The development of an ultrasonic measurement for the prediction of paper strength properties – Part II.

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Abstract

Following the successful development of ultrasonic techniques for the measurement of in-plane paper properties work has been undertaken to map, in detail, the strength variability of current commercially produced packaging papers.

A commercial paper was measured using a new in-plane testing technology and the ultrasonic measurements were related to ring crush measurements using proprietary algorithms that show high correlation and give good confidence to the sonic estimates.

Z-direction measurements (thickness direction) were also made using a technique developed by IPST in the 1980's and 1990's and the position of the thickness-direction measurement was matched to the position of the in-plane measurement. In this way overlapping mappings in all three principal paper directions – md, cd and zd have been generated. In addition, studies that show the variability associated with in-plane shear stiffness in the plane of the sheet are also presented.

From these three dimensional mappings a theoretical mechanism for the observed property variability is suggested and new measures for overall packaging board quality are proposed.

The impact of the scale and magnitude of commercial paper compression strength properties such as cd ring crush is also discussed in terms of packaging field performance under various conditions.

Introduction

One of the issues that has limited a proper understanding and wide spread knowledge regarding the inherent strength variability of paper manufactured on commercial paper machines has been the limited access to enough performance data to adequately describe the level of variation that exists from reel to reel and within a reel. As only small numbers of data points are used for quite large amounts of paper, the certainty that can be ascribed to these measurement and their meaning in terms of the "quality" of a given machine roll of paper is difficult to judge.

Current physical tests are relatively slow and cumbersome and do not allow many hundreds of tests to be taken in a short time to properly "map" the output of the paper machine. Without such test methods, the ability to investigate and correct or even to evaluate the magnitude of run-of-mill strength variation is at worst impossible and at best expensive and time consuming. In particular, tests such as ring crush, short span compression test and burst are important functional paper tests that directly impact on the ability of packaging papers to perform in corrugated boxes.

This paper describes the evaluation of packaging grade papers from a commercial paper machine and generates a strength "mapping" by using newly developed ultrasonic measurements coupled with proprietary algorithms to develop measurement proxies. These proxies are shown to describe the local paper property at least as well as the classical standard techniques but, as they require no destructive sampling and take only a few seconds to complete allow a fuller analysis of paper performance.

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Variation on the paper machine

Measurements taken on the paper machine using prototype instruments and classical testing methods suggest that the machine direction ring crush peak to peak variation ranges between 10 and 25%[1-3]. Cross direction strength profile variation can be as low as 3 or 4% and as high as 30% depending upon the machine design, hardware and machine width.

Figure 1 shows the typical "frown" profile for strength across the width of a paper machine. The edges of the machine roll are usually much lower in strength than the centre of the profile. It can be shown that this variation is independent of basis weight and thickness variation.

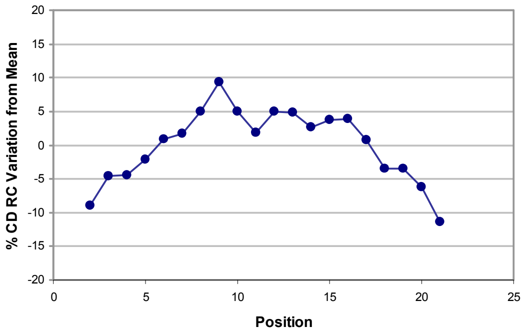


Figure 1. Typical "frown" profile for CD Ring Crush plotted as a function of cross direction position from front to back of a commercial paper machine.

Figure 2 shows data generated from a commercial paper machine showing the peak-to-peak variation in the md direction at various wavelengths or length scales. It seems appropriate to separate the variation time scales into those variations that can be controlled using paper machine process controls (longer time scales) and those variations that are functions of the process itself (shorter time scales).

If we assume control actuation on the paper machine is relatively slow, say 20 minutes – a function of refining and stock blending, we see from Figure 2 that the machine direction variation that could be moderated by existing machine variables (such as wet pressing, refining, furnish, additive and flow-box set up) is around 15-20%.

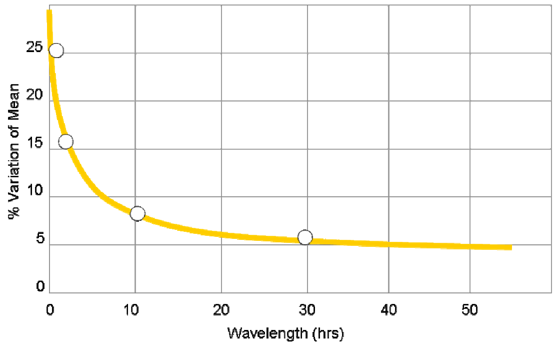


Figure 2. Magnitude of CD ring crush variation as a function of manufacturing time.

