Predicting Box Compression Strength

Roman Popil, Ph.D.
Senior Research Scientist
Georgia Tech/IPST
Atlanta, GA.
Roman@gatech.edu
404 894 9722
How to calculate BCT from component properties

• from medium and linerboard compression strengths (SCT or RCT), we can calculate the expected edge compression strength (ECT) of corrugated board

• From corrugated ECT, bending stiffness, caliper, box perimeter, the BCT can be calculated using:

  a) Simplified McKee equation (typical)
  b) Full McKee equation (more accurate)
Simplest and quickest way to estimate BCT

“Maltenfort” equal deformation model for ECT:

\[
ECT = C\left\{2 \times SCT_{\text{liner}} + \alpha \ S CT_{\text{medium}}\right\}
\]

\[C \approx 0.7\]

Simplified McKee equation for box compression (easy but not accurate):

\[
BCT(\text{lbs}) = C' \ ECT \sqrt{h \times Z}
\]

\[C' = 5.87\]

Take-up factor for the medium ~ 1.42 for C flute

Box footprint perimeter (in)

Corrugated board caliper (mils/1000)
For better accuracy, use the McKee equation in full form

This is the equation with constants fitted by McKee et al. using 1963 data

$$BCT = 2.028 \ ECT^{0.746} \ {\sqrt{(D_{MD}D_{CD})}}^{0.254} \ Z^{0.492}$$

This is the Geometric Mean of the MD and CD bending stiffnesses (~ flexural rigidity)

The form of the equation is derived from principles regarding the buckling of a plate under vertical compression:

$$BCT = C \ ECT^b \ {\sqrt{D_{MD}D_{CD}}}^{(1-b)} \ Z^{(2b-1)}$$

The best agreement with the data is obtained when this equation is used and the fit is made to calculate the constant $C$ and exponent $b$ for a given set of similar boxes, the empirical constant(s) are actually functions of panel rigidity and size, McKee et al., also assumed a square box footprint for simplicity.
Four point bending stiffness method is used for $D_{MD}$ and $D_{CD}$

For the panel buckling term in the McKee equation, calculate the geometric mean bending stiffness:

$$\sqrt{D_{MD}D_{CD}}$$

This term arises from the formula for the “critical buckling load” (aka $P_{cr}$) for a simply supported vertically loaded (solid) panel (ex Marsh 1954, FPL) and neglects transverse shear.

(Actually, the simpler 3 point method might be better because then this is affected by shear which lowers when board is crushed!!)
Which is the best way to predict BCT?

• RCT or SCT?
• Which relates better to ECT?
• What problems occur at low basis weights?
• How do converting operations affect the BCT prediction?
• Which McKee equation to use?
Box performance is predicted based on strength of the components of the board:

\[ \text{ECT} = 0.8 \times (\text{RCT}_1 + \text{RCT}_2 + \alpha \text{RCT}_{\text{Med}}) + 12 \]

For linerboards > 42 lb/msf

\[ \text{ECT} = 1.27 \times (\text{RCT}_1 + \text{RCT}_2 + \alpha \text{RCT}_{\text{Med}}) - 6 \]

For linerboards < 42 lb/msf

Different equations for different basis weights…why?...

Figure 1) Whitsitt Relationship of ECT to Composite Ring Crush
RCT is *supposed* to predict BCT...

Ring Crush specimen after testing; buckling and rolling edges clearly visible

BCT test

RCT measures a combination of buckling and compression failure; the former is a function of board caliper.
Short Span Compression (SCT) *should* Replace Ring Crush (RCT)

1. Short span compression is an *easier, quicker* and *cheaper* testing method, is available in automated systems, works for all basis weights – RCT does not track basis weight!

2. The *science* behind SCT is *sound* and established:
   - results correlate with basis weight, refining, fiber quality – RCT is affected by bending and edge rolling leads to misleading conclusions

3. SCT *correlates* directly with ECT, BCT, box lifetime – RCT correlates differently at basis weight classes

4. Using SCT instead of RCT *makes good sense* – rest of the world thinks so too !!
SCT is replacing RCT since 1980’s...

SCT and RCT testing worldwide:

• USA
  – Some are using only RCT
  – other only SCT
  – Some both, SCT on low basis weight and RCT on high basis weight

• Europe
  – SCT dominating

• Asia
  – RCT almost only

• Australia
  – Moving from RCT to SCT
Manual lab testing is being replaced by automated “one-touch” reel strip testing

RCT is unavailable as a test module

However, SCT, basis weight and TSO usually are for linerboard mill installations, so…
The Short Span Compression Test is SCT

STFI = Svenska Träforskningsinstitutet (transl. - Swedish Forest Products Research Laboratory), a part of the Royal Institute of Technology in Stockholm Sweden, now renamed as "Innventia AB")

the SCT test method was developed by Christer Fellers in the late 1970's as part of his PhD at S.T.F.I.,

L&W was the 1st to commercialize the method

The short span compression test is not "STFI" (aka "stiffy" (!))

