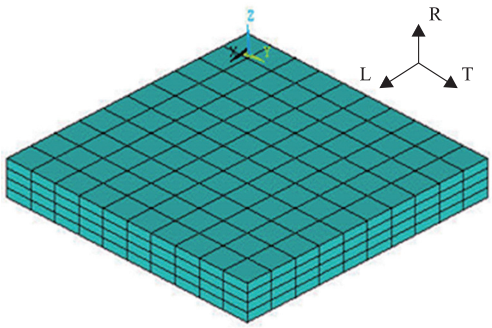

Fig. 2. Element mesh of the yellow birch plate.

where the bonded water will increase or reduce cohesion and stiffness of the tissues of wood. The MC varied from the top surface to the bottom surface in this study. Therefore, appropriate adjustments of these moduli calculated according to Equation (1) are shown in Table 1. These moduli, E and G, decreased with an increasing MC as anticipated.

Effects of panel type on warping

The hygroscopic warping of 2 types of panels, i.e., flat-sawn and quarter-sawn yellow birch plates, were simulated and analyzed. Results of the simulation and analysis of yellow birch plate warping are shown in Fig. 3, which displays the displacement in the Z direction, Uz, of the deformed body versus the un-deformed edge (dashed line). The shading indicates the extent of warping, which can be read on the horizontal scale. Simulation by the FEM showed that a higher MC in the bottom surface caused a concave deformation toward the top surface. Maximum warping occurred in the center of the plate, which combined the deflection along the length and deflection along the width. The maximum warping was read from the DMX in Fig. 3. The maximum warping in the flat-sawn plate, 0.770 cm, was higher than that in the quarter-sawn plate, 0.725 cm. The result was as expected since deflection caused by the tangential expansion coefficient is greater than that caused by the radial expansion coefficient on the base of the same plate size. In terms of the deflection percentage (the maximum warping/diagonal length), the maximum deflection percentage (1.81%) in this study

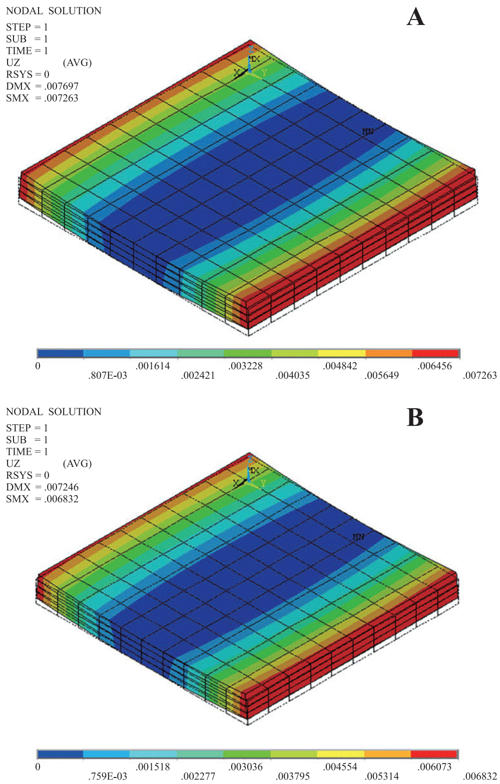

Fig. 3. Warping of yellow birch. A: Flat-sawn plate; B: quarter-sawn plate.

Table 1. Young's moduli (E) and shear moduli (G) of yellow birch plates

Modulus (GPa)		Bottom surface to 1/4 thickness	1/4 thickness to 1/2 thickness	1/2 thickness to 3/4 thickness	3/4 thickness to the top surface
	MC 12%	MC 20%	MC 18%	MC 16%	MC 14%
E_L	15.251	13.5669	14.0326	14.5144	15.0126
E_T	0.641	0.4413	0.4845	0.5318	0.5839
E_R	1.251	0.9248	0.9973	1.0755	1.1600
G_{LR}	0.242	0.8326	0.8653	0.8992	0.9344
G_{LT}	0.721	0.6008	0.6289	0.6582	0.6889
G_{RT}	0.242	0.1950	0.2058	0.2172	0.2293

E, elastic modulus; G, shear modulus; L, longitudinal; R, radial; T, tangential; MC, moisture content.

was close to that (1.34%) reported by Tong and Suchsland (1993).

CONCLUSIONS

It appears that the hygroscopic warping of orthotropic material due to MC gradients was successfully simulated and analyzed by an FEM in this study. Wood was assumed to be an orthotropic material, and its properties were strongly affected by MC changes. The hygroscopic deformations of flat-sawn and quarter-sawn plates were adequately reflected by this proposed FEM. The reliable results of this study obtained here can highly contribute to more-effective use of wood and help practitioners better understand complex warping behaviors and generate valuable ideas on how to reduce the magnitude of warping.

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