



Predicting Box Compression Strength

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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:

$$ECT = C \{ 2 \times SCT_{liner} + \alpha SCT_{medium} \}$$

$$C \approx 0.7$$

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

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

$$BCT(lbs) = C' ECT \sqrt{h \times Z}$$

$$C' = 5.87$$

Corrugated board caliper (mils/1000)

Box footprint perimeter (in)

For better accuracy, use the McKee equation in full form

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

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



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 :

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

The best agreement with the data is obtained when this equation is used and the a 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}



(Actually, the simpler 3 point method might be better because *then* this is affected by shear which lowers when board is crushed !!)

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

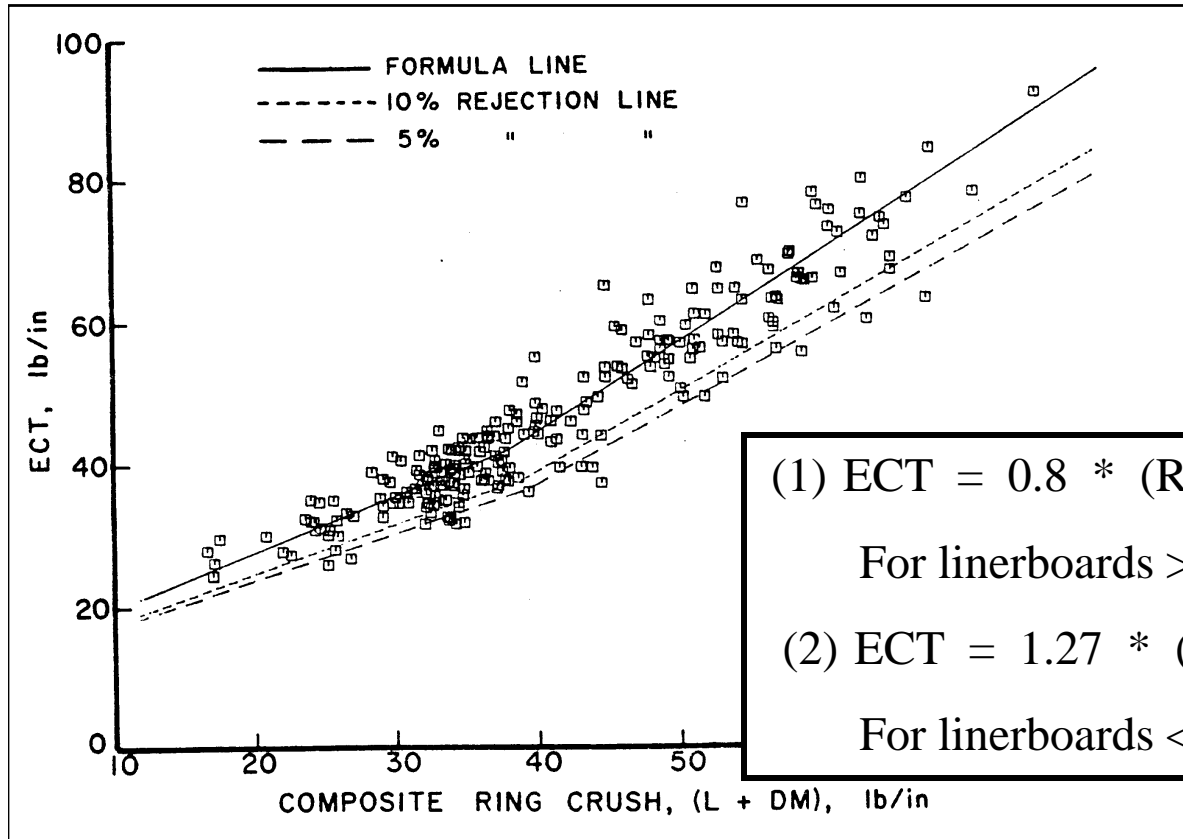
$$\sqrt{\{D_{MD}D_{CD}\}}$$

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.

