# Modeling of bagginess due to storage of paper reels with ridges

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**ABSTRACT:** Paper is subjected to stress relaxation during storage in reels. Ridges in the paper reel subject the paper in the ridge to a higher strain than the paper adjacent to the ridge. The strain difference can become a permanent strain difference, resulting in a baggy web after unwinding. Researchers used a geometrical model based on stress relaxation test results to determine when the bagginess is substantial enough to cause problems. The results showed that runnability problems will appear if the ridge is about 1–2 mm high. This applies for a reel with a diameter of 1.2–1.8 m stored for 1 week.

***Application:*** Papermakers could use ridge heights as a screening tool to reduce runnability problems caused by baggy webs.

Cross-direction variations in thickness can cause ridges in paper reels [1]. During storage of the reel, the portion of paper in a ridge is subjected to a higher strain than the paper beside the ridge, because of the diameter increase along the ridge [2]. This can produce a permanent nonuniform strain (or length) profile in the paper web [3]. Webs with nonuniform length are commonly referred to as baggy webs, and they can be the source of runnability problems during converting.

When the baggy paper is unwound, the longer part of the web buckles out of plane to accommodate the extra length, because it cannot push and stretch the adjacent tight bands [4]. This buckling gives rise to problems such as creases and misregistration when the paper is converted.

Roisum [4] claims that a web where the length varies by only 0.1% leads to severe bagginess on almost any material. For this study, we used this estimate as a limit for runnability problems. The literature contains some characterizations of bagginess [5] and some studies of how baggy webs behave [6,7], but few studies of the possible causes. Baggy webs can have a number of causes, but it is unclear which lead to the greatest problems.

In this study, we investigated whether storage of a paper reel with ridges can be a cause of baggy webs. Our hypothesis was that the paper in the ridge position develops a permanent strain that is significantly greater than that of the rest of the paper. The aim of the investigation was to find a relation between the ridge height and the permanent strain difference, and to determine what ridge height could cause runnability problems.

We performed creep and relaxation experiments on paper strips to determine the time-dependent behavior. The data obtained were used as input in a geometrical model of a paper roll, to determine the difference in permanent strain between paper in the ridges and adjacent paper without ridges.

Creep tests were performed under constant load and relaxation tests were performed under constant strain. The creep tests were performed as a "worst case" first study, because a creep study could be performed much more efficiently in time. If no significant strain differences resulted after a constant load test, no strain differences would result after a constant strain test, because during a constant strain test the load decreases with time. The loading mode in a reel is presumably constant strain rather than constant load.

## MATERIALS AND METHODS

We tested three commercial paper grades made from bleached chemical pulp. Two liners with grammages of 80 g/m$^2$ and 135 g/m$^2$ were compared with a 71 g/m$^2$ machine-glazed (MG) paper. The liner grades consisted of two layers with different compositions of short and long fibers. The MG paper instead contained a mixture of short and long fibers. The tensile properties of the papers were determined according to ISO 1924-3. All tests were performed at 23°C and 50% relative humidity.

### *Creep tests*

Tensile creep tests were performed under constant load on 10 mm × 500 mm paper strips hanging with weights in clamps on the lower end. All the paper strips were taken in the machine direction (MD). The load levels corresponded to 10%, 30%, and 50% of the tensile strength of each paper. At least four samples were tested at each load level.

The length of the strip, between two lines with a spacing of 200 mm in the unloaded state, was measured with a cathetometer after specified times of up to 1 week. The cathetometer was equipped with an eyepiece that could be moved vertically to be aligned with the lines on the paper. A level transducer with an accuracy of 0.01 mm recorded the vertical position of the eyepiece, corresponding to the lines on the paper strip. The initial length of the strip was measured under a load of 0.2 N, which was applied to straighten the sample. Data were fitted to exponential functions of the following form:

$$F(\varepsilon) = C_{1,t}(1 - \exp(-C_{2,t} \times \varepsilon)) \quad , \tag{1}$$

where $F$ is the load, ε is the strain, and $C_{1,t}$ and $C_{2,t}$ are time-dependent curve-fitting constants. We then replotted the data as isometric creep curves (load versus time at constant strain, as shown in **Fig. 1**) to allow comparison with relaxation curves.

### *Relaxation tests*

Relaxation tests were carried out in an Instron 4411 material tester. The test strips had a width of 15 mm and span length of 150 mm. The test time was 1 week. For each paper, we applied five different strain levels between 0.1% and 1%. One strip was tested at each strain level. After each test, the paper strip was left to relax unloaded for 1 min, after which the final length was measured with a high-precision digital slide caliper (0.03 mm accuracy). Five length measurements were made and an average value was reported. The 95% confidence interval was determined for the difference between the length before and after the test. Results from relaxation tests were used as input data to a geometrical strain difference model.