That is, we can identify the "accessible" strength variation as around 15-20%. This does not mean that the remaining variation cannot be dealt with, but it would have to be minimised by optimising standard running conditions, introducing new paper making practices and modifying plant equipment. This sort of optimisation requires a long term process improvement strategy.

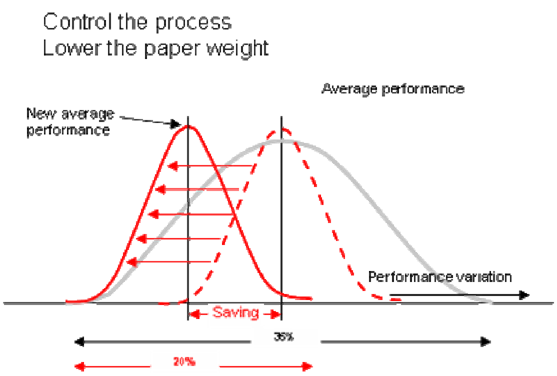


Figure 3. Decreasing property variation allows lower paper weights or strengths to be specified for the same minimum performance.

The minimisation of strength variation in the paper making process will also minimise downstream performance variation and ultimately allow over-specification to be usefully reduced. For most commercial papers, continuous monitoring and subsequent control should allow a 10-15% reduction in paper weight or strength. This effect is shown in Figure

3. To achieve this reduction the industry requires a suitable, non-destructive, continuous measurement for strength and relationships between the elastic properties of paper and relevant paper properties – such as ring crush.

Correlations for paper properties

Strong correlations exist between paper elastic properties and paper ring crush test and a typical correlation, between the two properties, developed by one of the authors is shown in Figure 4. In this case virgin fibre liners and recycled liners with varying degrees of size press starch addition are shown to correlate well with an ultrasonic measurement predictor. Both MD and CD ring crush are accounted for successfully by the same predictor equation. The quality of this predictor is significantly better than previous attempts at correlating ring crush with extensional stiffness [4-6].

Apart from the md, cd and zd sonic stiffness defined in previous work[9], proxy measurements for cd ring crush were also applied to the data set from a commercial semi-chem paper. To demonstrate the quality of the relationships physical testing was undertaken on chosen paper samples aligned with ultrasonic stiffness measurements.

Sonic proxy representations of the constituent elements of the equation were substituted and the overall representative equation was used to generate the predicted values for the correlation.

Table I shows the quality of the predictive relationships for the elastic properties and ring crush. As shown for these papers the predictive power of the sonic "proxy" properties are more than adequate to describe the chosen paper properties at a given paper machine.

Table I. Table of Spearman Rank Correlation Coefficients (r^2) for the paper tested.

Property	Liners
E_{md} (MPa)	0.96
E_{cd} (MPa)	0.94
E_{zd} (MPa)	-
Ring Crush (N)	0.99

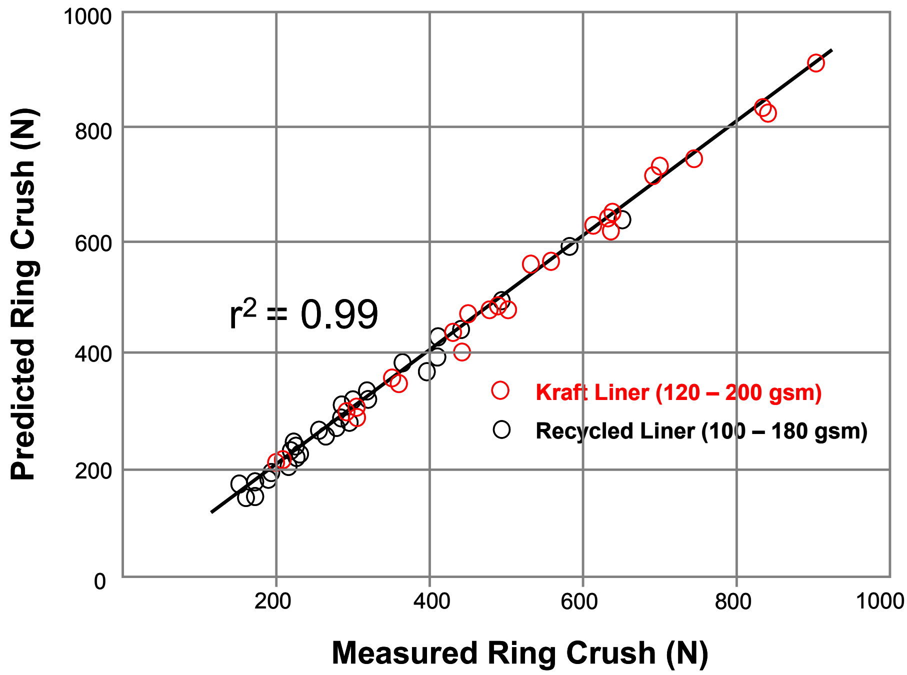


Figure 4. Representative correlation using the ring crush algorithm.