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:



Whitsitt
1983, IPC

Related
ECT to
RCT:

$$(1) \text{ ECT} = 0.8 * (\text{RCT}_1 + \text{RCT}_2 + \alpha \text{RCT}_{\text{Med}}) + 12$$

For linerboards > 42 lb/msf

$$(2) \text{ ECT} = 1.27 * (\text{RCT}_1 + \text{RCT}_2 + \alpha \text{RCT}_{\text{Med}}) - 6$$

For linerboards < 42 lb/msf

Figure 1) Whitsitt Relationship of ECT to Composite Ring Crush

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

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)

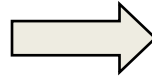
1. Short span compression is an *easier, quicker* and *cheaper* testing method, is available in automated systems, works for all basis weights – RCT does not track basis weight !
2. The **science** behind SCT is **sound** and established:
results correlate with basis weight, refining, fiber quality –
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.,

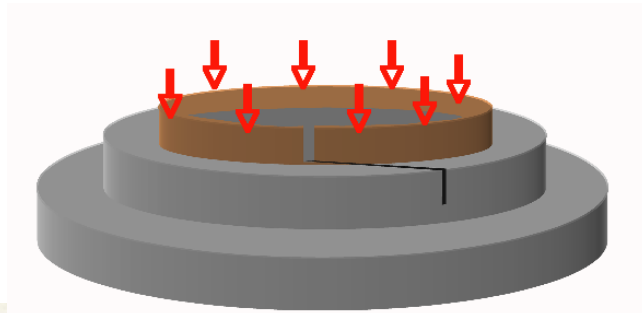
L&W was the 1st to commercialize the method

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

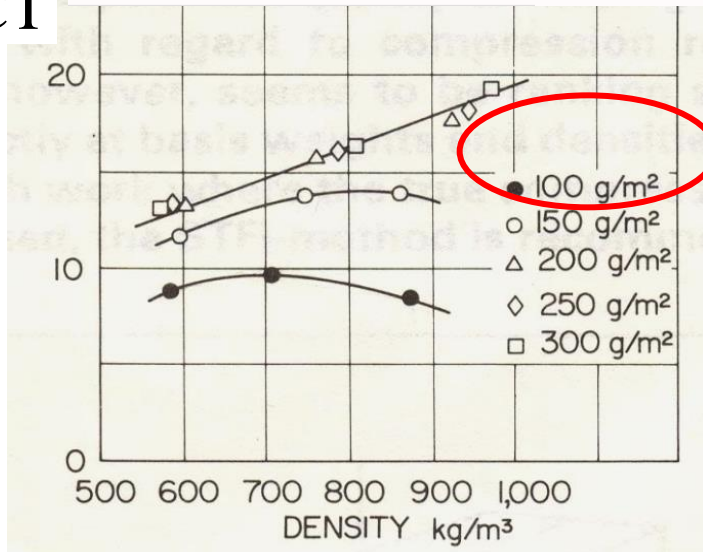


Christer gets a Tappi award from Jeffrey Suhling (Auburn₂U.)

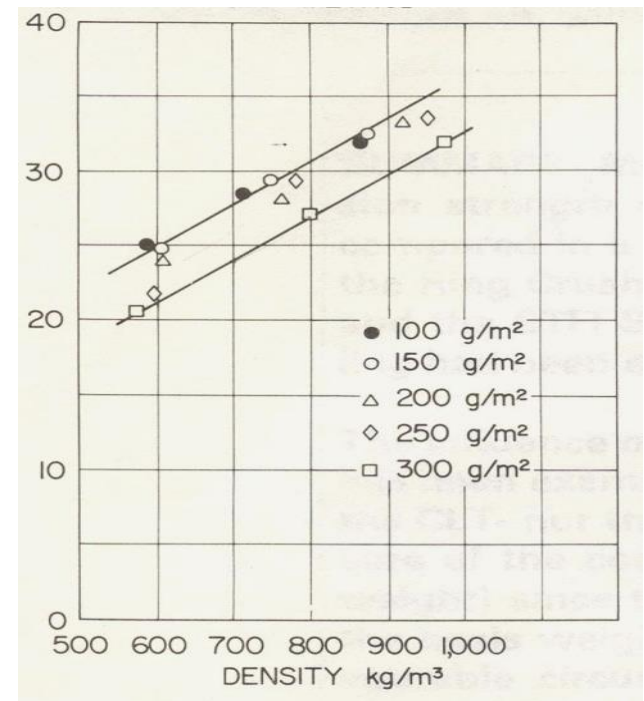
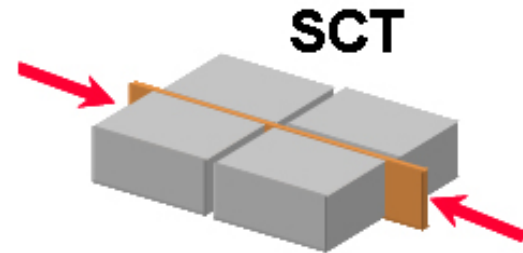
Short span compression has been shown in the published literature to be a correct measure of compression strength



