OUT-OF-ROUND PAPER ROLLS

by

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ABSTRACT

Paper is usually shipped in rolls covered by a thin wrapper to protect it from moisture and dirt. In effect, the roll becomes the shipping container for the paper. A single sheet of paper is weak and fragile, but in roll form it can withstand the substantial compressive forces required to lift it with clamps. However, even a small permanent deformation caused by clamping or impacts during transportation can cause a significant variation in web tension as the roll is unwound in a printing press. Tension variations can cause misregistration or flutter in a printing press. To compensate for out-of-roundness and the subsequent variations in tension, the operator will increase the average web tension, but that increases the chance of a web break. The ultimate solution is to make a paper roll that is resistant to the forces it will encounter between the winder and the printing press. As denser paper is made into longer and wider rolls, the force required to lift the roll increases, which may preclude handling by clamping. We have developed a mathematical model which shows that, for a given clamping pressure, the permanent deformation of the paper roll is related to the tension wound into the paper roll and the compressibility of the paper in the radial direction. The occurrence of out-of-round rolls can be reduced by tighter winding and using less compressible paper.

NOMENCLATURE

A	=	proportionality constant between maximum and permanent deformation	
E	=	modulus of paper roll	(kPa)
E_R	=	elastic modulus of a stack of paper	(kPa)
ε_p	=	permanent deformation	
F	=	force per unit width applied to the paper roll	(kN/m)
g	=	acceleration due to gravity	(m/s^2)
k_1	=	proportionality constant	(kPa)
k_2	=	paper springiness (dimensionless)	

N	=	clamp force	(N)
σ_R	=	compressive stress	(kPa)
σ_r	=	radial compressive stress	(kPa)
P	=	pressure applied by the clamp	(kPa)
ρ	=	roll density	(kg/m^3)
r	=	radius of paper roll	(m)
μ	=	coefficient of friction between the wrapper and clamp	(dimensionless)
w	=	width of the paper roll	(m)

INTRODUCTION

Out-of-round paper rolls are created during handling by clamping forces, impacts during transportation, or simply by storing on their side for extended periods. On a printing press, out-of-round paper rolls can vibrate and cause web tension variations that can break the web or cause registration errors. Although handling forces can be reduced in a paper mill, the manufacturer has less control once the roll leaves the plant. The ultimate solution to this problem is to wind rolls that are resistant to deformations from the external forces that they will receive between the winder in the paper mill and the customer's printing press.

Several studies of out-of-roundness (OOR) have monitored the shape of paper rolls from the paper mill to the printing press [1,2]. These studies had to contend with two independent factors: the forces applied to the roll during handling and transportation, and the propensity for permanent deformation of the roll from these forces. Both these factors must be monitored to relate OOR to roll or paper properties. Roll shape can be measured statically with devices such as the Radivarius [1–3]. The correlation between out-of-roundness measured statically with the Radivarius in the mill and dynamically with non-contacting optical devices on the press is weak [1,2]. This discrepancy is probably the result of differences in handling of each roll and differences between clamp position and the measurement point in the cross-direction on the roll (the Radivarius measures only on the edge).

The primary cause of paper roll vibration in a printing press is imbalance caused by OOR, off-centre cores, or off-centre chucking [2]. Vibration will cause web tension variations and flutter, and under extreme conditions could damage the cores, chucks, and the press. However, even without vibration, changes in length caused by mis-shaped rolls, can cause sizeable changes in web tension which can lead to misregistration [4,5]. Uneven clamping along the width of the roll can lead to periodic tension variations at particular cross-direction positions such as the edges.

The deformation of the paper roll increases with the clamp force with small diameter rolls being more affected [6]. The number of times the roll is handled is not important [1,6] but the shape of the clamp which determines the distribution of force on the roll appears to be a factor [1]. New clamps, designed to conform to the roll diameter and apply the minimum force to lift the roll by sensing slippage [7], minimize damage.

Winding more tightly or uniformly in the radial direction or using paper with a higher ratio of z-direction to in-plane elastic modulus will produce rolls that are more resistant to deformation [8]. Although paper rolls lose tension over time and should become more susceptible to handling damage [8], a mill study indicated that this factor is not significant [2].

In this study, the mechanics of out-of-round paper rolls is described to isolate the importance of roll structure and paper properties from handling conditions. The approach is to describe out-of-round rolls from the perspective of mechanics of deformable bodies. The minimum pressure to lift a paper roll can be calculated from its weight, the surface area of the clamps, and the friction between the clamp surface and the roll wrapper. From the equations that describe the stress-strain relationship of a stack of paper, it is possible to derive an expression for permanent deformation of a paper roll which includes wound-in tension and the compressibility of the paper. The theoretical work has been validated by experiments on commercial and laboratory wound paper rolls using large, laboratory stress-strain machines. Recommendations are made for paper roll structure and winder operation with comments on the importance of paper properties.

Tension Variations Caused by Out-of-Round Rolls

Tension variations caused by out-of-round rolls were measured on an experimental unwind stand. As part of a study on the factors that control runahead in printing presses [9], a rig was constructed to simulate the braking mechanism of a commercial printing press (Figure 1). The tension band contacts the paper roll over an angle α. The braking force is provided by a piston which exerts tension T_2 on the band. The reaction T_1 is [10]:

$$T_1 = T_2 \; e^{-\mu_b \alpha} \qquad (1)$$

where μ_b is the dynamic coefficient of friction between the band and the paper.

