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Variation of Paper Curl due to Fiber Orientation

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ABSTRACT

Transverse deviations from the ideal flat surface in paper, or curl, can be a serious problem in the paper industry. The manufacturing of paper materials results in the material being orthotropic and laminar. Moreover, the dominant fiber orientation in a paper sheet can vary through the thickness of the sheet. Many paper structures are produced by lamination of paper plies. In these products directions of symmetry of the elastic properties, and coefficients of moisture and temperature expansion/contraction, consequently differ through the thickness of the laminated material. When subjected to humidity changes, the top and bottom portions of a paper laminate therefore expand or contract different amounts, causing the structure to curl. Paper products that curl are difficult to convert in packaging applications and print or copy in automated feeding mechanisms, leading to large costs for companies. It can become impossible to machine process and dispense paper products (such as stamps) that have curled. The present research involves determining the moisture induced curl in [0/15] and [0/45] Whatman paper laminates using a full-field 3-D laser scanner.

1. Introduction

Curl, being the deviation of a sheet from its flat surface, is a prevalent occurrence in paper materials and often results from moisture changes. Such deviations from flatness in these materials are sometimes significant with respect to planar dimensions and can result in serious manufacturing consequences, problems during converting and printing processes, as well as improper machine-dispensing. With laminated products such as postage stamps, the different plies often have very different coefficients of moisture expansion in different orientations so any environmental moisture change can cause the laminate to bend out of its plane resulting in curl and/or twist. Storing laminated paper products in uncontrolled conditions can aggravate the situation. This particular investigation involves measuring the out-of-plane deflections of laminated plies of Whatman filter paper when the environment relative humidity is changed from 0% to 50% RH. The curvatures, twist, and radii of curvature in two-ply Whatman laminates having stacking sequences of [0/15] and [0/45] are evaluated by measuring the transverse deflections using a 3-D laser scanner.

2. Background

Several previous studies have been reported on the modeling and/or measurement of the transverse flexure (curl, twist) of paper or related materials, as represented by references 1 through 11.

Various methods have been employed to evaluate the curl/twist of paper materials. Although early means of measuring the transverse displacements of paper sheets involved such rudimentary techniques as viewing the deformed sheet through a transparent mesh of known pitch, Eriksson and co-workers [5] employed a commercial unit which consisted of a non-contacting distance meter and an environmental chamber. Viitaharju and Niskanen [6] utilized a previously developed PC-controlled curl meter. Nordstrom, Carlsson et al [7-9] assembled a system for measuring the shape of vertically-supported paper sheets using a non-contacting laser displacement sensor. By attaching the laser sensor to a translation stage, they were able to record the transverse displacements, $W(x,y)$, at several preselected positions across the deformed paper sheet. The x- and y-positions of the translation table (hence relative sensor position and therefore location on the paper sheet being interrogated) were computer-controlled and the recorded W-displacements stored for subsequent processing. Many of these approaches are not portable and testing can be somewhat arduous to implement for routine analyses, thereby hampering their application for routine quality control in a manufacturing environment. Reis et al. [11] recently proposed a procedure for measuring the diagonal curl which involves measuring the maximum transverse displacement of a sheet which is suspended at its corners.

3. Laminate Preparation

The present laminated specimens were prepared by bonding two plies of Whatman filter paper (Whatman International, Maidstone, Kent, UK, identified as Chromotography paper, model 3MM CHR and is 100% cellulose) together with a sheet of heat-activated photo mount dry adhesive (Dry Mount, from laminationplus.com). The combination of top and bottom plies of paper, separated by a sheet of the dry adhesive, were pressed between heated platens (76 °C) at load of 9000 N (2000 pounds) for 10 seconds. The platens reached the specified equilibrium temperature before applying the load; the much larger mass of the platen ensured constant temperature during pressing. An additional aluminum plate was placed between each of the top and bottom platens and the paper sheets. Care was taken to remove any adhesive exposed beyond the paper sheets to prevent bonding the paper to the aluminum plates. The laminate preparation was done at ambient temperature and humidity, but hot pressing the paper laminates brought them to essentially 0% RH. The prepared laminates were then stored for 24 hours at 50% RH at 23 °C. Within a few minutes of being removed from the hot press, individual sheets of Whatman paper had 0.33 mm caliper and two-ply laminated structure had 0.73 mm caliper. The measured caliper of individual Whatman plies and their laminates after being at 50% RH for 24 hours were essentially the same as at 0% RH.

