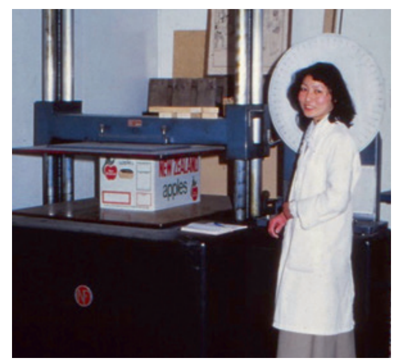
EVALUATING CORRUGATED BOX PERFORMANCE

IAN CHALMERS OF KORUTEST EXAMINES THE VARIOUS TESTING AND MATHEMATICAL MODELS.

Mathematical models can give us a very good idea of what is important to achieve a particular result and this is especially so with corrugated board and BCT (Box Compression Test). The McKee equation was a good first model for BCT and gives ECT (Edge Crush Test), box perimeter and flute size as the main variables for any particular box.



This photo shows a National Forge BCT tester from the 1950s. Modern box crush testers are essentially the same except the stresses and strains are measured electroncially.

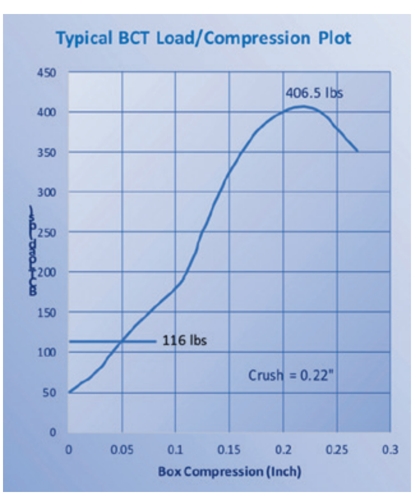
More modern mathematical BCT models using techniques like Finite Element Modelling can develop BCT from the paper component properties like grammage, density, Youngs modulus plus flute geometries and box dimensions. However, it has been found that these FE (Finite Element) Models also require a Shear Stiffness input to bring theory into line with reality.

Poor flute formation or crush damage often prevent a box's BCT from reaching its theoretical capability either through using the McKee model or a Finite Element Model. MD (machine direction) torsional stiffness is equivalent to MD Shear Stiffness and is the only parameter required to identify the quality of the corrugated board/box manufacture process.

It is generally accepted that corrugated boxes can be tested in a laboratory to see if they will meet the requirements the boxes will need to survive and protect their contents in the service environment. For some sensitive contents, transport shocks are important and these can be tested by a range of impact tests but compared to a BCT test, none of these tests are performed routinely in a corrugating plant.

A box's load carrying ability is almost always the most important test as it simulates the performance of a box on the bottom of a stack on a pallet that will have to carry the weight of the boxes above it as well as maybe another pallet load or two on top of that in a storage situation. This situation can apply to any corrugated box and BCT is the major strength parameter designed into most boxes. Failure of a box in a pallet in storage can lead to pallet load collapse and almost always leads to product spoilage.

BCT is the most common test used to get data on a box's load carrying capacity. This test has been around for at least 80 years and the same result, ie the maximum load to crush a box to failure, is still the result reported.



This chart reflects a typical BCT load/compression curve. The maximum load was 406.5 lbs at a crush of 0.22 inches. Applying a stacking factor of 3.5 would mean that the box should be able to withstand a load of 116 lbs during its service life.

BCT is the most common test used to get data on a box's load carrying capacity.

A good BCT result will generally also indicate enough box strength to handle most transit requirements. The BCT test is also very good at judging the effect of compression on sensitive contents like retail containers of yogurt.

The BCT test is performed in a box crush tester in a relatively short time, say less than 30 seconds. Because of the nature of the fibres in the corrugated board and the geometry of the box used for the box construction the BCT is only an estimate of the box's load carrying capability in the real world. A stacking (or safety) factor (SF) has to be divided into the BCT result to estimate the box's actual stacking performance. The smallest common denominator SF used for general packaging and Fast-Moving Consumer Goods (FMCG) is 3.5 which means that if the BCT result is failure with a load of 400 kg then the box can only be used if the load it is required to take is less than 114 kg.

The huge difference between what the BCT measures and what is realistic to use is because of compression creep over the time the box is under load. This compression creep is further accelerated in many common situations by changes in moisture content of the box panels under cyclic humidity environmental conditions – Cyclic Humidity Compression Creep (CHCC). In situations where the storage conditions of a loaded box in a warehouse is subject to significant changes in humidity on a daily basis, the safety factor applied to the box may need to be as high as 6, meaning a load of only 67 kg from our 400 kg BCT is realistic to use.