RCT

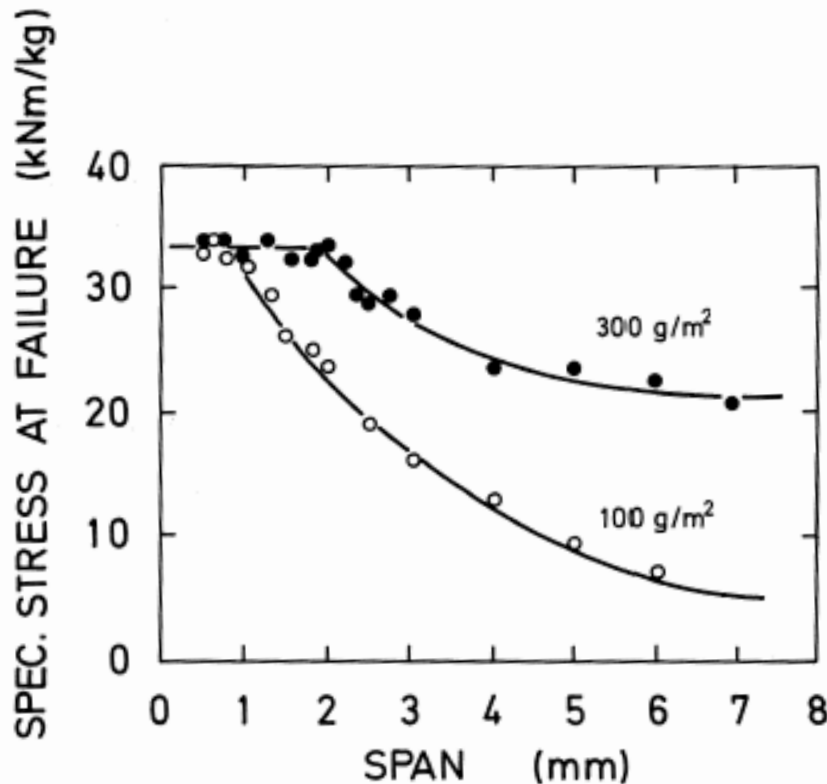


Increased buckling for lightweights decreases RCT with density



Christer Fellers' slide from Inventia, Sweden

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-

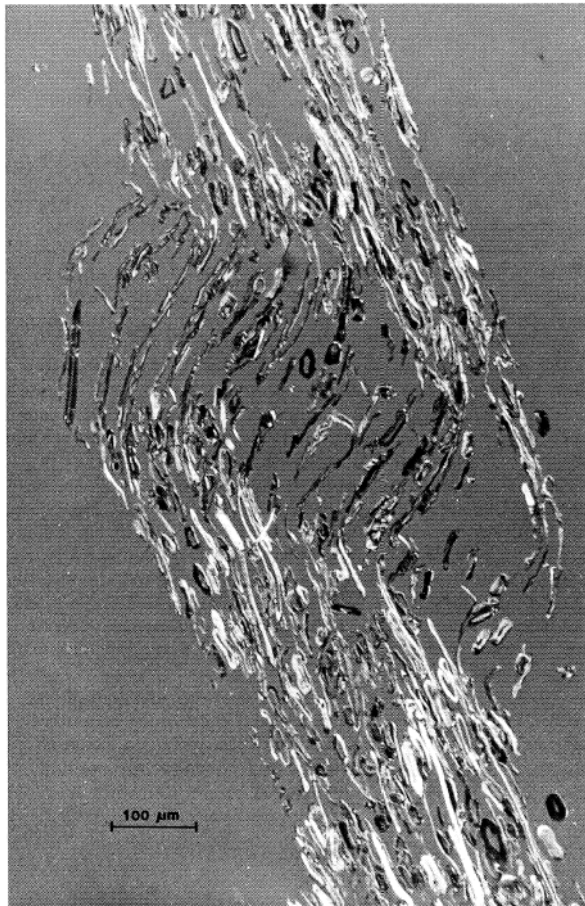


Fig. 32 Characteristic microstructural damage of an edgewise compression failure in paper. Photographed in partially polarized light. (Photomicrograph courtesy of Amin Eusufzai, Empire State Paper Research Institute.)