4. Specimen Configuration

The originally dry laminates (100 mm × 89 mm) were hung vertically during the 24 hours at 50% RH, Fig. 1. The specimens were clamped along the top edge, the other three edges being free. They were clamped using a traditional clip board except the board was cut away to enable the laminate to deflect either inwardly or outwardly. The [0/15] and [0/45] laminates were tested with the 0˚-ply vertically downward towards the camera and the angle ply behind this 0˚-ply, the off-axis angle of 15˚ or 45˚ is measured from the vertical downward direction.

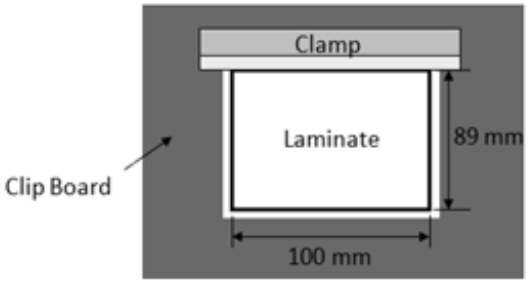


Fig. 1 Schematic of laminate loading

5. Deflection Measurements and Their Processing

The moisture-induced transverse deflections of the paper laminates were measured and recorded using a commercial 3-D laser scanner system (3-D REVscan scanner by Creaform, Levis, PQ, Canada; http://www.creaform3d.com). The scanner, which operates on the triangulation principle, consists of a laser which impinges light onto the surface of interest, and two cameras to capture the reflected light, Fig. 2. Triangles of known geometry are created by the fixed distance between the laser source and the cameras (dimension D in Fig. 2) and the angle created between the laser spot on the surface and cameras. Basic trigonometric principles are applied to calculate the distance between the scanner and the surface. A record of the surface in terms of relative transverse deflection is determined by repeating this triangulation process up to 20,000 times per second. The REVscan laser scanner is self positioning. It cannot directly create a scan; rather, it uses positioning features (targets) near the region of interest in order to be able to create a spatial model of the surface relative to the scanner's position in space. These "positioning features" or targets are small reflective circles which are placed near the scanned surface, Fig. 3. The accompanying VxScan software recognizes these targets, uses their relative placement to locate the scanner in space, and creates a reference frame in which the data may be collected and read. The targets should not be placed in a symmetrical fashion and the target array needs to be sufficiently dense so the scanner sees at least four targets at all times. The VxScan software is used to collect, analyze and store the scan data, and is a necessary part of every scan. Although the scanned data can be processed in a number of ways, Matlab® provides convenient options for manipulating the data and generating contour maps of a scanned surface, Figs. 4 through 6. The in-plane horizontal and vertical axes of all displacement images illustrated have units of mm.

Unlike many of the methods used previously to record transverse displacements, the 3-D REVscan laser scanner is highly portable, results are available almost instantaneously and the system indicates whether the transverse motion is towards or away from the camera. Accurate, quantitative results necessitate a preliminary calibration using a provided calibration plate.