Christer gets a Tappi award from Jeffrey Suhling (Auburn U.)
Short span compression has been shown in the published literature to be a correct measure of compression strength.

Increased buckling for lightweights decreases RCT with density.
SCT works because over the 0.7 mm short test span, there is no bending

Shows that specific STFI (SCT) is independent of basis weight and is a property of the fiber consolidation

“Euler” buckling curves ...go as $1/(\text{length})^2$

Fig. 15 Specific stress at failure in compression versus span for two kraft pulp handsheets of different basis weight according to the STFI short-span test.
Only when the column height is relatively short (region III) can the true edgewise compression strength be measured. Failure in this region is characterized by a well-defined localized crease produced through the thickness of the sheet at maximum load. This permanent localized failure event is shown exquisitely in the photomicrograph in Fig. 32. Unlike failure in ten-

Real compressive failure is marked by material breakdown and occurs when the column height prohibits buckling

When testing a strip, the crease is often hard to see – looks like nothing has happened
SCT replacing RCT

SCT tracks basis weight, RCT does not and is ~1/2 SCT, but error bars are smaller for RCT

from Popil Tappi PaperCon 2010
Examples of RCT not increasing with other properties as expected abound in the literature

ECT increased in accordance with SCT results.
RCT predicted an ECT decrease.
Note the difference between STFI and RCT (about 2 X)

Why is that? Both are supposed to be the same property!!

At very high basis weights (90#) and calipers, get slip: more surface compression – (could increase clamping pressure)

---

Fig. 31 Comparison between the compression strength of linerboard in the CD versus basis weight according to different test methods. (Courtesy of Christer Fellers, STFI, and Raj Seth, PPRIC, Stockholm, Sweden, and from Ref. 19.)
Comparison of various compression tests – effect of basis weight

Figure 4.6 shows the results of a comparison between the four different methods for determining the compression strength of liner and fluting medium. The sheets were in this case manufactured from a typical liner pulp in grammages between 100 and 300 g/m² and wet pressed in the same way to a density of about 750 kg/m³. In the fig-

4.6 The compression index as a function of the grammage for the SCT, CCT, RCT and CLT tests.

Excerpted from: Malstrom, L&W handbook
Condebelt- Effects of higher density

Slide from: Christer Fellers, STFI

Figure 13. CD compression strengths improvement of Condebelt dried testliner compared with cylinder dried board.
This data set shows the only way to change SCT is to change the furnish and beating of fibers.
Effects of Processes on Compressive strength using SCT

Table 5. Qualitative effect of various factors on tensile and compressive strength.

<table>
<thead>
<tr>
<th></th>
<th>Compressive strength</th>
<th>Tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beating</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Fiber orientation</td>
<td>+ in MD</td>
<td>++ in MD</td>
</tr>
<tr>
<td></td>
<td>- in CD</td>
<td>-- in CD</td>
</tr>
<tr>
<td>Felted sheet</td>
<td>+ or ±0</td>
<td>-</td>
</tr>
<tr>
<td>Wet pressing</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Drying shrinkage</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>Humidity</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>Sizing</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

Table 5 compares the qualitative effect of some process variables on tensile and compressive strength. Beating and wet pressing improve compressive strength. The

Excerpted from “Paper Physics” by Niskanen
Measuring SCT on the same sample on 2 different labs, an example, IPST Paper Analysis lab data

A mill measured the same sample 150 times in an attempt to improve accuracy!

Error bars in c.i. decrease as $1/\sqrt{n}$, Tappi standard is $n = 10$

Overlapping error bars (n=20) indicate **no** significant difference, but this high variability (cv %) is bad for quality control
RCT vs SCT for quality control – “real life” examples

46# liner, same mill, same machine, different reels

RCT says Sample G > H, I  SCT says they are all equal in strength
RCT vs SCT for quality control – “real life” examples 2

Same mill, same product, different reel numbers

- Error bars are 95% confidence interval about the average values from 10 measurements, so for RCT can say D > E, C,B,A

- For SCT can say D > E & C. Reels D and B are within statistical agreement
But the variation in SCT ~7%, is still too high for quality control, why so?