An alternative statistical evaluation of the goodness of predictors can also be obtained from an observation of the root mean standard error generated by the correlation[10]. For this analysis the standard error is calculated in the following manner:

1. For each data set example, calculate the difference between the model's prediction and the measured values.
2. Square the differences.
3. Determine the mean of the squared differences, over the entire data set.
4. Calculate the square root of the mean.

The RMSE is not normalized; therefore, its units are the same as the units of the output.

In this instance a rule of thumb can be offered and will be used to give some confidence regarding the "goodness" of the correlations by comparing the RMSE with the measurement standard deviation (MSD)[10].

- If RMSE < MSD, the model is fitting the noise, and the model is "too good to be true."
- If RMSE = MSD, the predictive model is exact.
- If RMSE = 1.2*MSD, the model has about half the error of the physical measurement.
- If RMSE = 1.4*MSD, the model is about as accurate as the physical measurement.
- If RMSE = 1.7*MSD, the model has about twice the error of the physical measurement.

Table III. Measurement standard deviation values and Standard Error values for correlations (expressed as a % of the mean).

Property	Liner	
	MSD	RMSE
E_{md} (MPa)	2-4	
E_{cd} (MPa)	2-4	
E_{zd} (MPa)	-	-
CD Ring Crush (N)	2.5-5.0	2.8

* Denotes sonic modulus estimates

Methodology

Full deckle width samples and around 60 meters of machine production were obtained from a commercial paper machine making semi-chem, 120 gsm medium. Ultrasonic measurements were made at approximately 400 mm square pitch down the length of the sample. The sample properties are listed in Table II.

Table II. Representative properties of the SC120 medium.

Property	Paper 1
Grade	120 SC medium
Basis weight (g/m²)	119
Thickness (μm)	150
MD/CD Stiffness Ratio	2.43
2D - GM Stiffness*	7.36
3D – GM Stiffness**	1.89

* Value proportional to the area of the polar sonic stiffness area plot (md-cd).
** Value proportional to the volume of the polar sonic stiffness volume (md-cd-zd).

None of the samples were conditioned to ISO standards but measurements were undertaken as closely in time as possible in an air-conditioned environment to minimise moisture effects on the magnitude of the property estimates.