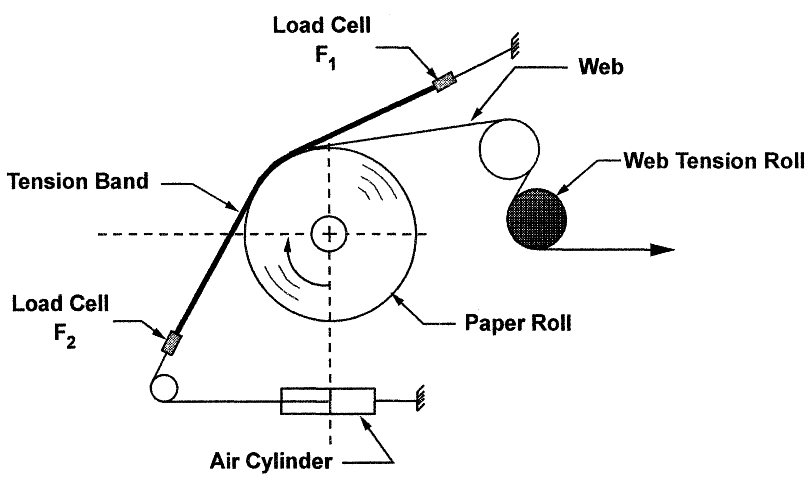


Figure 1. Instrumentation to measure the tension variations in the web caused by out-of-round.

Paper rolls up to 1.27m in diameter and 0.6m wide were mounted on the unwind stand. A single band, identical to those used on a commercial printing press, wrapped the paper roll. One end of the band was attached to a solid support and the other was attached to a pneumatic piston to control the tension. The tension in the unwound paper was measured with a roll equipped with load cells in the bearings. The tension in the band was measured by means of load cells located at the attachment point between the piston and band, T_2, and between the band and support point, T_1. The wrap angle was determined on the run with a template mounted on the side of the unwind.

An out-of-round paper roll causes the tension to change in the tension band and in the paper web (Figure 2). For this roll, which was not visibly out-of-round, the tension variation in the web was approximately 0.1 kN/m (0.6 pli).

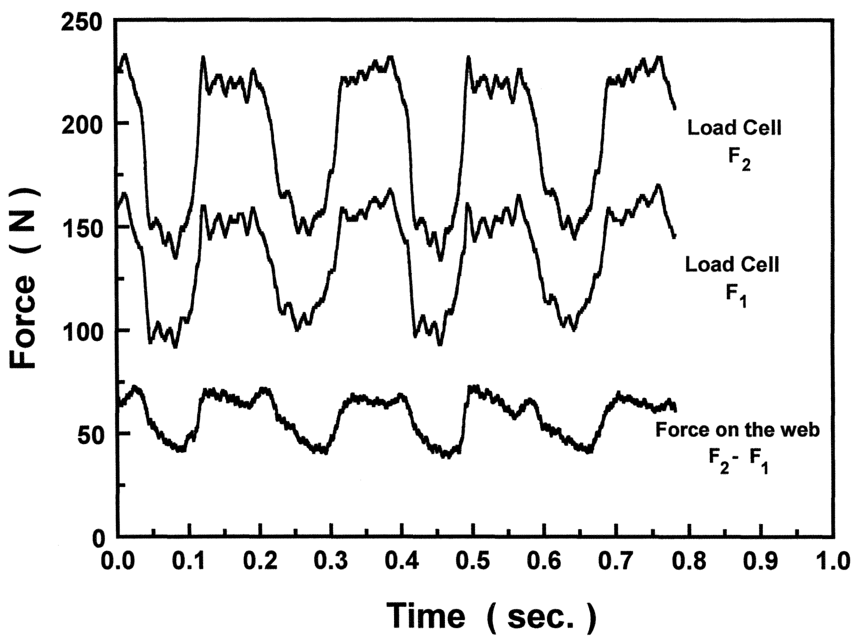


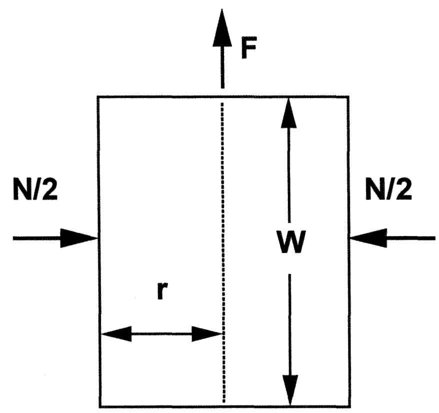
Figure 2. Web tension variations induced by an out-of-round paper roll.

Clamping Force and Pressure Applied to a Paper Roll

The minimum clamp force to lift a paper roll is proportional to the weight of the roll and the coefficient of friction between the wrapper and the clamp surface (Figure 3):

$$N = \frac{\rho g \pi w r^2}{\mu} \tag{2}$$

Minimum Clamp Force



g = Acceleration due to gravity

ρ = Roll density

μ = Coefficient of friction between clamp and wrapper

$$N \cong \frac{\rho g w r^2}{\mu}$$

Figure 3. Minimum clamping force to lift a paper roll depends on the roll weight and the coefficient of friction between the clamps and the wrapper.

In practice, the clamping force should be significantly larger than the minimum force to avoid accidental slippage.

The deformation of the paper roll is caused by the pressure applied by the clamp surface on the paper roll. Assuming that the pressure is uniform, the pressure is the clamping force divided by the surface area of the clamps (A):

$$P = \frac{N}{A} \tag{3}$$

The minimum pressure to lift a paper roll is:

$$P = \frac{\rho g \pi w r^2}{\mu A} \tag{4}$$

To minimize the pressure, the clamping area should be as large as possible and the clamp shape should conform to the radius of the roll to apply the pressure uniformly. Obviously increasing the width, or radius of a paper roll will make it more susceptible to handling damage.