### *Geometrical model*

If a paper roll has a ridge, the roll circumference is locally higher at that point. The difference in circumference, $\Delta o$, is given by

$$\Delta o = o_{ridge} - o_0 = 2\pi(r_{ridge} - r_0) = 2\pi h, \tag{2}$$

where $h$ is the height of the ridge and $r$ is the roll radius. The strain difference, $\Delta\varepsilon$, is then

$$\Delta\varepsilon = \varepsilon_{ridge} - \varepsilon_0 = \frac{o_{ridge} - o_0}{o_0} = \frac{h}{r_0} \ , \tag{3}$$

where $\varepsilon_0$ is the wound-in strain assumed to be constant across the web, and $\varepsilon_{ridge}$ is the sum of $\varepsilon_0$ and the strain resulting from the diameter increase.

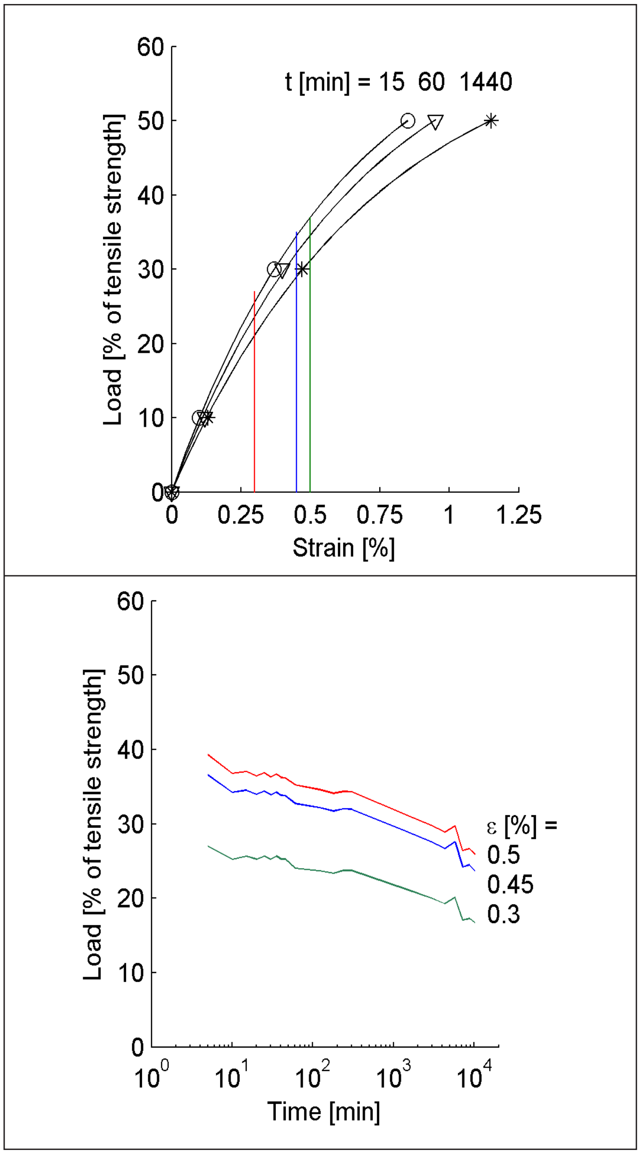
To assess the magnitude of the permanent strain difference associated with this strain difference, we carried out relaxation tests. A straight line was fitted to the plot of measured permanent strain, $\varepsilon_{perm}$, versus applied strain, ε, during the relaxation test:

$$\varepsilon_{perm} = A \cdot \varepsilon + B \ , \tag{4}$$

where $A$ and $B$ are paper-dependent fitting constants.

Assuming this can be applied to the reel conditions, the expected permanent strain difference in the paper between ridge and nonridge positions is then