Strip width is about 2 flocs wide

SCT tests a length only 0.7 mm long across 1 - 2.5 flocs along the strip length.

Mass formation cv% 6 – 8% , SCT is proportional to mass, mass is proportional to modulus, therefore **SCT variation is inevitable!!**
Back to BCT, Assumptions in the simplified McKee – why it is better to use the full form

\[ BCT = C \ ECT^b \ \{ \sqrt{D_{MD}} D_{CD} \}^{(1-b)} Z^{(2b-1)} \]

Bending stiffness measurement may not be available so...
For a corrugated board the bending stiffness is approximated as a sandwich beam:

\[ D_{MD,CD} \cong \frac{E_{MD,CD} t h^2}{2} \]

The medium contributes to D less than 5%

\[ \sqrt{D_{MD} D_{CD}} \cong \frac{E_{MD} t h^2}{2} \frac{E_{CD} t h^2}{2} \cong \sqrt{\frac{E_{CD}^2}{2} t^2 h^4} \cong ECT \ h^2 \]

The last assumption draws a linear correlation between CD tensile stiffness of the liners ECD and ECT.

Micrograph by Roman Skuratowicz, Corn Products
Simplified McKee equation derivation

Approximate the bending stiffness to be proportional to ECT times board caliper squared:

\[ \sqrt{D_{MD} D_{CD}} \approx ECT \ h^2 \]

Assume the typical \( b = \frac{3}{4} \)

\[ BCT = C \ ECT^b \ \{\sqrt{D_{MD} D_{CD}}\}^{(1-b)} Z^{(2b-1)} \]

\[ \approx C' \ ECT^{3/4} \ (ECT \ h^2)^{1/4} \ Z^{1/2} \]

\[ = C' \ ECT \ \sqrt{hZ} \]

Crushed board recovers caliper but not loss in \( D \), therefore loss in predictive accuracy in BCT when not measuring bending stiffness.

Note: Measurement of \( D \) is more sensitive to board crush than caliper \( h \).

Chalmers’ DST (gaining popularity) measures MD twisting stiffness (by twisting board strips) which is also a sensitive indicator of crush damage.
A box under vertical compression

Note how the panels bulge outward whenever $d$ is high enough.

Note the interflute patterned buckling of the linerboards.

The McKee equation assumes panel buckling (bulging). For this condition to occur, the boxes have to be high enough to allow this:

$$d \geq 2 \times \frac{(L + W)}{7} \quad \text{or} \quad d \geq \frac{Z}{7}$$

Otherwise: $BCT \approx C'ECT \times Z$
Corrugated board, ECT basics and problems

Linerboard single-face

Fluted medium

Linerboard double-face

Direction assignments for corrugated board

ECT test clamping fixtures (T 839)

“Neck down” sample cutter (T 838)

ECT is prone to artifact depending on type of board and method of sample prep
Comparison of different ECT methods, lab made A flute boards

T 838 “neckdown” method has the best agreement with predicted ECT for all samples
Clamp ECT can produce low results for crushed or lightweight board

*Figure 2.* A common version of the T 839 ECT clamp fixture (left) with a close-up (right) of the unclamped region showing the convex bowing of the facings of a previously crushed 112 g/m² C-flute corrugated board undergoing vertical compression.
Video studies at IPST have characterized interflute buckling during ECT. When buckling occurs, we can have a better predictor than: \[ ECT = C \{ 2 \times SCT_{\text{liner}} + \alpha SCT_{\text{medium}} \} \]

*Figure 13. Excerpted time sequence video snapshots of a glancing angle illuminated ECT test of a 35-26C flute board: a), 5.7 kN/m load, 1.3% strain, some buckling is evident b), peak load 6.7 kN/m, 1.6% c), post failure 4.5 kN/m, 2.1%, crease forms joining micro-plate buckling crests.*
How to fit the McKee equation constants:

1. Get $BCT$, $ECT$, Bending stiffness $D_{MD}$ and $D_{CD}$ and perimeter $Z$ data for a set of similar boxes of interest. At least 6 data points are required covering a range of BCT values. Enter as data in separate columns into Excel.