Deformation of Paper

Paper is a non-linear material under compression because the stiffness or modulus of paper increases in proportion to applied pressure. For a stack of paper this can be expressed as [11,12]:

$$E_R = k_1 k_2 + k_2\ \sigma_R \tag{5}$$

This leads to a non-linear stress-strain relationship [11,12]:

$$\sigma_R = k_1\ (e^{\ k_2 \varepsilon} - 1) \tag{6}$$

Typical stress-strain behaviour of a stack of paper for one loading and unloading cycle is shown in Figure 4. For small-applied pressures, paper behaves as an elastic material and the stack returns to its original height when the pressure is released. Larger pressures lead to permanent changes in stack height. Calendering would be an extreme example of a permanent strain but smaller thickness reductions are induced by the compressive stresses in winding and roll handling.

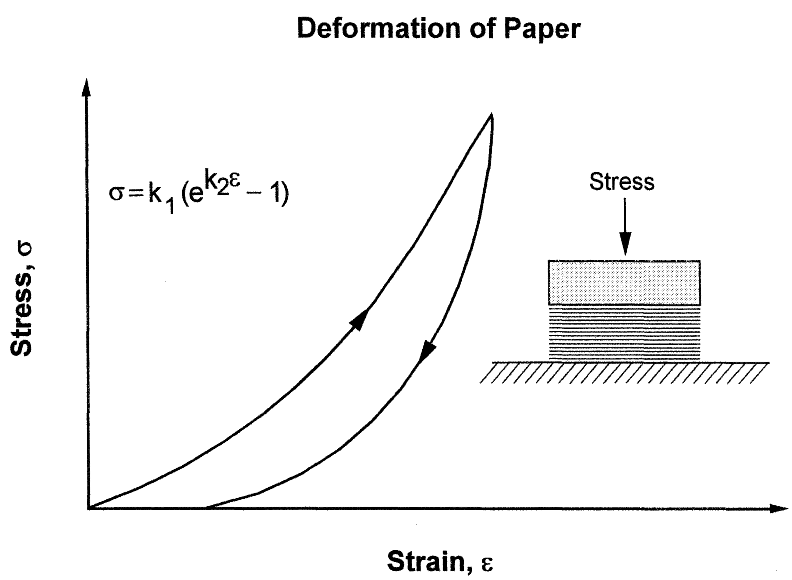


Figure 4. Stress-strain relationship for a stack of paper.

Deformation of Paper Rolls

The deformation of paper rolls was measured in an 810 MTS tensile-compression material tester as shown in Figure 5. The cores were plugged with a wooden cylinder to prevent core deformation. A 51mm thick plate contacted the paper roll. The plate was attached to the load cell with a universal joint to minimize shear stresses which could damage the cell. The paper rolls were loaded at a constant strain rate of 5 mm/min to a maximum load of 294N and the applied line load was recorded.

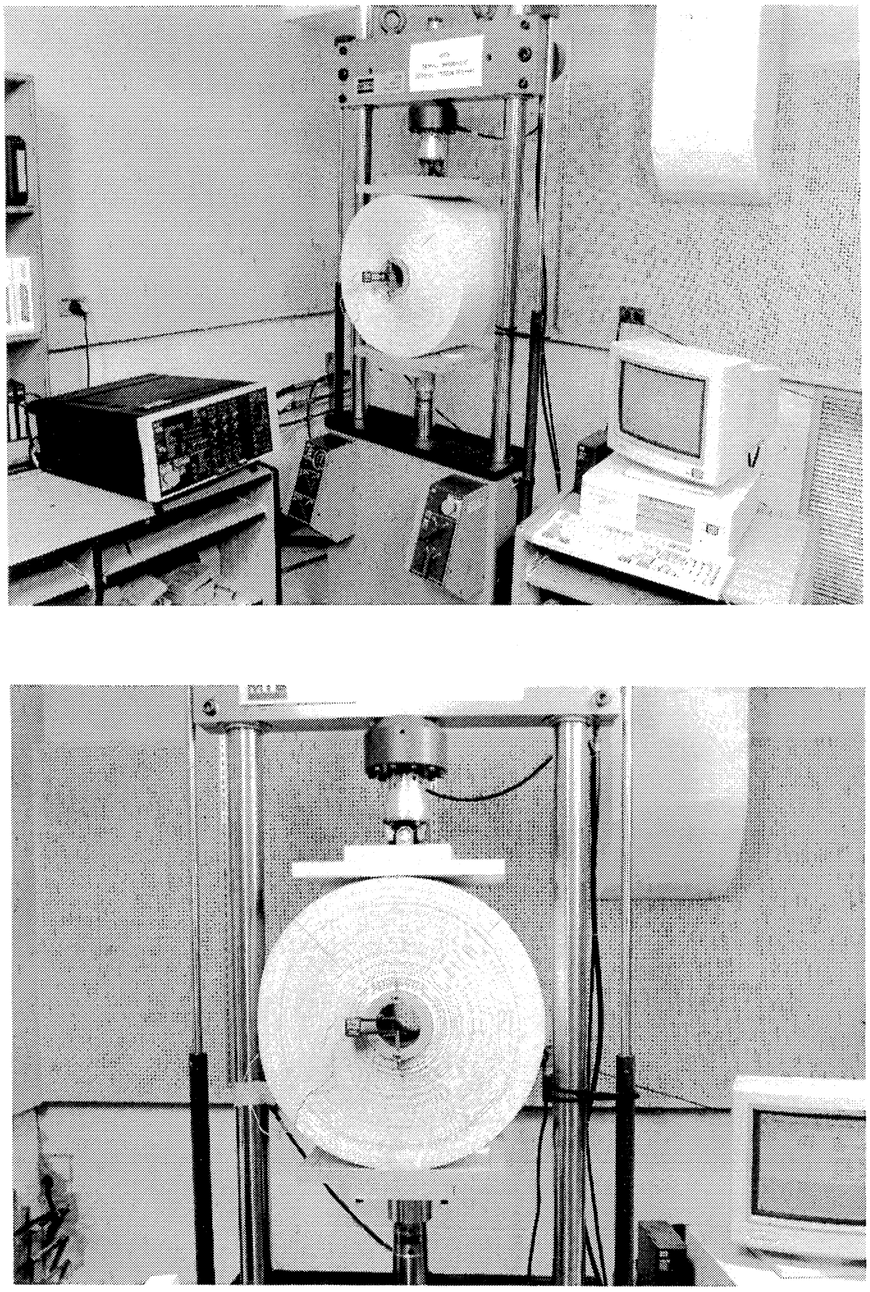


Figure 5. Paper rolls were deformed in a large compression tester.