$$\Delta\varepsilon_{perm} = A \cdot \frac{h}{r_0} \ . \tag{5}$$

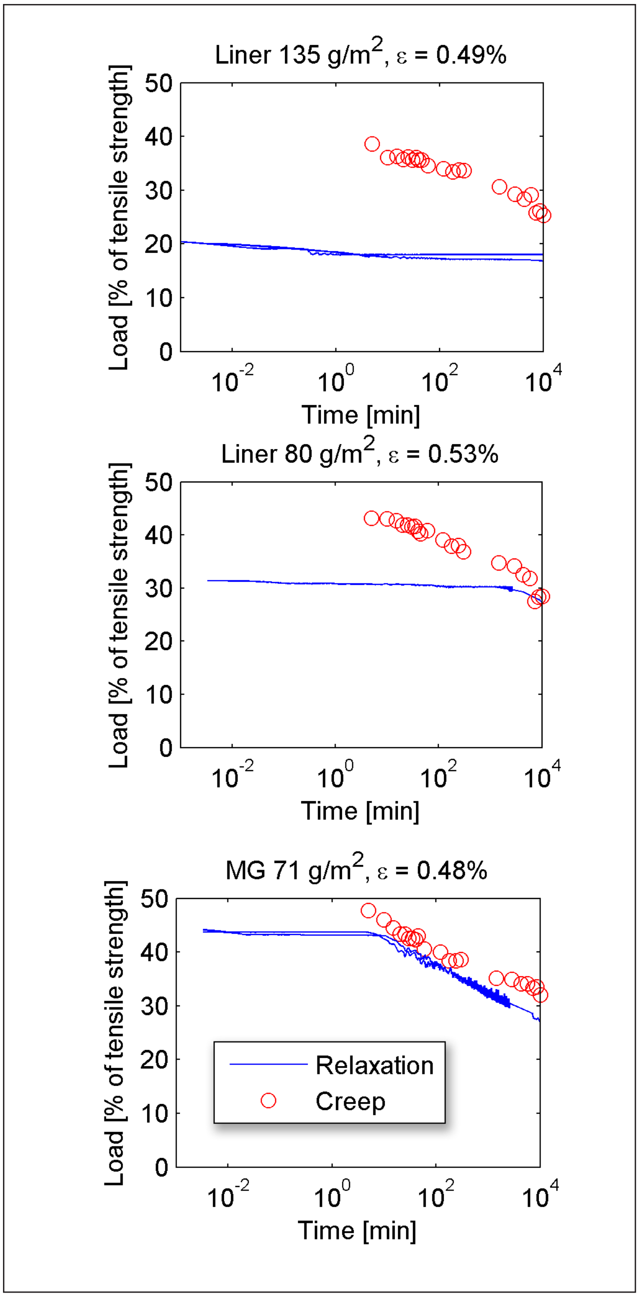



***1. Construction of isometric creep curves for the 135 g/m² liner. The top graph shows load during creep tests as a function of the strain. Curve fit according to Eq. (1). For clarity, only three curves are shown. Isometric creep curves (bottom) can be made by taking data from all available times at an arbitrary strain. Time is on a logarithmic scale.***

## RESULTS AND DISCUSSION

The creep experiments revealed significant differences in permanent strain when different loads were applied. The creep test results supported the hypothesis that a significant strain difference develops during storage, and the investigation proceeded with relaxation experiments.

**Figure 2** shows the results of the creep and relaxation tests together for comparison at a strain level of about 0.5%, an arbitrary number that could reasonably occur in a reel. For the liners, the slopes of the relaxation curves were lower than the slopes of the creep curves. This was expected because, for constant strain, the load decreases with time and is thus

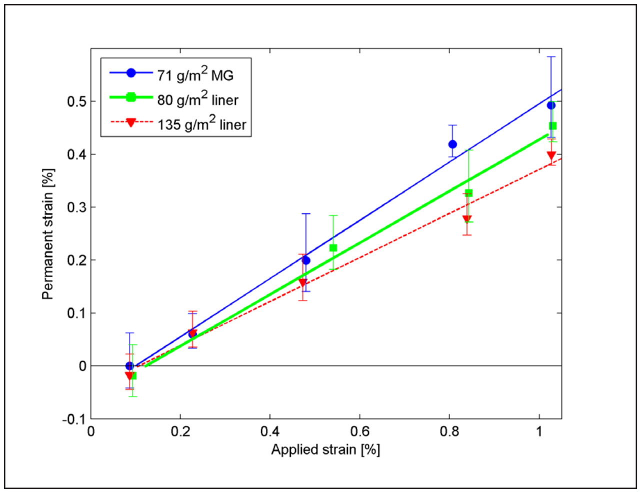



***2. Isometric creep curves plotted together with relaxation curves. Time is on a logarithmic scale.***

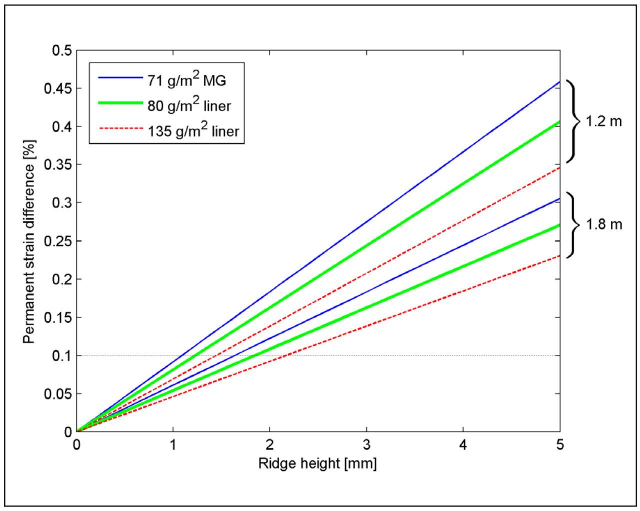
lower than for the constant load.