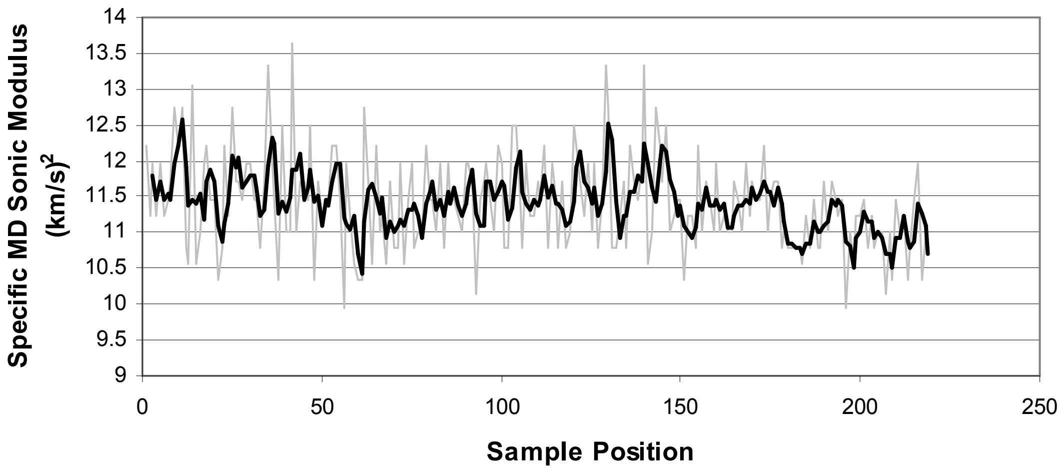
Results

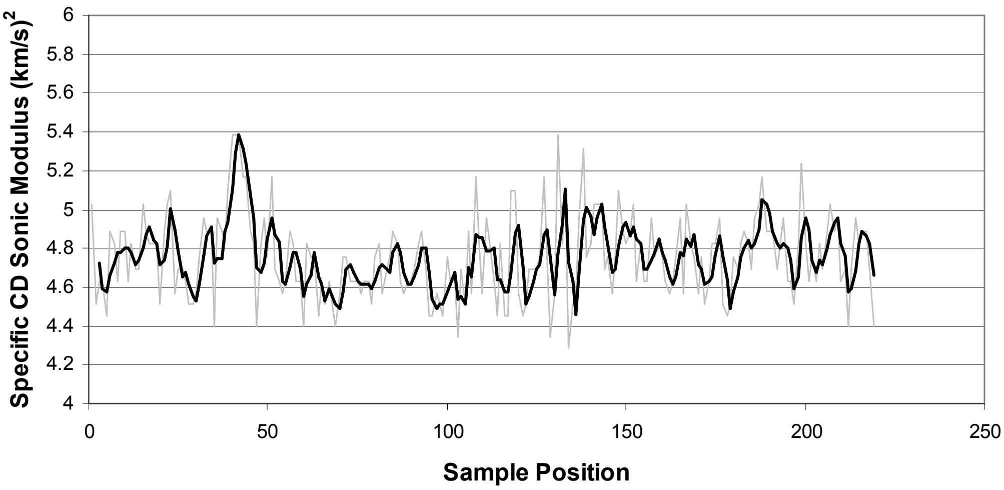
Directional Analysis

Figures 5, 6 and 7 show the time trace for one cd position for the 60 meter machine traces.

The plots of specific moduli show a number of features that are relevant to an analysis of the manufacture and performance of the paper. The first relates to a strong periodic component occurring every 8 to 10 samples – equivalent to a wavelength of around 3 to 4 meters. Such variation is usually attributable to either rotating elements on the paper machine or variations in stock flow that cause orientation variation either in the plane of the sheet or in the thickness direction.

Figure 8 shows a fast Fourier transform plot of the variation of the machine





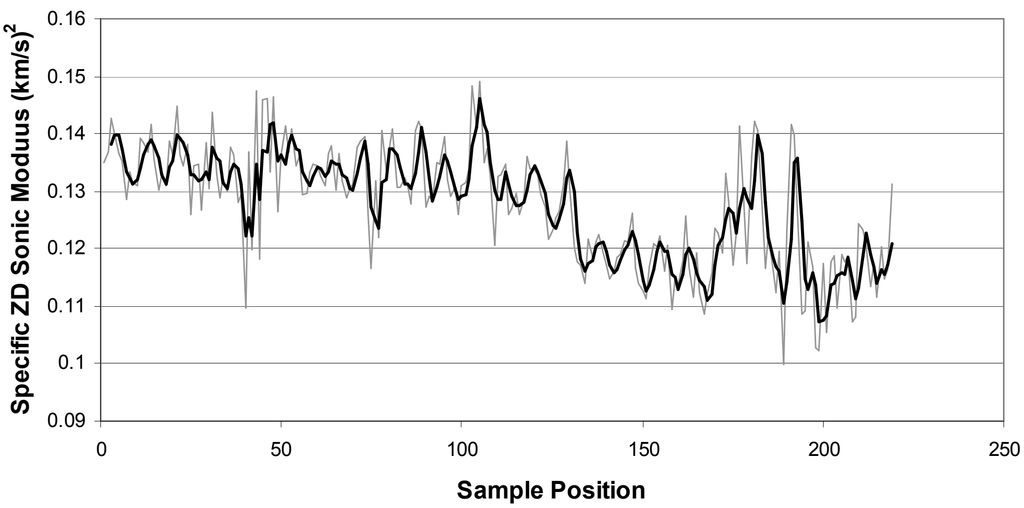


Figure 5, 6 and 7. Time traces of the raw and filtered sonic modulus measurements taken in the machine direction at a single cross machine position.

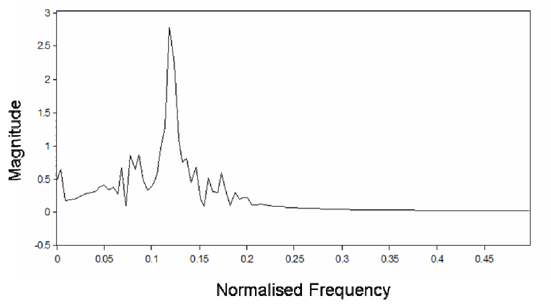


Figure 8. Fast Fourier transform of the MD sonic modulus time trace

instability in the forming process. Partly, this reflects a common view that property variation is due to basis weight and formation (another scale of basis weight) instability.