The compression behaviour of paper in a roll is different than that in a stack (Figure 6). As a stack of paper is compressed, it becomes stiffer. The deformation of a paper roll under an applied force is approximately linear with small displacements but becomes easier to deform at higher loadings (Figure 6). Using Hertzian theory, which assumes an isotropic material with constant elastic modulus, the change in radius of a roll clamped between two flat plates is [13]:

$$\Delta r = \frac{2F}{\pi E}\left(\frac{1}{3} + ln\frac{4r}{b}\right) \tag{7}$$

and, *b*, is the contact distance between the plate and roll surface:

$$b = 1.60\sqrt{\frac{2Fr}{E}} \tag{8}$$

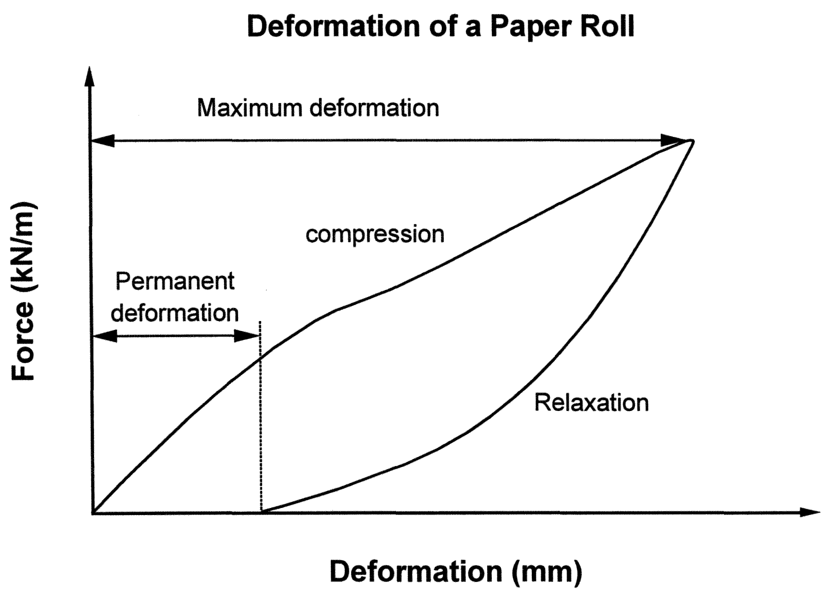


Figure 6. Deformation of a paper roll for a load applied at a constant rate of strain.

The Hertzian equations, (7 and 8) which assume a constant modulus *E*, would predict that the change in radius would be smaller at higher forces because of the flattening of roll against the plates, *b*. In reality, the effective modulus of the paper roll, *E*, decreases with the applied force because of interlayer movement and disruption of the wound-in radial compressive stresses, as shown by Eriksson [8].

The permanent deformation of a paper roll is proportional to the maximum deformation induced under the applied stress, as shown in Figure 7a. These rolls were 95 cm in diameter and 34 to 43 cm wide. In general, the relationship between the permanent deformation, ε_p, and the maximum deformation ε_m, is linear:

$$\varepsilon_p = A\varepsilon_m \tag{9}$$

where, A, is the constant that links the two. For these particular rolls, A was 0.37, as shown in Figure 7b.

Paper in a roll below the immediate surface is subject to compressive stress as the result of loop stresses exerted by overlying layers [4,11,14]. Light clamping further compresses the paper immediately under the clamp surface. For moderate clamping forces, where the deformation of the paper roll is approximately linear with the clamping force, the permanent deformation of the paper roll is primarily a result of the permanent deformation of paper rather than a redistribution or lateral movement of paper layers. Combining equations (5) and (9) for a radial compressive load that includes the effect of wound-in tension, σ_r, and the clamp pressure, P, gives an expression for the permanent deformation, ε_p:

$$\varepsilon_p = \frac{AP}{E_R} = \frac{AP}{k_2\ (\sigma_R + k_1)} \tag{10}$$

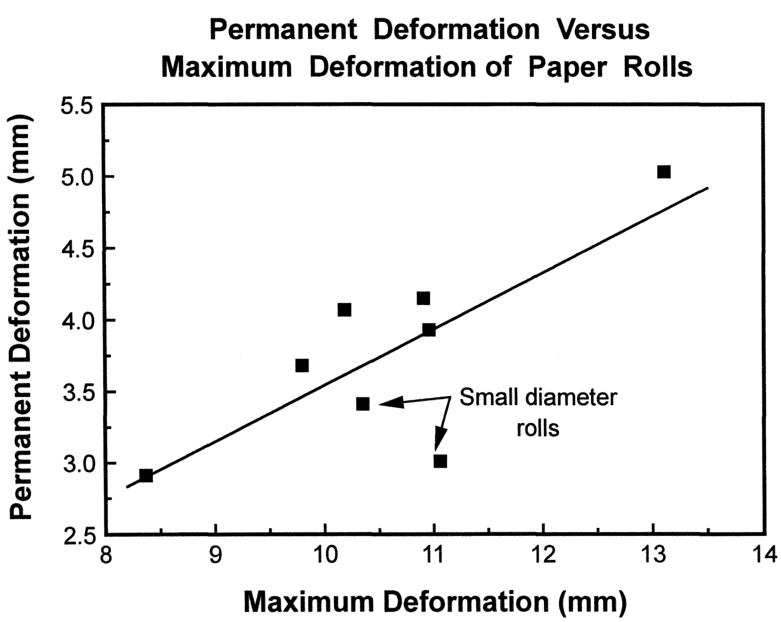


Figure 7a. Permanent deformation of a paper roll as a function of maximum deformation.