For the MG paper, the curves matched each other after a fairly short time. For the 80 g/m² liner, the relaxation curve approached the creep curve at the end of the experiment, whereas the curves for the 135 g/m² liner did not reach such a point during the test period, but likely would have if the test had lasted longer.

The creep tests and the relaxation tests showed that, at a given strain, the MG paper carries a relatively higher load in proportion to its tensile strength than do the liners (Fig. 2). The tensile test also showed that the MG paper had a higher




***3. The permanent strain as a function of the applied strain during the relaxation tests. The test duration was 1 week. The error bars show the 95% confidence interval. Curve fit according to Eq. (4) with fitting constants shown in Table 1.***




***4. Calculated strain difference in the paper web after storage for 1 week and unwinding for different ridge heights on different papers. Calculation according to Eq. (5), for reel diameters of 1.2 m and 1.8 m.***

tensile stiffness index (**Table I**) and tended to show a higher permanent strain after the test than did the liners (**Fig. 3**).

Applied strain of about 0.1% or less (the intercept on the x-axis in Fig. 3) caused no permanent deformation in any of the paper grades. When applying the strain difference model, we assumed that the web strain during winding was greater than or equal to 0.1%. This assumption simplifies the model greatly and is generally reasonable. Without this assumption, we saw only a slight difference in the results at very low ridge heights.

**Figure 4** shows the strain difference that would arise, according to the model, as the result of a ridge of a given height. The resulting strain is dependent on the percental diameter; a given ridge height causes smaller strain differences if the reel diameter is large. Although our study used reel diameters of 1.2 m and 1.8 m, results for other reel diameters

| | A | B | Tensile strength [kN/m] | Tensile stiffness [kN/m] | Tensile stiffness index [kNm/g] |
|---|---|---|---|---|---|
| 71 g/m² machine-glazed paper | 0.55 | -0.055 | 8.6 | 827 | 11.6 |
| 80 g/m² liner | 0.49 | -0.059 | 8.9 | 826 | 10.3 |
| 135 g/m² liner | 0.42 | -0.044 | 15.4 | 1445 | 10.7 |

***I. Curve-fitting constants and machine direction tensile properties for the three paper grades.***

can easily be calculated with Eq. (5), as long as the strain $\varepsilon_{ridge}$ in Eq. (3) does not exceed about 1%, the maximum measured strain.

The MG paper was the most sensitive to ridges; a ridge height of about 1.1 mm, or 1.6 mm for the larger reel, being sufficient to cause a strain difference of 0.1% (**Fig. 5**). The liners were somewhat less sensitive, but as shown in Fig. 3, the differences between all paper grades are small and the experimental error is quite high. Differences between the paper grades could result from each being made from different furnishes and on different machines. The drying method, in particular, might cause differences, because the MG paper was partly dried restrained on a Yankee cylinder, whereas the liners were dried in a conventional dryer section.

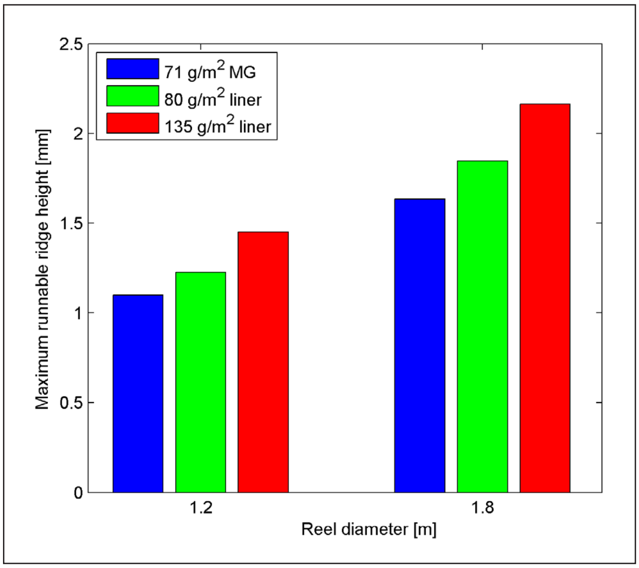
The liners were similar in tensile stiffness index (Table I), but when considering the actual stiffness, the liner with high grammage was much stiffer. The difference in calculated strain difference between the liners was, however, not much greater than the difference between the MG paper and the 80 g/m² liner. These two grades were similar in tensile stiffness, but differed in calculated strain difference. The viscoelastic behavior of the paper is thus not fully explained by tensile stiffness. Instead, relaxation trials are needed to evaluate papers with regard to strain difference.