Some of the CHCC box creep testing equipment at Scion in New Zealand.

We now have an FE Model that predicts a BCT from liner and medium properties and other board and box related geometries but the model also needs an input of MD torsional stiffness to allow for manufacturing deficiencies.

The McKee equation for predicting box crush performance was published in 1963 and is still used by many corrugators today. Though it gives an insight into how a box may perform in a Box Crush Test its accuracy is often poor, with Thomas J. Urbanik and Benjamin Frank in 2005 reporting percent errors from different researchers over the previous 46 years as varying from 6 to 56% from the model prediction. The original equation used bending stiffness as a major variable but this test is difficult to do and a simplified version of the equation using caliper is more commonly used.

Unfortunately, caliper is a crude differential that just signifies flute size and not small variations in size caused by say crushing or densification of liners.

The most important part of the McKee model for any particular sized box is ECT, which is an indicator of the basis weights and the quality of the components and whether or not there is enough fibre to do the job. Consequently, ECT became very important in the U.S. and after a great deal of discussion finally replaced Burst as the specifier for the Rule 41 box transport regulations/recommendations. ECT certainly made a lot more sense than Burst as a specifier of performance especially after the development of high-performance liners. There have been many excellent models proposed of ECT vs paper qualities and most of them suggest that ECT is mostly a paper property rather than a corrugated board one.

The McKee equation has a few drawbacks, two of them being that it does not give any information on likely performance of different liners used on each side of the board or flute shape as it only applies to a solid uniform material and cannot tell the difference between a solid fibre pasted board or a corrugated board. However, the McKee equation also has a very practical advantage and that is that it can easily be used by designers in any corrugating plant.

With the advent of huge changes in computing power and the development of Finite Element and other advanced mathematical Models like curved beam theory in the late 1980s some engineers in Australia (Bennett P.G., McKinlay P.R., “Box Compression Prediction – Beyond McKee” Appita presentation 1987) started to develop far more sophisticated BCT models that used liner and medium paper properties, flute geometries and box construction geometries to give them a far better understanding of the important variables associated with BCT and performance in the service environment. One of the major outcomes from the development of the FE Model was the discovery that the actual BCT of current boxes tested were significantly lower than they should have been as determined from their model (see chart below). The differences were traced back to compromised shear stiffnesses of the corrugated board produced by crush damage during board and box manufacture. The identification of the importance of shear stiffness led to the development of an MD Torsional (shear) Stiffness Tester to measure the board and box manufacturing weaknesses and produce a BCT on a corrugated box that met the FE Model BCT.

Medium Grammage g/m² (lbs)	Percent difference BCT actual/model
112 (23)	-40%
120 (25)	-38%
145 (30)	-30%
160 (33)	-20%

Differences between a Finite Element model for BCT and actual box BCT from a range of commercial box samples in the late 1980s (Allan R.J., Appita Conference 2011).

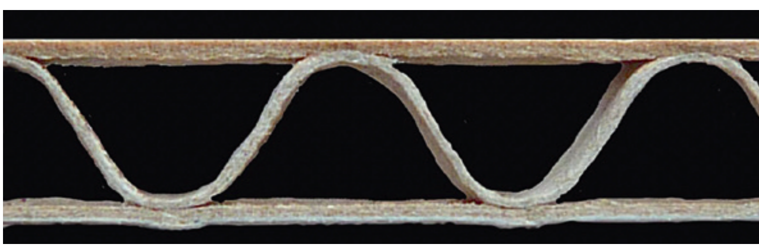
So, we now have an FE Model that predicts a BCT from liner and medium properties and other board and box related geometries but the model also needs an input of MD torsional stiffness to allow for manufacturing deficiencies. Or better still, the manufacturing needs to be improved so that the full MD torsional stiffness as calculated by the model is obtained. Under these conditions the box will give its maximum performance. Any degradation in MD torsional stiffness will show a degradation in box performance — the tested MD torsional stiffness expressed as a percentage of the MD torsional stiffness model for that board grade can be regarded as a BCT degradation factor.

From our experience over the last 12 years with MD torsional stiffness we feel that the huge variability in this initial Finite Element model work can also be applied to the McKee equation variability as described by Urbanik and Frank. We have a lot of evidence that most boxes supplied from any corrugating plant are crush damaged and therefore have reduced BCT and service environment performance.

As well as engineers from Australia working on FE Models, engineers from Europe and the USA were also working in similar areas on corrugated box and board design. For example, Tomas Nordstrand from Sweden as part of his PhD at Lund University developed a mathematical Model based on curved beam theory and used it to investigate four different flute shapes and calculate the shear modulus coefficients for each shape (see Figure 1). The triangular shape was shown to provide the highest shear moduli.