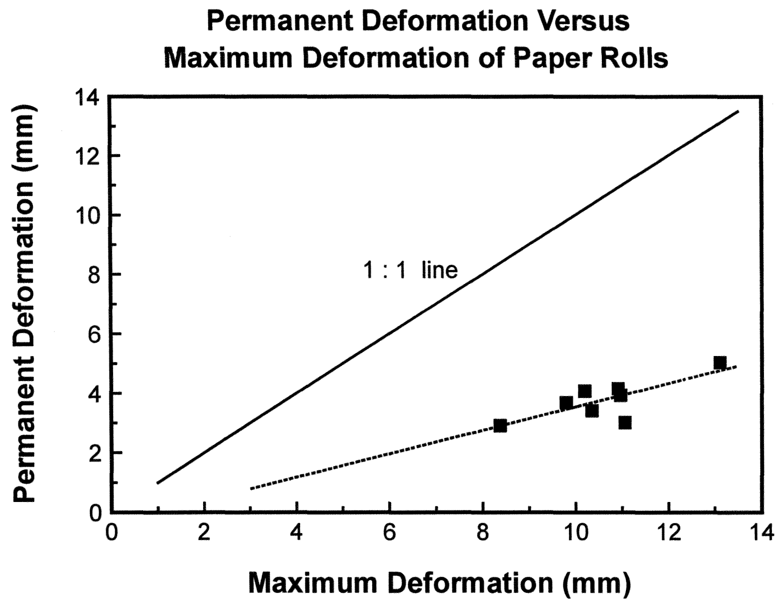


Figure 7b. Permanent deformation is less than the maximum deformation.

Under most conditions, $\sigma_r >> k_1$ so that equation (10) can be simplified to:

$$\varepsilon_p \cong \frac{P}{k_2 \sigma_r} \qquad (11)$$

The permanent deformation of a paper roll is proportional to the clamping pressure. Increasing the wound-in tension (radial compressive stress, σ_r) or the k_2 of paper makes the roll more resistant to clamping pressure.

Factors that Affect Paper Roll Stiffness

As shown in equation (11), the ability of a paper roll to withstand clamping and handling forces is related to two factors: wound-in stresses and paper properties. To separate these two factors, experiments were performed on a series of rolls 356 mm in diameter and 76 mm wide. These rolls were wound from papers with different material properties (Table I) to several levels of wound-in tension on a commercial centre-winder. The radial compressive stress was measured at approximately five positions for each roll using the method described in Appendix A. The readings for each roll were independent of radius and were averaged to give a representative value. The modulus of each paper roll was measured in a model 810 MTS tensile-compression testing machine by taking the slope of the stress-strain curve in the linear region.

TABLE I
Material Properties of Paper Used in Deformation Experiments.

Paper	*Basis weight*	*Caliper*	*Apparent density*	*In-plane Elastic Modulus*	*Coefficients for Radial Compressive Modulus E_r^+*		*Coefficient of Friction*
	(g/m²)	*(μm)*	*(g/cm³)*	*E_t (GPa)*	*k_1 (kPa)*	*k_2*	*μ*
United States	*47.6*	*85.6*	*0.556*	*3.96*	*76*	*33*	*0.32*
Quebec	*42.6*	*84.8*	*0.565*	*4.21*	*106*	*26*	*0.39*
Ontario	*42.2*	*74.7*	*0.565*	*5.53*	*95*	*34*	*0.63*
Directory	*33.5*	*61.2*	*0.547*	*5.16*	*83*	*37*	*0.65*
Recycled	*43.8*	*77.2*	*0.567*	*4.54*	*108*	*44*	*0.24*

(+) $E_r = k_1 k_2 + k_2 \sigma_r$; where σ_r is the compressive radial stress

The machine-direction elastic modulus (E_t) was measured on a model 1123 Instron at an elongation rate of 10 mm/s, by taking the initial slope of the stress-strain curve.

Permanent deformation is 37% of the maximum deformation (Figure 8) which is the same value as measured for the large diameter rolls. The relationship appears to be independent of the material properties of the paper such as modulus and coefficient of friction.

The permanent deformation of the paper roll is inversely related to the modulus of the roll (Figure 9). This is consistent with the form of equation 10 and its simplification, equation 11. The plot of the roll modulus versus wound-in compressive stress also gives a single relationship independent of the material properties of the paper (Figure 10). Because the papers in this study had similar values for k_2 (Table I), the modulus is also linear with the product of radial compressive stress, σ_r, and k_2, consistent with equation 5.

Material Properties of Paper

The compressive modulus of paper is a consequence of operations intended to achieve other product specifications. Measurements of compressive modulus have shown that the type of furnish is important [12] and paper formed with thicker-walled pulp fibres will be stiffer [15].

Although the degree of calendering does not change the stiffness (k_2) of the paper (Figure 11), the reduction in caliper increases the radial compressive stress in the paper roll under constant winding conditions. Thinner paper gives a tighter, harder roll on any winder because more energy is imparted to the paper per unit thickness. This effect is amplified on two-drum winders because more calendering increases both the density of the sheet and roll which leads to greater nip forces causing higher radial compressive stress.