We assumed that the permanent strain in relaxation tests can describe the behavior in the outer layers of a reel, where the MD stress is tensile. Problems with bagginess are greater in the outer layers of a paper reel; deeper into a good reel, the MD stress is usually zero or slightly compressive [8]. Regardless of the stress level, a ridge is associated with a length and strain difference.

Tensile stress could give rise to a small thickness difference in the paper, but we did not include that as a factor in this study. Our focus was to determine the effects of ridge height, not how thick the paper is in the ridges.

Reels also undergo z-direction compressive forces, which vary with the reel diameter. The z-direction compression is larger closer to the reel core. This compression might affect the paper length, but we assumed this effect was small and ignored it in these calculations.

We assumed that the strain profile can be predicted by making measurements on separate paper strips. In the paper




***5. The maximum runnable ridge height if the strain difference limit is assumed to be 0.1%.***

reel, where the paper in the ridge is continuously connected to the non-ridge paper, the different positions affect each other. Shear forces probably arise in the boundary between the ridge and the rest of the reel. If the shear forces restrict the strain differences from appearing, the critical ridge heights would be somewhat higher than the values reported here. In the future, we intend to compare the results presented here with measurements on paper reels.

Further research is needed to determine the maximum paper strain difference that can be run in different kinds of paper converting machines. Different machine elements are sensitive to different degrees, thus a more complex analysis than using Roisum's criterion of 0.1% could be insightful.

## CONCLUSIONS

We used a simple geometrical model to determine the strain difference in a roll with ridges. The critical ridge height for runnability problems was between 1.1 mm and 1.5 mm for the papers tested, when the reel diameter was 1.2 m. When the reel diameter was 1.8 m, the critical ridge height was 1.6-2.2 mm. The calculation showed that MG paper was more susceptible to permanent strain differences resulting from ridges than were the liner grades. The critical strain difference was assumed to be 0.1%.

The calculated critical ridge heights are very small, and could occur in actual reels. The critical ridge height in practice would likely be somewhat higher. Still, significant strain differences can appear during storage. Ridges are thus a plausible cause for baggy lanes in paper.

Relaxation trials are needed to evaluate papers with this kind of model, because the tensile stiffness did not fully explain the longer-time behavior. After a long time, creep tests could also explain the relaxation behavior of the paper. **TJ**

## ACKNOWLEDGEMENTS

We thank Johan Larsson and Annica Sonemalm for performing the creep tests, and Jonny Widstrand (Billerud Gruvön, Sweden) for ideas and feedback during the work, and for supplying the paper samples and tensile properties data.

*Received: January 23, 2009*
*Accepted: June 8, 2009*

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## INSIGHTS FROM THE AUTHORS

Baggy webs have been a problem for converters, and thus papermakers, for many years. Paper manufacturers told us they had been working on solving these problems, but had not made notable progress. There are no methods available in the paper mill to test the bagginess of the paper web. Furthermore, bagginess at the paper machine can often be temporarily solved by stretching the web in a way that is not possible at the converter. It is also possible that baggy webs appear during handling and storage of reels. We started a project about baggy webs to investigate whether some suspected causes are important.

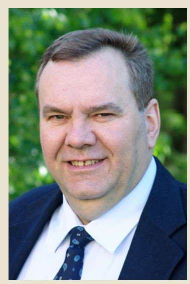
There is very little published research about baggy webs. The published research has been concentrated on how baggy webs behave, but we wanted to evaluate the possible causes. It was important to find a method that was accurate enough to measure the small length differences that give rise to baggy webs. An option is to test very long samples and thus get a low percental error, but for practical reasons we could not do this in this study and instead had to choose methods with very high accuracy.

In this work, we saw that ridges in paper reels indeed are a plausible cause of baggy webs. The calculated critical ridge height was surprisingly low, but it is important to remember the differences between lab scale tests and converting in practice. Still, it is possible that ridged reels are more sensitive to runnability problems than is generally assumed.

The next step in this research is to test real reels with ridges and measure web tension profiles and web length profiles.

***Land***

***Stolpe***



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