Shape	Circular	Circular-straight	Sinusoidal	Triangular
				
$\Gamma \times 10^3$	0.53	1.52	3.77	19.5
$\Gamma^* \times 10^3$	0.43	0.96	2.75	8.72

Figure 1: Nordstrand's calculations of a non-dimensional MD shear modulus coefficient ($\Gamma^* = G_{xz}/E$) for various flute shapes using curved beam theory.



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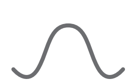
Two Commercial C Flute Profiles		
Pitch	7.9mm	7.9mm
Height	3.6mm	3.6mm
Take-up Ratio	1.428	1.407

4

Figure 2: These typical flute profiles of "good board" (1) and what a line of print can do to a flute (2) seem closer to Nordstrand's circular model at the poor performing end of the shapes. Photo 3 is approaching the sinusoidal shape and has a 30% better MD torsional stiffness performance). Number 4 shows two commercial flute profiles available where the second one provides both lower take up factor (TUF) and significantly higher tested DSTs (dynamic stiffness tester).

In Figure 1, Γ(Gamma) represents a liner that is rigid and Γ* represents a liner that can buckle. Most corrugated boards can be expected to be somewhere between these two extremes. We have heard of a 30% improvement in MD torsional stiffness on exactly the same paper grades by moving from a conventional flute profile to a more triangular profile.

Apart from Nordstrand's corrugated board models, other engineers developed corrugated board panel and complete FE models for corrugated boxes. Unfortunately, the FE type models require a lot of computing power and commercial models and are not readily available for box designers to use. The McKee equation has a lot of life left in it yet.

As far as shear stiffness is concerned, it has been shown that torsional stiffness is substantially the same as shear stiffness and more importantly, far easier to measure. It is accurate, reliable, repeatable and actually captures all the "in-plane and out of plane" shear forces that occur in a corrugated box panel that a pure shear stiffness test could not. Shear stiffness is almost impossible to measure within a reasonable time frame and this is why a useful measure of this property had not been developed until P.R. McKinlay proved that in a corrugated box, torsional stiffness and shear stiffness were essentially the same. The Chalmers DST (dynamic stiffness tester) is said to be the only torsional stiffness tester commercially available to corrugators to allow them to maximize the performance of their corrugated board. A suggested improvement for specifying a corrugated box from just ECT to including a DST value to guarantee box performance was published in the May/June 2016 issue of *Corrugated Today*.

The Chalmers DST goes much further than just being helpful to improve BCT. Another article published in Nov/Dec 2012 *Corrugated*

Today highlighted its measurement of corrugated board crush and its ability to indicate likely cyclic humidity compression creep performance as measured on the type of CHCC equipment available at Scion.

Along with customer demands, what do modern mathematical models require and tell us about box making? In a nutshell, the variables that define a corrugated box are in the following chart:

Variables	Paper Related	Geometry Related	Box Construction Related
Finite Element Model	Grammage Poissons ratio Density Tensile Stiffnesses (x2) SCT	Flute size, single or twin cushion etc. Flute profile (Fig 5) Box and panel size Shear stiffnesses (x3)	MD Torsional Stiffness
Other requirements (Appearance etc.)	Liner type, KL, WTL etc. Medium type SC, RF etc Colour, Finish, Printability	Hand holds etc.	Pins (flute adhesion) Diecutting, creasing, crush Gluing, alignment during gluing etc.

Figure 3: Simplified list of variables used for a FE Model and other variables not considered in an FE Model that complete the box description.

In Figure 3, the paper related variables are defined during the selection and purchase of the liners and medium and are management decisions. Geometry variables are also determined pre-manufacture.

Box construction includes the quality of the board off the corrugator and handling during printing and box making. These are completely under control of the corrugated plant and converting operations and the only variables the box maker may have control over. These are the variables that separate quality manufacturers from ordinary ones.

If everything else is taken as satisfactory, to optimize a corrugated box there is one really important variable from each of the above three areas and they are tensile stiffness for paper, flute profile for geometry and MD torsional stiffness for construction. The singular most important variable is MD torsional stiffness because if you optimize this in your final box you will be achieving the highest strength attainable for any set of variables. ■

Ian Chalmers is the principal of Korutest Limited. He has spent his entire career in the technical side of the paper and packaging Industry. For 17 years he was employed as a senior scientist/Group Leader at Papro (Scion) researching corrugated board performance. He can be reached at **Ian@korutest.com**

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