As the in plane variation is out of phase with the zd or out-of-plane periodic variation, these results suggest property variation unrelated to basis weight or thickness variation on this machine has a root cause in the periodic re-orientation of the fibres into and out of the plane

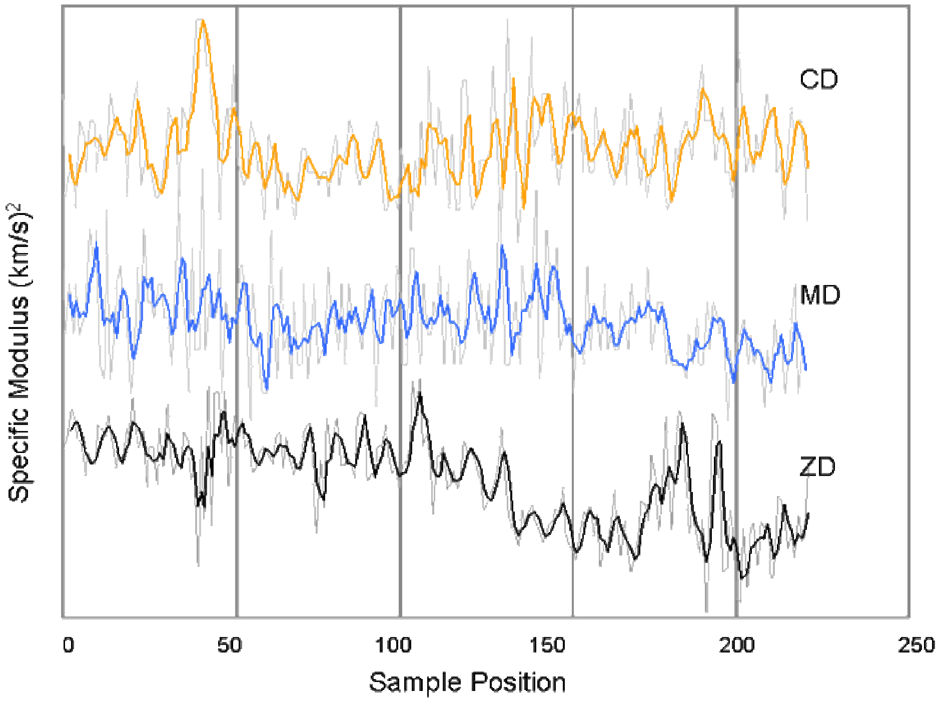


Figure 9. Comparison of the three directional moduli traces with time.

Of great interest is the dynamic performance of modern paper machines in terms of property variation with time and the process levers that are available to the paper maker operator, in real time, to control and minimise that variation. Although variation is known to occur on the paper machine, broad discussion arguing the mechanism for such variation have not been prominent in the literature. Generally, diagnostic approaches to paper machine performance have relied on measuring the level of pressure fluctuations within the approach system of the paper machine and assuming that variation in property is a manifestation of of the sheet. This orientation is affected by pressure and flow fluctuations coming forward in the stock approach and onto the forming section. If the periodic variation was caused by, say a press roll, the variation for all three directions would be synchronised in time. That is, if an increase in one directional property was due to variation in density (and so, fibre-fibre bonding) then properties in all three directions would increase.

Using the previously presented correlation between ring crush and moduli (Figure 4), it is possible to generate the corresponding time trace for CD ring crush – expressed as a percentage of the mean value determined over the 60 meters of machine running. This data is presented in Figure 10. The raw sample measurement is shown in grey and a running average (n=5), is shown in orange. It is clear that the periodic component is still present in the ring crush trace.

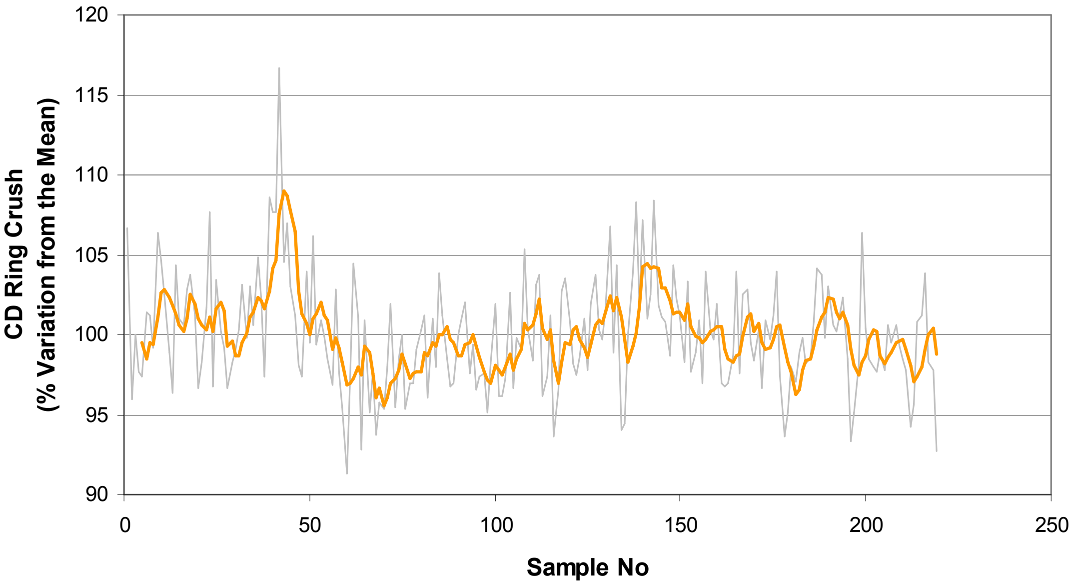


Figure 10. CD ring crush estimate measured in the machine direction.