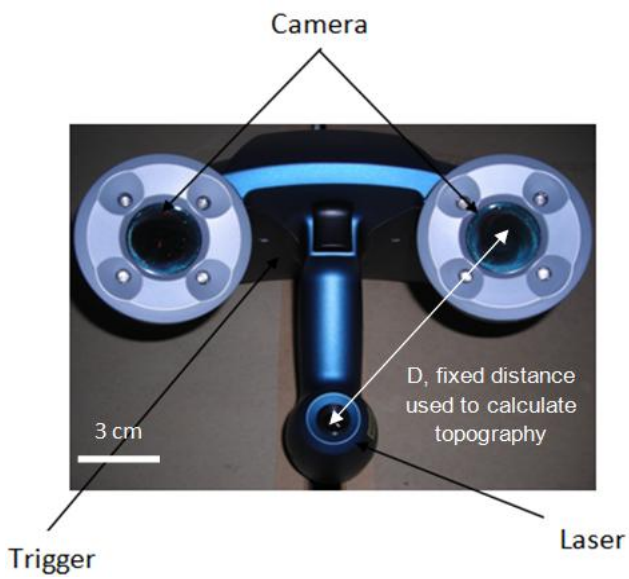


Fig. 2 Front view of laser scanner

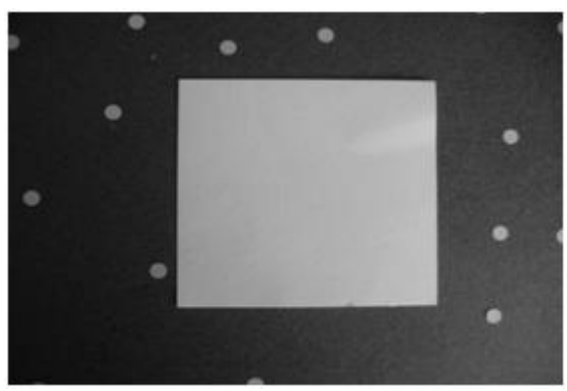


Fig. 3 Positioning features (targets) surrounding Whatman material

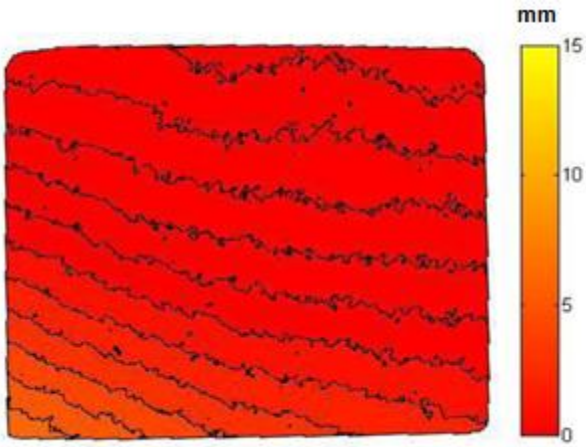


Fig. 4 Contour plot of transverse displacements in [0/15] laminated Whatman composite at 50% RH. The in-plane dimensions are 100 x 89 mm (Fig. 1).

