A review of Australian R&D into corrugated box performance and the evolution of on-machine measurement of Ring Crush

PETER BENNETT¹ and RUSSELL ALLAN²

SUMMARY
This paper highlights some of the important developments from the APM/AMCOR research groups over 50 years, especially as they relate to the long and continuing quest to improve the performance of corrugated packaging – both its effectiveness and cost. The paper includes in particular, an explanation of why ring crush paper strength has been a dominant target property in the Australian packaging paper industry, and the story of measurement developments for that property.

KEYWORDS
paper strength, ring crush strength, paper stiffness, corrugated box performance, containment, stackability, on-machine measurement, ultrasound

INTRODUCTION
The world-wide paper industry has a rich history of technical achievement and development. This tradition has for the most part been mimicked in Australia, but is sadly in decline as the 21st Century begins. In the second half of the 20th Century however, came a most remarkable joining of technical expertise and organisational vision. Australian Paper Manufacturers (APM, later to become AMCOR) research groups, from relatively small beginnings, ultimately grew to over 120 engineers, scientists and technicians. These groups generated a series of developments that included amongst other things: the mathematical basis for identifying machine direction basis weight changes more efficiently from cross machine profile data (unpublished internal APM report, 1971), the first in-process consistency meter using polarised light (J) and the first real change in fundamental corrugated board design seen in a 100 years. (The Xite™ design - discussed later in the paper). Many of these innovations have been absorbed by the industry, some have been appropriated and built upon by others and a few have been set aside to gather dust and be forgotten.

As the paper industry struggles with the role of research and development in the modern age it is worth remembering that it was not always so; in times past, and for good reason, the value of in-house innovation and research was accepted a priori.

This paper highlights some of the important developments from the largest Australian pulp and paper research group over the past 50 years, especially as they relate to the long and continuing quest to improve the performance of corrugated packaging – both its effectiveness and cost.

The usefulness of Cross Directional Ring Crush
The move towards using ring crush (test method now standardised by ISO 12192) as an important measure started in 1951, when Kellicut and Landt (2) of the U.S.D.A. Forest Products Laboratory showed that the best predictor of the potential top to bottom compression strength of corrugated boxes was the cross directional (CD) Ring Crush of the liners. In this study, ring crush was compared to other paper properties traditionally measured for packaging papers such as tensile, burst and stiffness. (The study focussed on the potential strength, recognising that the compression strength of a corrugated box is also very sensitive to other factors such as moisture (hence testing in standard atmospheres), physical damage during manufacture, and storage history (load, vibration, atmosphere and time).

This was confirmed in Melbourne, in 1965 by Stott and Craven (3) in a major, but unpublished, investigation using 64 different liners ranging in weight from 117 gsm to 410 gsm with furnishes including short and long fibre Kraft pulps, semi-chemical pulps, waste paper and combinations of these. The majority of test liners were from various mills of APM and these included Fourdrinier, Inverform and cylinder machine products. Liners from non-Australian sources included Fourdrinier liners from U.S.A., New Zealand and South Africa, and cylinder liners from the U.S.A. and New Zealand. This work confirmed the excellent correlation between CD Ring Crush and top-to-bottom compression strength of the Regular Slotted Containers (the most common style of corrugated box) tested.

At the time bursting strength was widely used in the US as an indicator of corrugated board strength, and it still is to some extent. However, Craven and Stott found correlation with burst to be non-existent in practical terms.

The question of stacking vs. containment
At the same time significant effort was put into finding the best combination of stacking strength (the extent to which a box can be loaded top to bottom) and “containment” (the ability of a box to retain its integrity in handling during shipping). Boxes filled with steel cans full of water were tested to failure in a revolving drum (Tappi test method T800) and boxes filled with wheat were tested to failure using the drop test (Tappi test method T802). The important outcome of this work was that no single liner or corrugated board test method correlated to a useful degree with either the revolving drum or drop test results. Statistical analysis showed that a combination of MD Tear and CD Tensile of the liners explained 69% of the revolving drum variation between samples. Burst on the other hand only explained 31% of the revolving drum test variations. Thus the Containability Factor (MD Tear⁰.⁶¹⁴CD Tensile⁰.₃₉ divided by grammage) was established (4) and used in-house for many decades when ranking linerboards (Fig. 1).