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

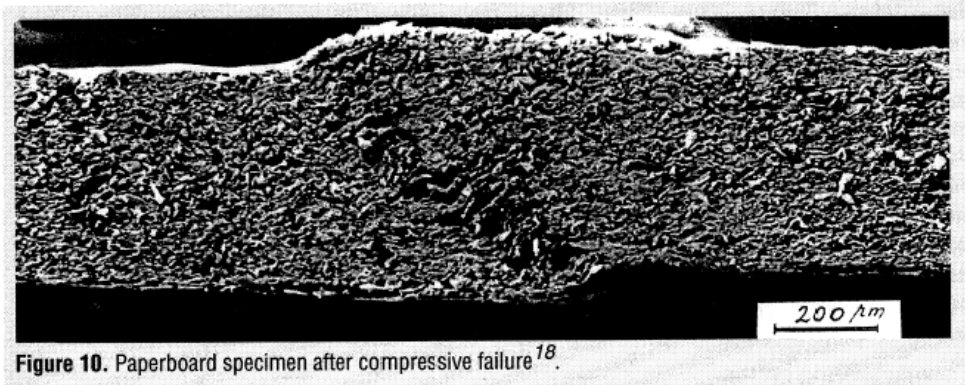


Figure 10. Paperboard specimen after compressive failure¹⁸.

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

SCT replacing RCT

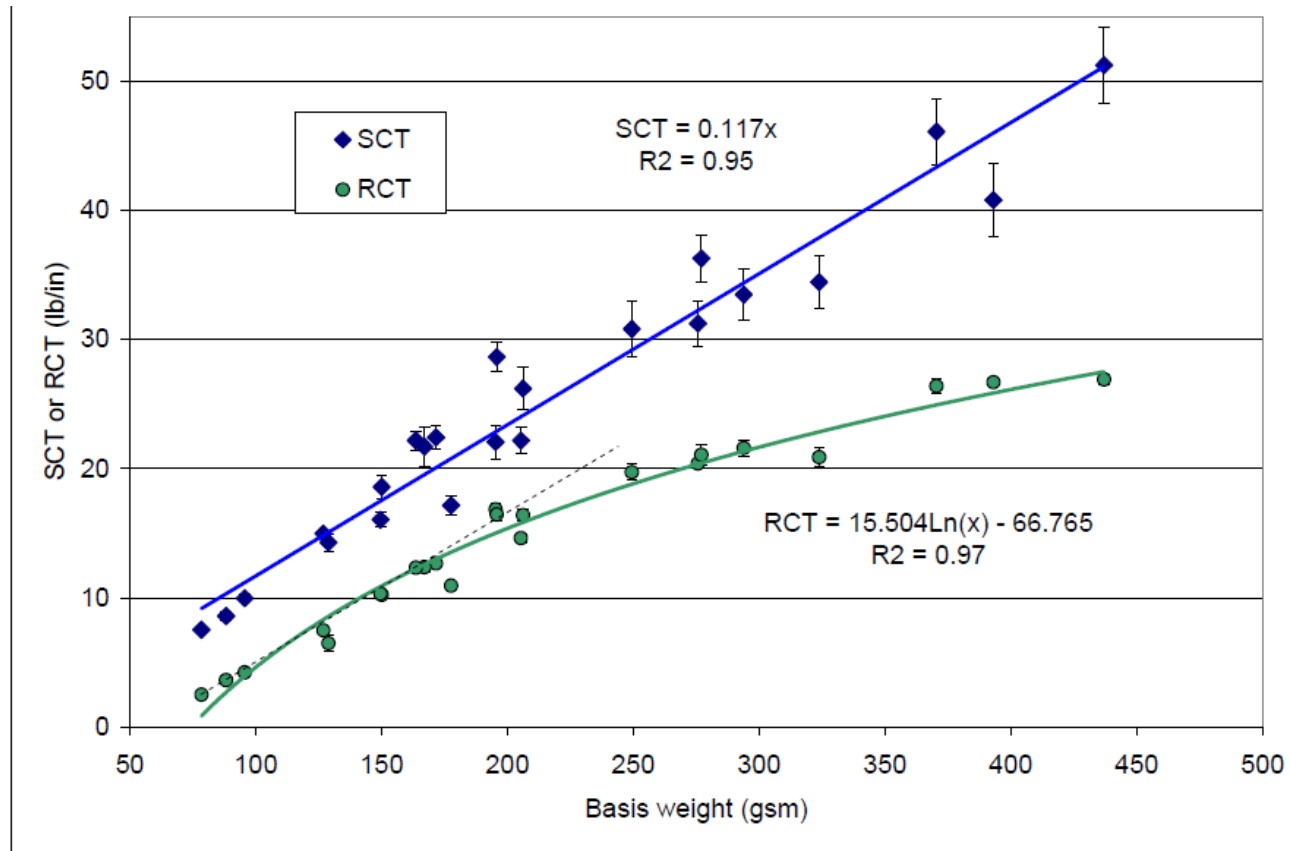
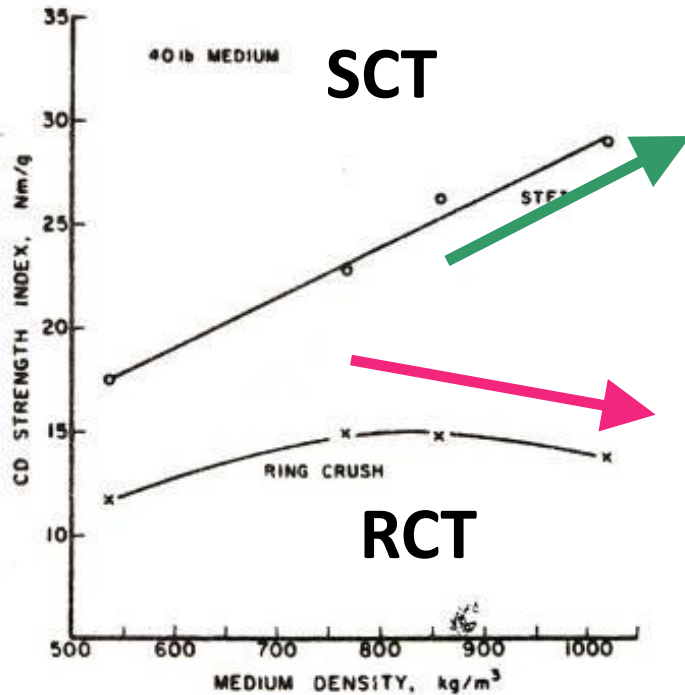