Figure 10 shows a raw peak-to-peak variation over this period of around 100 N which is approximately 25% of the mean value. The averaged orange plot, representing a sample length of around 1.5 meter (the length of paper used in a typical corrugated box), shows a peak-to-peak variation of around 50 N or approximately 15% variation around the mean.

The periodic variation due to re-orientation of fibres into and out of the plane of the sheet represents 12N or approximately 3% of the mean value. A single one-off event occurring at sample number 50, represents an excursion of around 30 N (8%), and "slower" rising and falling variation with wavelength greater than 50 samples represents around 5% variation around the mean.

Performance mapping.

Armed with cross direction profiles and machine direction variation with time, it is possible to generate a cd ring crush mapping of the percentage variation away from the mean for the sheet area being considered in this study. Results have been presented graphically below as a:

1. 3D – colour relief map (Figure 11)
2. 2D – colour contour map (Figure 12)

Figure 12 represents a more convenient way of presenting the ring crush variation data over the 60 meter long, deckle wide area of paper evaluated. It is enough to note that large areas of the paper corresponding to a relatively small amount of machine running time vary by more than 5% of the overall ring crush mean. Such variation, which must be accepted as typical on commercial paper machines, is at the scale of individual box areas and must have an impact on final product performance – particularly in stacking applications. An equivalent 1 m^2 area is shown as a red box in Figure 12

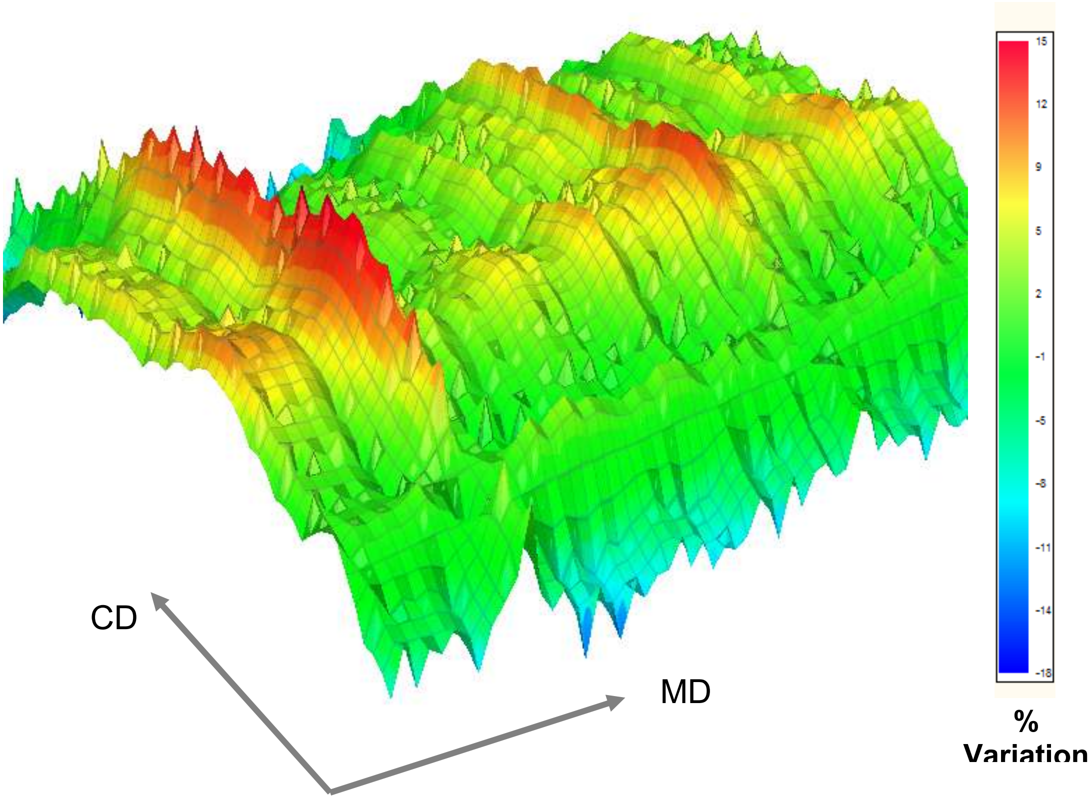


Figure 11. 3-D mapping of percent variation for CD ring crush away from the sample mean.