¹Private consultant and corresponding author (jfbpgb@bigpond.com).
²Technical Director
AIP Pty Ltd
Melbourne, Australia.
machines and semi-chemical pulp mediums at Botany and Maryvale. For a long time APM had wanted to produce a virgin fibre liner especially for use in corrugated boxes for the fresh fruit and vegetable market where it was known that virgin fibre boxes survived longer in cool room conditions than boxes made from recycled fibres including OCC (Old Corrugated Containers).

A major research program was set up and, keeping in mind a saying by Alfred Nissan that: "...we are selling properties, not products", a fairly crude basket of properties was established which were known to be important for the end use performance of a corrugated box, empirically weighted based on many years of collective wisdom and knowledge from field performance and laboratory testing.

The major end-use performance properties for corrugated boxes were deemed to be stackability, containability and rigidity. The big question was, given the unavoidable trade-offs: "what should be the relative weighting for each of these properties?" From an understanding of modern distribution systems the conclusion was reached that it was best to maximize stackability and let containability drop somewhat. In undeveloped countries with largely manual and often rough handling of boxes the opposite may well be the better option.

**The development of Australian High performance liners**

By now, unpublished work by Peter McKinlay, a principal research engineer at Amcor’s R&T (Research and Technology) centre, using sophisticated computer modelling of the corrugated box, had confirmed earlier work by Ern Shaw (6) that CD Ring Crush was the best single predictor of box compression.

This theoretical work underwrote a two day trial at Maryvale where twenty-three different combinations of furnish (pine Kraft, eucalypt NSSC and recycled fibre including OCC, starch treatment on and off at the size press) were run on the paper machine followed by extensive box making trials. This work rewarded the company with a huge data base from which to fine-tune the final furnish of the then new Australian Paper Kraft liners. These trials required extensive planning and really stretched the resources of the research group with about a third of the staff working shift at the mill.

The outcome of this work was the product range “Australian Correx Kraft liners” which exceeded from day one the then American definition of “High Performance Linerboards”: a container board having greater than 2 lbs of Ring Crush per lb per 1000 ft². This was achieved by incorporating in the liner-board furnish a significant amount of high yield eucalypt NSSC pulp found to contribute significantly more to Ring Crush than Pine Kraft pulp (Fig. 2). The papers were designed to avoid excessive compromise of containability or rough handling performance. The development of these new Kraft Liners allowed corrugated boxes with components 293/112/293 (liner/medium/liner gsm) to be replaced with 210/112/210 while maintaining equivalent field performance. All this was achieved without the benefit of current technologies such as extended nip presses.

**Understanding the Ring Crush test**

The next major step forward was the...
development of a fuller understanding of the paper physics of the ring crush test – giving insights as to how it could be improved on the paper machine. The dream was to ultimately develop a sensor to measure a quantity which correlates highly with ring crush (or, even better, with box stacking strength for which ring crush is a proxy), preferably controlled by the same intrinsic properties as those which determine the value returned by the ring crush test – but this would prove to be a difficult task. By controlling Ring Crush on-line to an aim Ring Crush level (rather than controlling to a fixed Basis Weight target), the aim was to be able to sell square meters of useful paper rather than tonnes as this would clearly deliver huge savings.

This was a major change in thinking for any paper company at that time. Historically from the beginning of the 20th century, linerboards had been made to a burst and basis weight specification in an attempt to protect US transport companies from damage claims. (It can be argued that the introduction of this requirement, known in the United States as Rule 41 (7), delayed the advancement in corrugated board optimisation for over 100 years.)

Before changes could be made to packaging paper design, a better understanding of the mechanism of the Ring Crush test was needed. The common belief at the time was that the test measured the catastrophic crushing of the sample when it got to its yield point but this was proved to be incorrect. Investigations using finite element analysis (Fig. 4) clearly showed that Ring Crush was not a failure test but rather a measure of the resistance to out of plane buckling. Further, because of the sample dimensions of the test, it actually simulated the inside liner micro-panel buckling between flutes for C-flute board. McKinlay, at that time often said “Look inside the box to see how it fails” (Fig. 3). Boxes which have failed under load over time generally have side panels which have bulged outwards. The outside liner is in tension, but the inside liner is in compression and you can clearly see many micro panels which have popped in and out, starting from the corners. By apparent chance, the Ring Crush test was producing just this buckling behaviour.

