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A MATLAB-based image processing algorithm for analyzing cupping profiles of two-layer laminated wood products

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ABSTRACT

This study developed a MATLAB-based image processing algorithm for calculating the cupping of two-layer laminated wood specimens made of densified and undensified balsam fir (*Abies balsamea* (L.) Mill.). A six-week moisture cycling treatment followed by an oven-drying treatment was conducted to produce cupping. Two series of images, recording the undeformed and deformed shapes of each specimen, were scanned using a computed tomography (CT) scanner. The algorithm developed in the study accurately detected the two end points and the top point at the bottom edge of deformed specimens and then calculated the cupping using a quadratic curve fitting method.

1. Introduction

A novel two-layer laminated wood product was made by adhesively bonding a thin thermo-hydro-mechanically (THM) densified wood (D) laminate as surface layer to a thick undensified wood (V) laminate as a substrate. The grain of the two laminates is parallel in. Such a product has high surface hardness due to the use of densified wood and can be fabricated at a lower cost than a symmetric, three-layer laminated wood product (i.e., D–V–D). One application of this two-layer laminated wood product is flooring. However, warp of such an asymmetric laminated wood product (e.g., cup, crook, and bow) would appear due to its asymmetric structure in both material properties and geometric profile, causing a critical issue that significantly degrades the appearance quality of its end-products. Considering the aforementioned laminated wood product, cupping in the cross-section of the layered system is the most probable type of warp because of larger swelling/shrinkage coefficient differential between two wood layers in the transverse direction than the longitudinal (*L*) direction. The degree of cupping varies with the fluctuations of the surrounding temperature and moisture, which is defined as the distance from one top point to the line linked by two end points of a convex curve stipulated in ASTM D1037 [1]. Based on residential construction standards published in 2009 [2], cupping in strip hardwood floor board shall not exceed 1.58 mm (1/16″) in height in a 76.20 mm (3″) maximum span measured perpendicular to the long axis of the board.

In previous work, the cupping of wood and wood-based composites was measured by means of a digital dial gauge [3,4]. Blanchet et al. [3] measured the cupping values of three types of three-layer cross-laminated and two types of two-layer cross-laminated wood flooring using a dial gauge. They found that the cupping of two-layer cross-laminated wood flooring was larger than that of three-layer wood flooring.

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Nilsson et al. [4] studied the cupping of three types of three-layer cross-laminated engineered wood panels (EWPs) made by THM densified wood. Scots pine (*Pinus sylvestris* L.) was the material for undensified wood and for making THM densified wood. The dimensions of the EWPs were 500 mm (length) by 500 mm (width) by 12, 14, and 16 mm (thickness). The configurations in thickness included 4-mm-thick densified wood as the surface layer, 6-mm-thick undensified wood as the middle layer, and 2, 4, and 6-mm-thick undensified wood as the bottom layer. The 500-mm-long square EWPs were made by bonding 10 pieces of cross-laminated wood strips together using a polyvinyl acetate (PVAc) adhesive. The relative humidity (RH) was set at (1) 40% for 35 days, (2) 65% for 107 days, (3) 40% for 175 days, (4) 85% for 56 days, and (5) 40% for 50 days. A dial gauge was used to measure the cupping of all EWPs. They found cupping increased with increasing thickness of the bottom layer. After the 400-day exposure, the EWP having the 6-mm-thick bottom layer had the largest cupping of about 7.90 mm, which were about two and six times larger than the EWPs having the 4 and 2-mm-thick bottom layers, respectively.

However, in their studies the dial gauge was good for manually measuring relatively large cupping of wood-based composites under limited locations. Recently, advances in digital image processing technology provide new possibilities for applying various digital image acquisition devices (e.g., X-ray computer tomography (CT) scanner) and processing approaches to measure the in-plane deformation of an object. An important advantage of digital image processing methods is its flexibility that can deal with objects having complicated configurations and any dimensions.

Some free image processing software products (e.g., Image J) have been developed to measure simple geometric characteristics, such as line, angle, circle, and area, in an image. Inputs are done manually by visually determining the locations of the start and end points of each measurement. However, measurement errors can be caused by the subjective judgment of an operator. Manually measuring many images is time-consuming. Moreover, some complicated geometric characteristics, such as cupping, may not be directly measured using such software. These barriers can be overcome by means of MATLAB software [5], which has powerful image processing and numerical computing abilities. Using it to compile a suitable program, repetitive operations in numerous images is possible. Compared with manual measurement, computer-assisted image measurement has higher precision, is faster, and has good reliability.

A review of the literature indicated that only limited studies have dealt with 'automatically' measuring cupping in a series of images for wood and wood-based composites. The aim of this study was to develop a MATLAB-based image processing algorithm for automatically measuring the cupping values of deformed two-layer laminated densified wood products. To reach this goal, an X-ray CT scanner was used to serially take images because it can, as a non-destructive scanning instrument, acquire both the outer profile and the inner features of an object [6–9].

2. Materials and methods

2.1. Materials

The wood species was balsam fir (*Abies balsamea* (L.) Mill.) of a mean oven-dried density of 320 kg/m^3 with standard deviation (SD) of 10 kg/m^3. Clear, straight-grain, and flat-sawn lumber was used for making undensified and densified wood strips, which could minimize bow and crook along the *L* direction. The densified wood was made by a THM densification technique developed by Li et al. [10].

The laminated wood specimens were made by bonding one densified wood strip and one undensified wood strip together using one-component polyurethane adhesive along the *L* direction and the bonded edge of each wood strip was the edge near to the pith. There were two types of specimens: one was made of 3-mm-thick densified wood and 16-mm-thick undensified wood (code: D3V16-1, 2, and 3) and the other included 7-mm-thick densified wood and 12-mm-thick undensified wood (code: D7V12-1, 2, and 3). Each type had three replicates. The overall dimensions of each specimen were 52 mm (width) by 19 mm (thickness) by 280 mm (length). All specimens were placed in a conditioning chamber at 20 °C and 65% RH to stabilize their moisture contents (MCs) before testing.

2.2. Dimensional stability experiment

The dimensional stability experiment was performed in two conditioning chambers, one of which was set up at 20 °C and 80% RH and the other was set up at 60 °C and 10% RH. First, a six-week cyclic treatment was conducted based on the schedule that is shown in Fig. 1. Then, an oven-drying treatment at 100 °C was conducted to further decrease the MC of all specimens to 0% in order to create the greatest cupping.

2.3. Image acquisition

The X-ray computed tomography (CT) scanner used in this study is a third-generation sliding gantry Siemens Somatom Volume Access medical CT scanner in the FPInnovations laboratory in Quebec City, Canada. Each specimen was scanned along the *L* direction before and

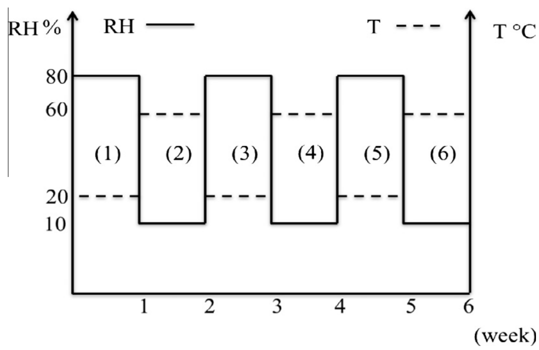

Fig. 1. Cyclic relative humidity (RH) and temperature changes.