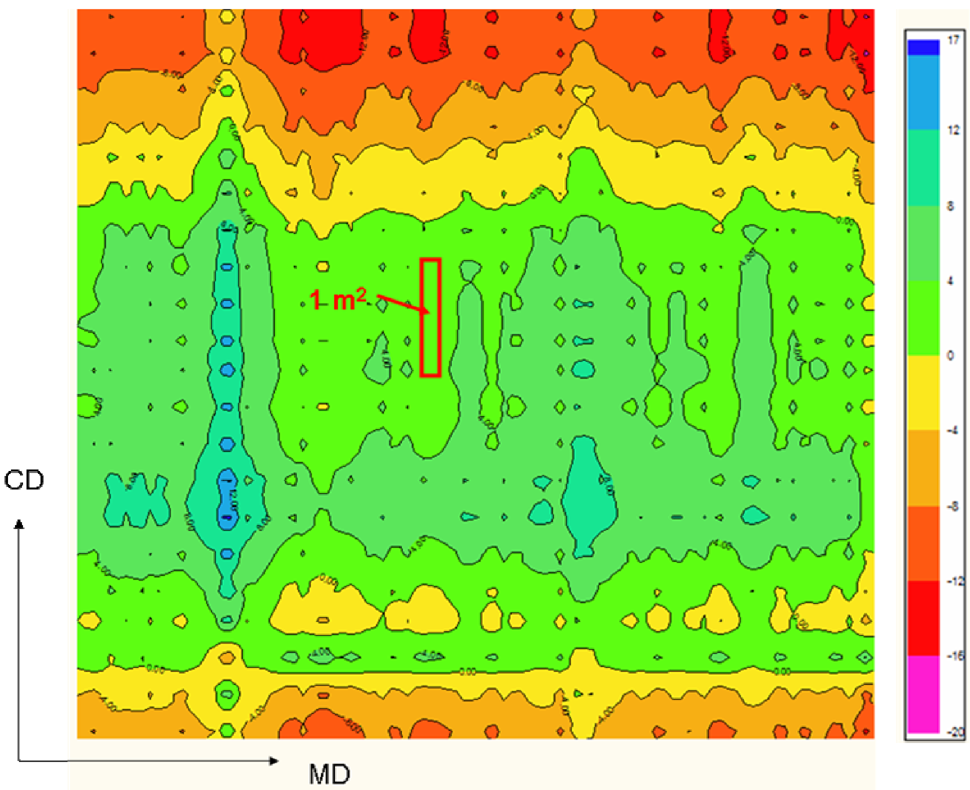


Figure 12. 2-D Contour map of percent variation CD ring crush away from the mean of the sample. An approximate square meter area is represented by the red box.

Implications for packaging performance

To judge the impact of paper property variation on box performance we choose to consider the impact of cd ring crush results as these most directly relate to box compression strength[1]. Relationships between CD ring crush of medium and liners and box compression have been developed. One such relationship, for C-flute board, is from Kellicutt et al[2,3] :

$$P = kP_x\sqrt[3]{Z} \quad [3]$$

Where

P is the box compression (N)
P_x is the sum of ring crush of the liners and medium (N)
Z is the box perimeter (m) and
k is a scaling constant

For this cursory analysis we assume the box perimeter to be constant. For the comparison, under these circumstances, the percentage variation in box strength is equivalent to the percentage variation in total cd ring crush of the components.

To calculate the effect on survival time, a measure of the field performance of the box in stacking applications, we assume an exponential relationship between the box strength and the time before failure under constant load stacking[4]. The relationship used represents constant load stacking under constant high humidity conditions (19.5% moisture) where the normalising load is 50% of the conditioned box failure strength (BCT).

Table III calculates the effect on box survival time of cd ring rush variation in the liners and medium (assuming similar levels of variation in total ring crush of the box components to that measured in this study).

Figure 13 shows the variation in performance over the measured area as a probability distribution of the estimated cd ring crush values assuming a minimum area of 1 square meter – approximately the area of a corrugated box. The figure allows a user to calculate the percentage of boxes that will perform at a certain level based on the inherent variability in this particular paper. Figure 14 shows equivalent representations for box survival for constant humidity and cycling humidity environments using equation [3] to map CD ring crush variation to box strength and ultimately to box survival time.

It becomes clear that the variation in cd ring crush associated with commercial paper manufacture introduces large variations in field performance at the scale of individual boxes.

Summary

Ultrasonic testing offers a way to conveniently characterise the performance of packaging papers. New algorithms showing good correlation with traditional testing allows the ultrasonic data to be transformed into proxy measurements of the usual industry derived performance paper properties such as ring crush, short span compression test and burst. Analysis of several papers shows that the expected variability in strength properties is expected to be high and will have a severe effect on the performance of the papers when subjected to long term loading in boxes.