Experimental confirmation came by one of the authors using the newly available rigid platen crush testers. With the old style beam testers for ring crush the sample was catastrophically crushed after it was loaded beyond its yield point. The test sample, having buckled out of plane and no longer able to support the load, was crushed by the energy stored in the beam of the tester. Inspection of the failed and crushed sample certainly led one to believe it had failed by in-plane crushing of the sample.

However, with the new rigid platen testers it was found that you could take the load up to within a few percent of the known failure load, back the load off and see no damage at all in the test sample. This could be repeated many times without apparent damage to the sample. A test

[Fig. 3 Inside of a loaded box showing the development of micro-panels.]

[Fig. 4 FEA model showing the build-up of micro panels around a section of the ring crush test ring. Hot colours represent higher stresses.]

[Fig. 5 FEA model of an ECT coupon under compression showing the development of micro panels. Hot colours represent higher displacements.]

[Fig. 6 Amcor’s MD Shear Twist Unit.]
on the same sample would also follow the same load deflection curve each cycle confirming that the sample was being loaded and un-loaded within the elastic range of the sample.

How and why the Ring Crush test was originally developed is unknown to the authors, but to date it is certainly the best predictor of top to bottom compression strength of corrugated boxes. With rigid platen crush testers the same experiment with Edge Crush (refer ISO Test standard 3037) test samples (ECT) can be undertaken and one observes that in most cases they also fail by out of plane buckling of micro panels. (Fig. 5) (The exception is when samples made with very heavy liners are tested. Such samples do fail by short column in-plane crushing.)

The role of corrugated medium
At the same time as the importance of the ring crush test was confirmed in the late 1980’s, McKinlay was developing his structural engineering computer model of the corrugated box. One of the engineering inputs he needed for his model was the MD Shear strength of the medium in the made-up board. Some initial attempts were made to measure this, directly culminating in the realisation that the resistance to twisting of an ECT sample was a very good measure of the MD Shear strength of the medium. From this work the patented MD Shear test instrument was designed and built (8). The commercial unit designed in-house at Amcor R&T is shown in Figure 6.

The MD Shear property was found to be very sensitive to flat crushing damage (during the conversion process). (Flat crushing refers to crushing the corrugated board in the thickness direction). This test offered a new way of ensuring the potential performance of a particular corrugated board grade could be met. The commonly used measure of damage, board caliper, was shown to be very insensitive to crushing due to spring-back. (Fig. 7). An understanding of the shear medium property gave an insight into the mechanism of how a box panel fails under load and though largely ignored by industry, had the potential to impact box stacking strengths by up to 25% (9).

This measure was used in the Amcor box plants to monitor quality with great success, especially in New Zealand.

Corrugator roll optimisation
As a direct result of the investigation of MD shear effects it became clear that it should be possible to improve the shape of the corrugator roll teeth, increasing the MD shear developed and providing an increase in resistance to conversion crushing and improvement in box performance. It was found that by redesigning the corrugators roll/flute profile the MD shear and box compression strength could be increased significantly, with the added advantage of increased resistance to conversion damage. An additional benefit was a 2-3% decrease in medium usage as a result of the newer high efficiency teeth shapes.

Development of Xitex
Following directly from the modelling work looking at the medium’s contribution to box performance, the next major development of the Amcor R&D group was Xitex™. In 1985 Stott, now approaching retirement, was given the task of undertaking a “what if” analysis of how to improve top to bottom compression of corrugated boxes by playing with, and interrogating.
McKinlay’s computer model.

One of the variables included in his study was the “X” flute structure. (Fig. 8) The model showed that corrugated board made in this configuration would have in excess of 20% increase in compression strength for the same weight of board. Alternatively one could save 20% in material costs for the same end use performance. Trials and laboratory work subsequently showed that Stott’s estimates of potential improvement had been conservative. (11). There are now two corrugators in Australia producing Xitex board.