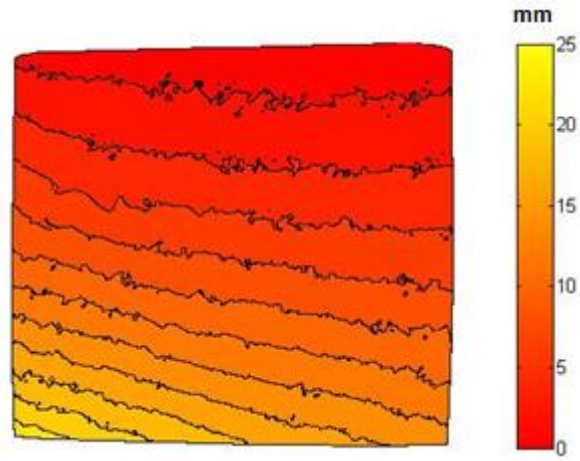
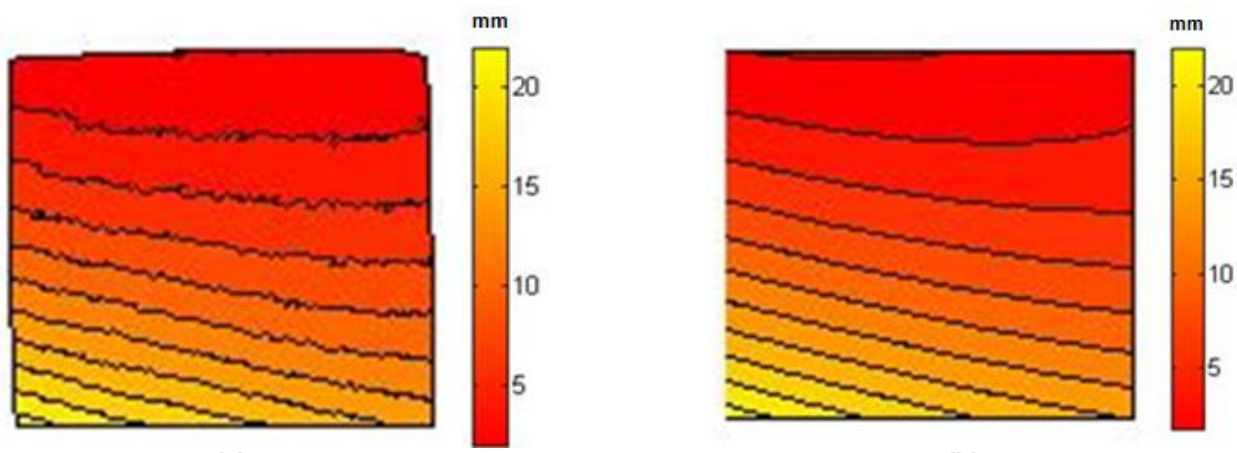


Fig. 5 Contour plot of transverse displacements in [0/45] laminated Whatman composite at 50% RH. The in-plane dimensions are 100 x 89 mm (Fig. 1).



(a) **(b)**

Fig. 6 Contour plots of transverse displacements in [0/45] laminated Whatman Composite at 50% RH. The in-plane dimensions are 100 x 89 mm: (a) from VxScan software, (b) least-squares fit of eqn (1) to output from VxScan software.

The 3-D REVscan laser scanner has an accuracy of 0.05 mm (0.002”) in each of the x, y and z directions. Although the resolution in the z-direction depends on the size of the object being scanned, and can be as fine as 0.1 mm, the data used in Figs. 4 through 6 were recorded at a z-resolution of 0.4 mm. Data for these displacement images were also collected at an in-plane resolution of 0.4 mm; that is, each data point originates no closer than 0.4 mm to any other point. Hence, the Matlab® generated contour plots of Figs. 4 through 6 are based on approximately 50,000 input data values. The contour plot of Fig. 6(b) is a least-squares fit of eqn (1) to the approximately 50,000 output values from VxScan. Comparing Figs. 6(a) and (b) demonstrates how well maps of $W(x, y)$ can be represented by fitting the data to the simple polynomial:

$$W(x, y) = C_1x^2 + C_2xy + C_3y^2 + C_4x + C_5y + C_6 \quad (1)$$

The curvatures, κ_{xx} and κ_{yy}, and twist, κ_{xy}, and the associated radii of curvatures are given by

$$\kappa_{xx} = -\frac{\partial^2 W}{\partial x^2} = -\frac{1}{R_x}, \qquad \kappa_{yy} = -\frac{\partial^2 W}{\partial y^2} = -\frac{1}{R_y}, \qquad \kappa_{xy} = -\frac{\partial^2 W}{\partial x \partial y} \quad (2)$$

and from eqn (1)

$$\kappa_{xx} = -2C_1, \quad \kappa_{yy} = -2C_3, \quad \kappa_{xy} = -C_2 \tag{3}$$

The sign conventions utilized in eqns (1) through (3) are compatible with those of reference 4.