Paper is a viscoelastic material and will creep over time under the stresses imposed by the wound roll. These changes in dimensions will lead to lower stresses and loss of hardness [8,16,17]. To illustrate this effect, paper pads 5mm in thickness were compressed to 200 kPa in a MTS tensile-compression material tester. After reaching this

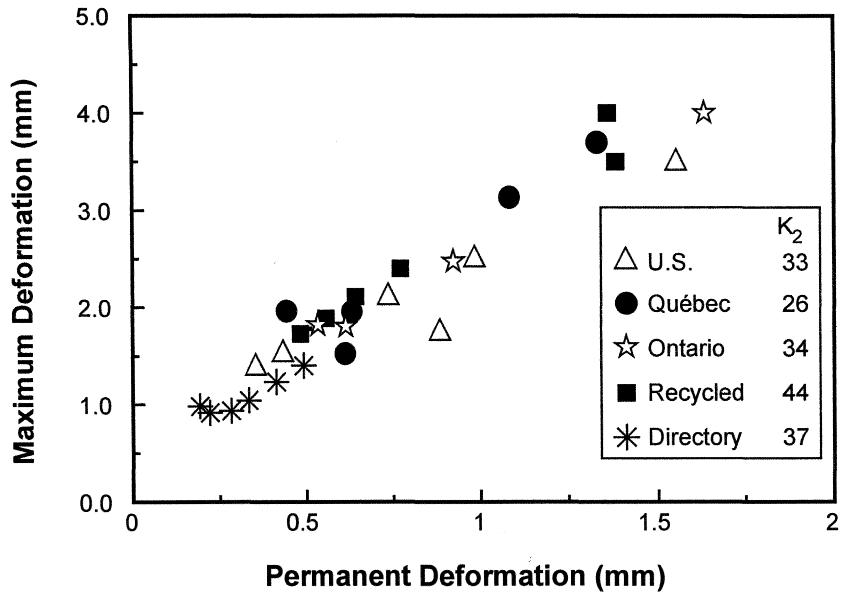


Figure 8. Permanent deformation of the small rolls is 37% less than their maximum deformation.

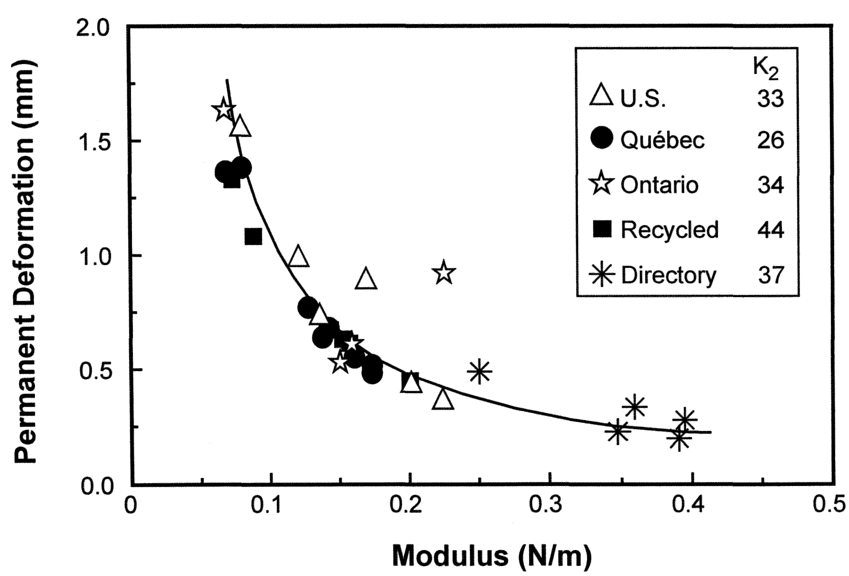


Figure 9. Permanent deformation decreases with roll modulus.

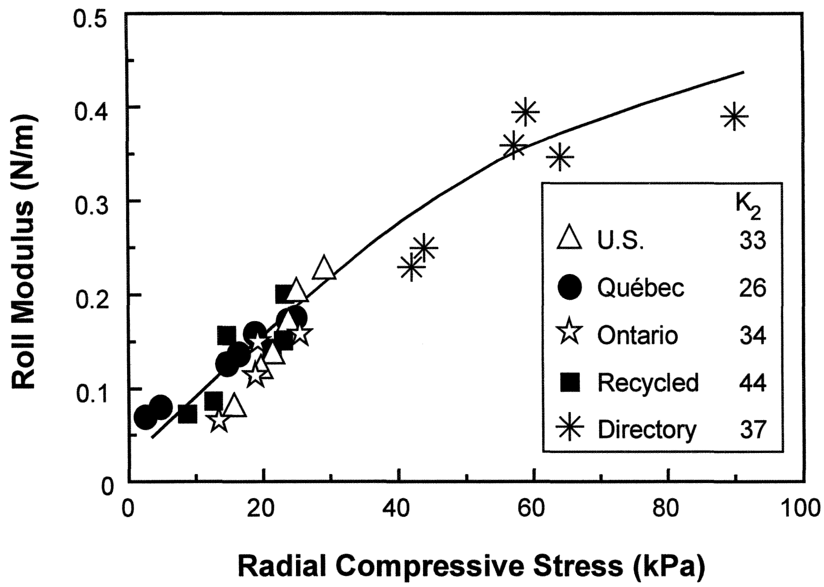


Figure 10. The modulus of the paper roll increases with the radial compressive stress wound into the roll.