Controlling paper qualities

So the scene was set for optimising and designing the performance of corrugated boxes and what effect would that have on the performance of a box under extended stacking load?

Three barriers existed to using measured paper strength to control paper quality. The first was the difficulty in making adjustments to paper quality during manufacture because of the delay between top-of-reel measurement and response. Secondly, a measurement method was needed that could be applied continuously on the paper machine and characterise the paper performance in real time. Thirdly, the development of accurate and reliable algorithms to convert the measured non-destructive properties to a reliable measure of CD ring crush and other important performance properties.

Despite a 20 year effort to solve these practical problems by a number of groups around the world and a number of trials on commercial paper machines, by the start of 2000 these problems were still not resolved satisfactorily (15,16).

Knowing that Ring Crush largely consisted of out-of-plane buckling mechanisms meant that it should be possible to predict it from the measurement of paper elastic properties. In May 1995 a strong physical relationship between sonic stiffness (measured using ultrasonic wave propagation through the paper) was developed at Amcor R&T; driven by an oblique interest by one of the authors and supported by Dennis Shore, Jim Bonham and others.

This relationship was found to be superior to other existing attempts at predicting CD ring crush. Figure 10 shows the level of improvement that the new algorithms provided in predicting CD ring crush compared to a published correlation from 1993 (17). The most obvious improvement is the ability of the new predictor to accommodate both the MD and CD test results in a single relationship, supporting the view that the new relationships described the true physical reality of the ring crush test more closely.

A practical on-machine ring crush measurement.

It has taken a further fifteen years to develop and engineer a suitable system for the on-line, continuous measurement of paper properties on the paper machine (18). While the development of this ultrasonic measurement was originally designed to obtain a proxy for ring crush, the measurement also reflects fundamental performance characteristics of the paper. At this time the technology of on-line strength measurement has been applied successfully to six commercial paper machines around the globe, including Kraft, recycled fibre based packaging paper machines and sack Kraft machines.

The most common application relates to reducing the manufacture of reject material and removal of over-specification so as to permit significant reductions in basis weight for the same guaranteed performance. A corollary is that this approach provides otherwise unobtainable data to support investment of management resources and capital in better process control techniques and better equipment. Also, the cost savings from closer process control are more able to be retained by the paper manufacturer, rather than being passed on to end customers.
This work allows us to answer the questions: “What is a typical level of property variation on the paper machine?” and “What effect does paper variation have on the box-to-box stacking performance of corrugated boxes?” Figure 11 shows cumulative peak to peak variations attributable to a number of commercial paper machines. In broad terms it shows that, assuming active control on the machine is possible for variation greater than around 20 minutes, most machines have peak-to-peak variation of 20% that would be amenable to removal by using existing machine “levers” such as refining, furnish and rush-drag ratio. The shaded arrow represents the time scales over which active machine control should be possible.

Using the relationships generated in previous plots it is straight forward to calculate the effect of property variation on corrugated box survival time in a cycling high humidity environment.

The sum of fifty years of technical and development work now allows us to estimate the potential contribution of this work to the paper manufacture and box manufacture stages of corrugated carton manufacture and to the future improved performance of fibre packaging (Fig. 12).

New machine control and developments, new tests, new understandings of paper physics, new component designs and new corrugated structures have all conspired to provide improved box performance and ultimately increased suitability – not just for APM as it was originally, but for the paper industry in Australia and, as a result, for the global paper and corrugated industry.

CONCLUSION

In summary, this paper has traced the history of developments from the realisation of the importance of ring crush to the design of a novel furnish for Correx™ liners to the fundamental understanding of ring crush, the development of the novel MD shear test, the invention of Xitex™ and ultimately the application of on-line ultrasonic technology. All of this highly innovative work had direct commercial benefits, which were realised to varying degrees.

Seen as a consistent progression of targeted research, it is an impressive achievement that one relatively isolated research group, over many decades, has made to the potential improved performance of corrugated packaging.

REFERENCES


Original manuscript received 21 April 2011, revision accepted 5 July 2011.