Table III. Sensitivity analysis of total ring crush to BCT and box survival time. The data is modelled for high humidity stacking performance (Total RC = 1000N).

Level	Total CD Ring Crush (N) P_x	% of Average CD Ring Crush	% of Average Box strength variation	% of Average survival time
Lowest	900	90	90	13
Average	1000	100	100	100
Highest	1100	110	110	772

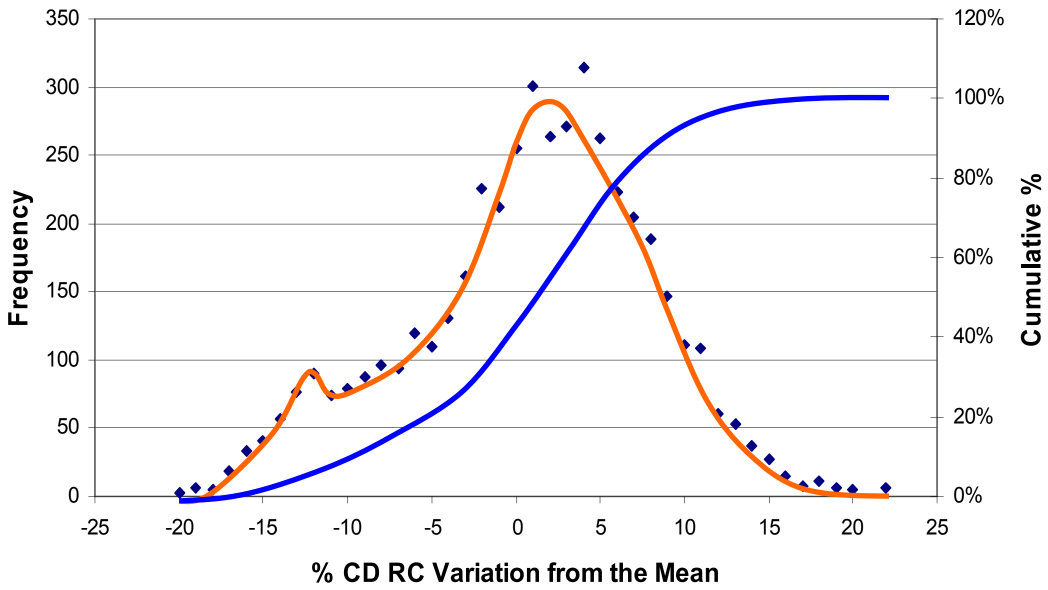


Figure 13. Distribution plots for CD ring crush over the ~420 m^2 measured. The plots show the frequency for each CD ring crush quality (based on ~1 m^2 area) and the cumulative frequency plot.

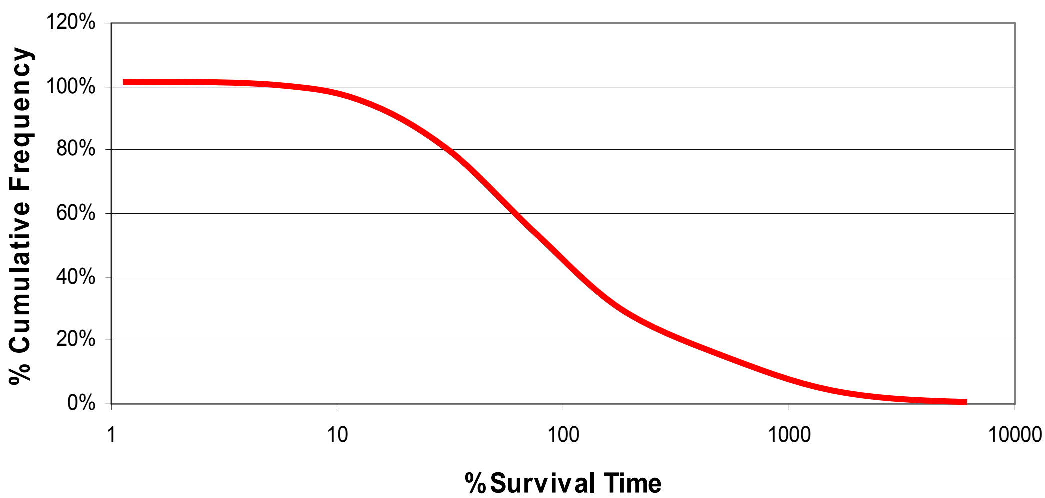


Figure 14. Cumulative frequency plot showing the estimated survival time of boxes as a function of the CD ring crush variability data generated in this study.

Strength “mappings” of the papers in the three principal directions show that the variability of property for the papers can mostly be assigned to variations of fibre orientation either in the plane of the sheet or in the thickness direction – with a minor component attributable to material variability. The material variability component is expected to have a greater effect as the measurement time scales increase from seconds to minutes to hours of production.

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