6. Results

Based on eqns (1) through (3), the Cartesian components of curvature and twist for the [0/15] and [0/45] laminates of Figs. 4 through 6 are given in Table 1. The *x*-direction is horizontal and the *y*-direction is vertical. Values of Table 1 recognize the Mohr's Circle analogy for plates, Fig. 7, such that κ_{xx}, κ_{yy}, κ_{xy} are the curvatures and twists, respectively, with respect to the *x,y* coordinates, κ_1 and κ_2 are maximum and minimum values of the curvatures, and R_x, R_y, R_1 and R_2 are the associated radii [4].

Table 1 Scanner determined curvatures and radii of moisture induced curl in [0/15] and [0/45] laminates of Whatman paper material (moisture increased from 0 to 50% RH).

	Laminate	
	[0/15]	[0/45]
$\kappa_{xx} = -\frac{\partial^2 W}{\partial x^2} = -\frac{1}{R_x} = -2C_1$ (10^{-4} mm^{-1})	-5.76	-7.04
$\kappa_{yy} = -\frac{\partial^2 W}{\partial y^2} = -\frac{1}{R_y} = -2C_3$ (10^{-4} mm^{-1})	-7.64	-24.00
$\kappa_{xy} = -\frac{\partial^2 W}{\partial x \partial y} = -C_2$ (10^{-4} mm^{-1})	-4.27	-9.50
$\kappa_1 = \frac{1}{R_1}$ (10^{-4} mm^{-1})	-2.30	-2.80
$\kappa_2 = \frac{1}{R_2}$ (10^{-4} mm^{-1})	-11.10	-28.20
$\lvert R_1 \rvert$ (m)	4.35	3.60
$\lvert R_2 \rvert$ (m)	0.90	0.35

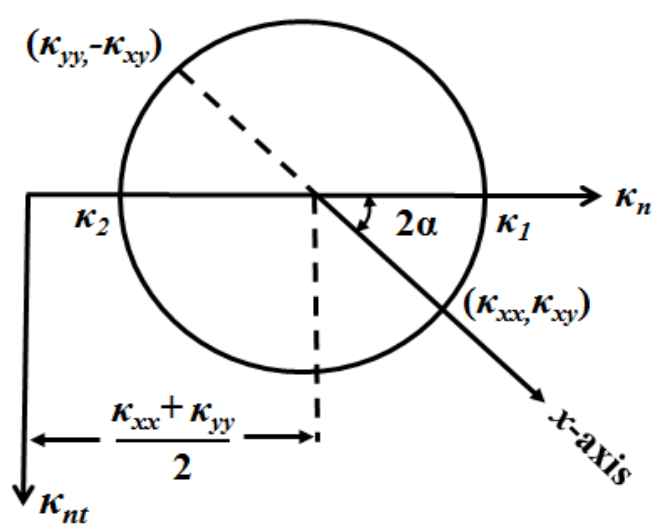


Fig. 7 Mohr's circle analogy for plate curvatures and twist [4].

7. Summary, Discussion and Conclusions

The 3-D REV scanner is well suited for measuring transverse deformations of thin flexed sheets. The scanner was used here to evaluate moisture-induced curl (curvatures, twist, and radii of curvature) in [0/15] and [0/45] Whatman laminates. Recognizing a paper ply has its greatest coefficient of moisture expansion in its cross-machine or 2-direction, the mismatch in moisture coefficients between the top and bottom plies of a laminate is greater for the [0/45] than the [0/15] stacking sequence. This is compatible with the smaller physical radius of curvature, $|R_2|$ = 0.35 m (associated with κ_2 in Table 1), for the [0/45] laminate, compared to 0.90 m for the [0/15] case. It is also consistent with the former's increased overall transverse displacement (Figs. 4 through 6). Future research will consider more stacking sequences, additional humidity changes and numerical predictions of the observed responses.

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