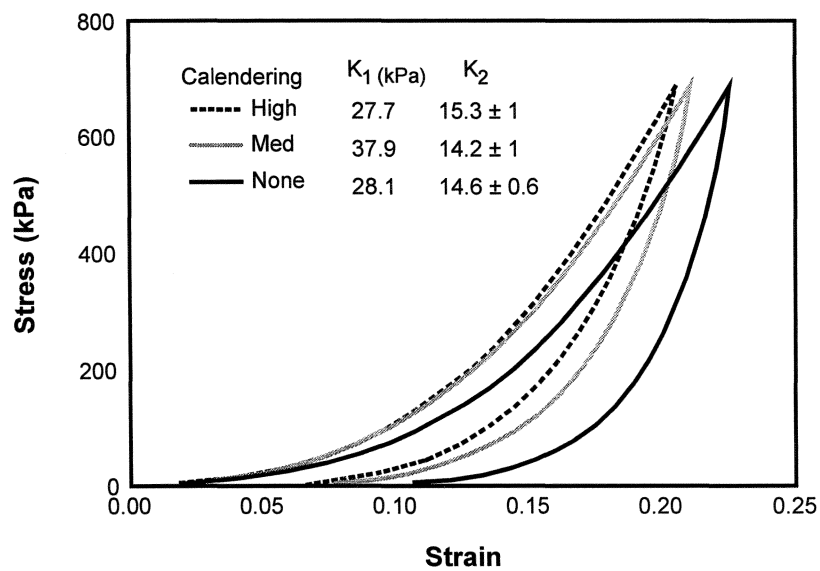


Figure 11. Increased calendering increases the stress required to strain a stack of paper to a given level.

pressure, the jaw position was held constant to measure the decay in stress. The loss in stress is largest in the first hour after winding (Figure 12) and probably continues for hours, days and months afterward. This means that paper rolls in storage will progressively become softer and be more susceptible to handling damage. Calendering does not affect this process but an interesting line of research would be to identify the factors that do.

The machine direction elastic modulus does not enter directly into equation 11, which gives an expression for permanent deformation as a function of winder operating conditions and paper properties. However, it does have an indirect effect on σ_r. For centre wound rolls, increasing the ratio of Z-direction to in-plane modulus increases the radial compressive stress, σ_r, for the same winding conditions [8].

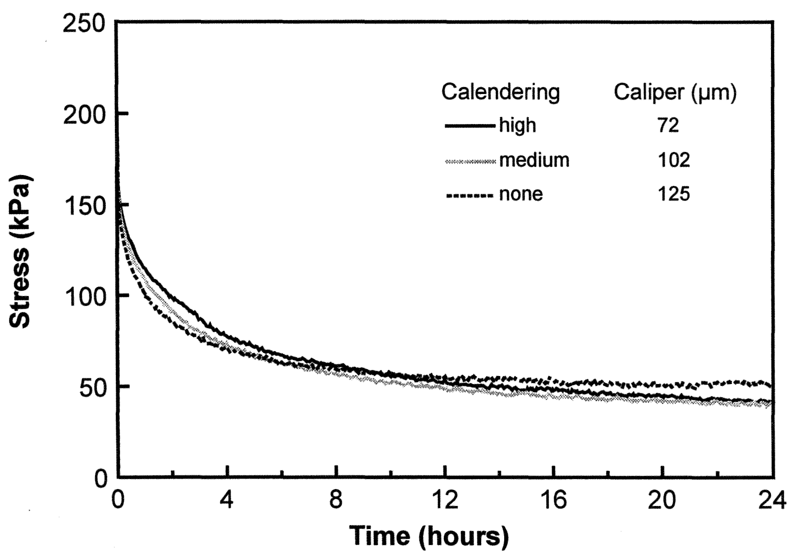


Figure 12. The stress in a pad of paper, clamped to a constant thickness, diminished over time.

Machine direction elastic modulus is sometimes monitored and controlled but only to achieve uniformity in the cross-direction to reduce defects and improve runnability. Machine direction elastic modulus is related to factors such as fibre alignment, web restraint in the dryer section and moisture content, as well as the furnish. It is unlikely that either machine direction or compressive modulus could be altered to reduce OOR given the other quality targets that must be met. However, understanding the role of material properties could lead to better adjustment and selection of winding equipment.

Core Stiffness and Diameter

The compressive stresses generated by clamping forces are transmitted through the body of the roll to the core. The deformation of the core was measured with a displacement extensometer gauge shown in Figure 5. As shown in Figure 13, the core deforms and its permanent deformation can be significant for high clamping pressures. Replacing the fibre core with a metal core changes the shape the stress-strain curve but has a small effect on the permanent deformation (Figure 14). Increasing core diameter, spreads the force exerted on the core over a larger area. This lowers stresses near the core which reduces the permanent deformation (Figure 15).

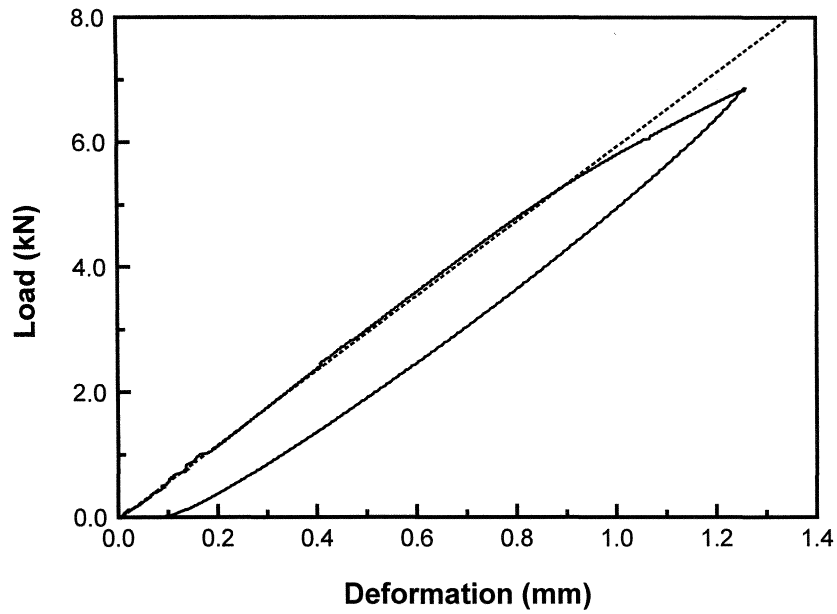


Figure 13. Core deformation for a paper roll exposed to clamping forces.