2. Keep values for the McKee $C$ and $b$ in a separate area of the spreadsheet.

3. Assume the usual McKee constants for $C = 2.028$ and $b = 0.75$, calculate in a separate column the predicted McKee BCT using:

$$BCT = C \cdot ECT^b \cdot \left\{ \sqrt{D_{MD}D_{CD}} \right\}^{(1-b)} Z^{(2b-1)}$$

4. Calculate in a separate column, $\Delta BCT =$ the absolute value of the differences between actual and predicted McKee BCT’s.

5. Calculate the sum of the $\Delta BCT$ errors in a separate cell.

6. Use Excel® Solver function to Minimize the sum $\Delta BCT$ error by changing the cells containing the McKee $C$ and $b \rightarrow$ function returns new $C$ and $b$. 
Fitting the McKee constants to improve prediction, an example

Excel Solver function window pop-up menu to minimize the sum of errors by fitting McKee C and b

Spreadsheet set-up with raw data and McKee predicted BCT’s

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>BCT</th>
<th>ECT</th>
<th>D MD</th>
<th>D CD</th>
<th>Z</th>
<th>McKee</th>
<th>error</th>
<th>original McKee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box 1</td>
<td>956</td>
<td>42</td>
<td>141</td>
<td>94.0</td>
<td>48</td>
<td>924.25</td>
<td>31.75</td>
<td>759.31</td>
</tr>
<tr>
<td>Box 2</td>
<td>1150</td>
<td>56</td>
<td>135</td>
<td>90.0</td>
<td>48</td>
<td>1150.00</td>
<td>0.00</td>
<td>931.97</td>
</tr>
<tr>
<td>Box 3</td>
<td>1100</td>
<td>47</td>
<td>136</td>
<td>90.7</td>
<td>48</td>
<td>1002.68</td>
<td>97.32</td>
<td>818.72</td>
</tr>
<tr>
<td>Box 4</td>
<td>975</td>
<td>48</td>
<td>163</td>
<td>108.7</td>
<td>48</td>
<td>1058.81</td>
<td>83.81</td>
<td>870.27</td>
</tr>
<tr>
<td>Box 5</td>
<td>967</td>
<td>44</td>
<td>148</td>
<td>98.7</td>
<td>48</td>
<td>968.65</td>
<td>1.65</td>
<td>795.85</td>
</tr>
<tr>
<td>Box 6</td>
<td>836</td>
<td>41</td>
<td>136</td>
<td>90.7</td>
<td>48</td>
<td>899.98</td>
<td>63.98</td>
<td>739.01</td>
</tr>
<tr>
<td>Box 7</td>
<td>1039</td>
<td>45</td>
<td>157</td>
<td>104.7</td>
<td>48</td>
<td>998.25</td>
<td>40.75</td>
<td>821.41</td>
</tr>
<tr>
<td>Box 8</td>
<td>856</td>
<td>47</td>
<td>146</td>
<td>97.3</td>
<td>48</td>
<td>1017.65</td>
<td>161.65</td>
<td>833.37</td>
</tr>
<tr>
<td>Box 9</td>
<td>1078</td>
<td>53</td>
<td>143</td>
<td>95.3</td>
<td>48</td>
<td>1114.29</td>
<td>36.29</td>
<td>907.23</td>
</tr>
<tr>
<td>Box 10</td>
<td>1234</td>
<td>57</td>
<td>140</td>
<td>93.3</td>
<td>48</td>
<td>1175.11</td>
<td>58.89</td>
<td>953.05</td>
</tr>
</tbody>
</table>

sum of errors = 576.0885757
Summary: Predicting BCT

• Best to use the **SCT** of liners and medium, calculate the “Maltenfort” **ECT**, plug in Tappi board Caliper **h** and perimeter **Z** into standard McKee **BCT** formula

• Better to include Bending Stiffness **D** of board, use McKee full form equation, and check Maltenfort **ECT** with actual values, (there can be ECT problems at small or high basis weights, low pin adhesion values etc.)

• Use box and board data to fit McKee equation constants **C** and **b** for the best predictive model for sets of similar style boxes
Thank you!
Send: testing samples, inquiries of interest, to Roman@gatech.edu
404 894 9722

“A Graduate Research Center Dedicated to the Pulp and Paper Industry

500 10th St NW., Atlanta, GA., 30332

“serving the paper industry since 1929…to survive is to do research, but to thrive is to implement …”