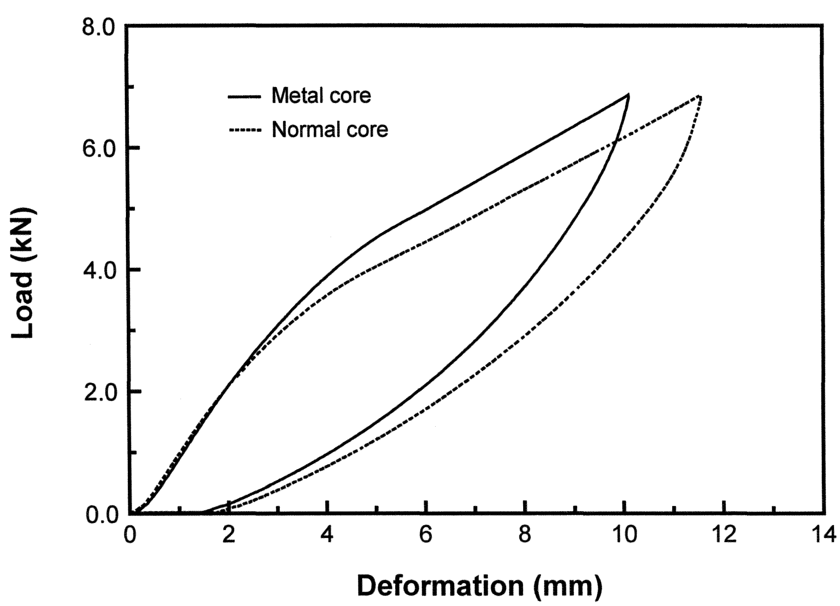


Figure 14. A metal core changes the stress-strain curve of the paper roll but has little effect on permanent deformation.

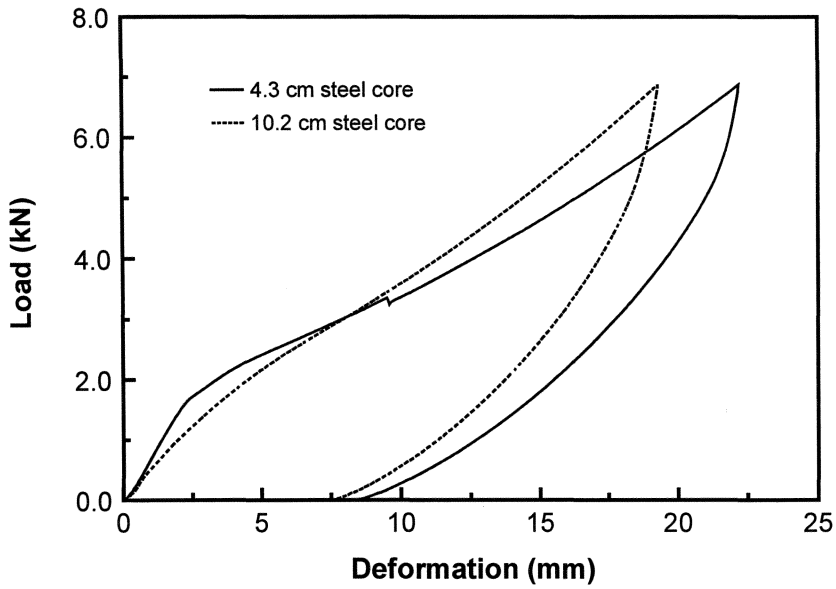


Figure 15. A larger core diameter reduces permanent deformation.

SUMMARY

Out-of-round paper rolls are created when clamping and handling forces exceed critical levels. Once the paper rolls have left the mill, the papermaker has limited control of these forces. The only recourse is to make the rolls as hard and resistant as possible. Permanent deformation of the roll is proportional to the maximum deformation created during handling. This in turn is directly related to the radial compressive stress wound into the roll and the paper springiness, k_2.

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APPENDIX

Measurement of the Radial Compressive Stress within Paper Rolls

The radial stress (σ_r) within the paper rolls was measured using a technique based on the pull-tab test [18,19]. Thin stainless steel strips (76μm thick and 5mm wide), sanded with 800 grit paper and washed in acetone, were inserted through the rolls with a custom tool. This technique is suited to the narrow rolls (76.2mm) used in our experiments because the small insertion force does not buckle the strip. The force required to remove the strip was determined with the TMI 36-20 coefficient of friction tester for each type of paper by measuring the force required to move the strip for different dead weights, as shown in Figure 16.

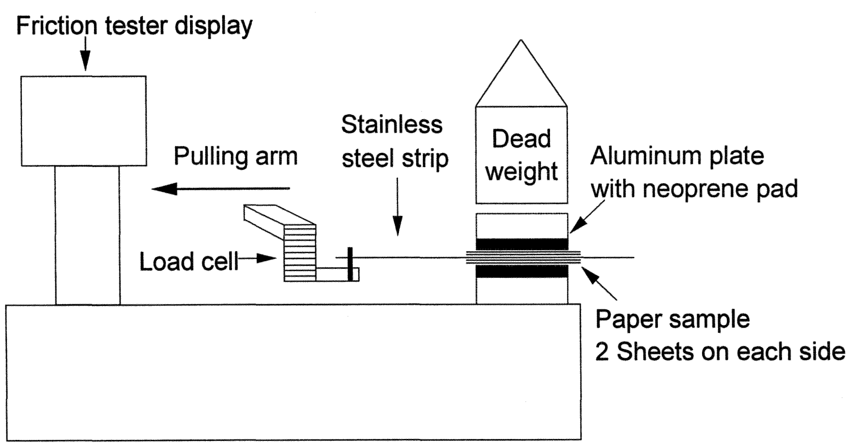

Figure 16. Apparatus for calibration of steel strips used to measure radial stress (σ_r).