Figure 4. Comparison of SCT and RCT with basis weight of samples.

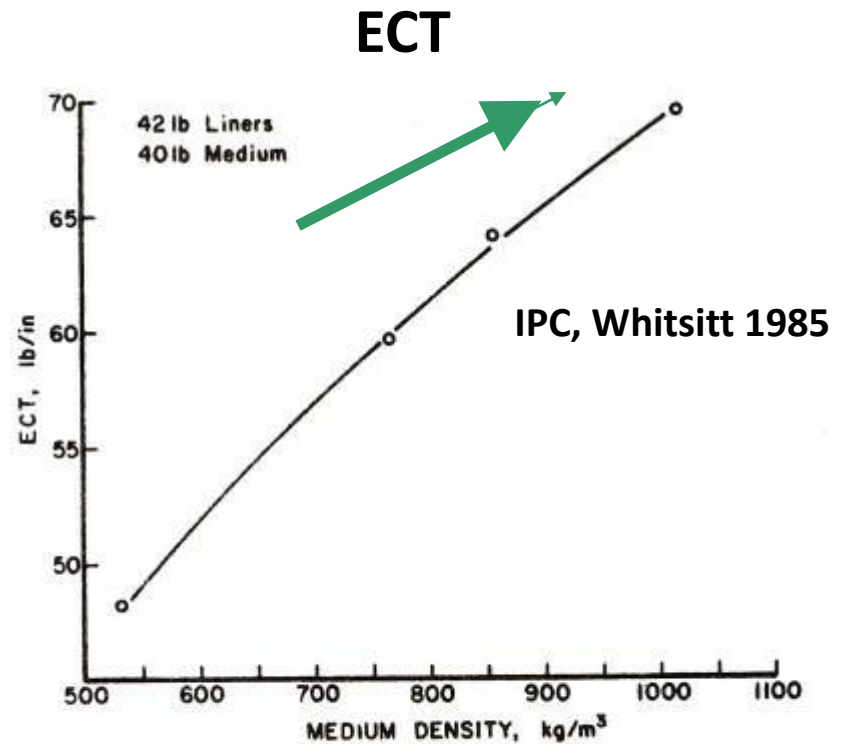
SCT tracks basis weight, RCT does not and is ~1/2 SCT, but error bars are smaller for RCT

from Popil Tappi PaperCon 2010

Examples of RCT not increasing with other properties as expected abound in the literature



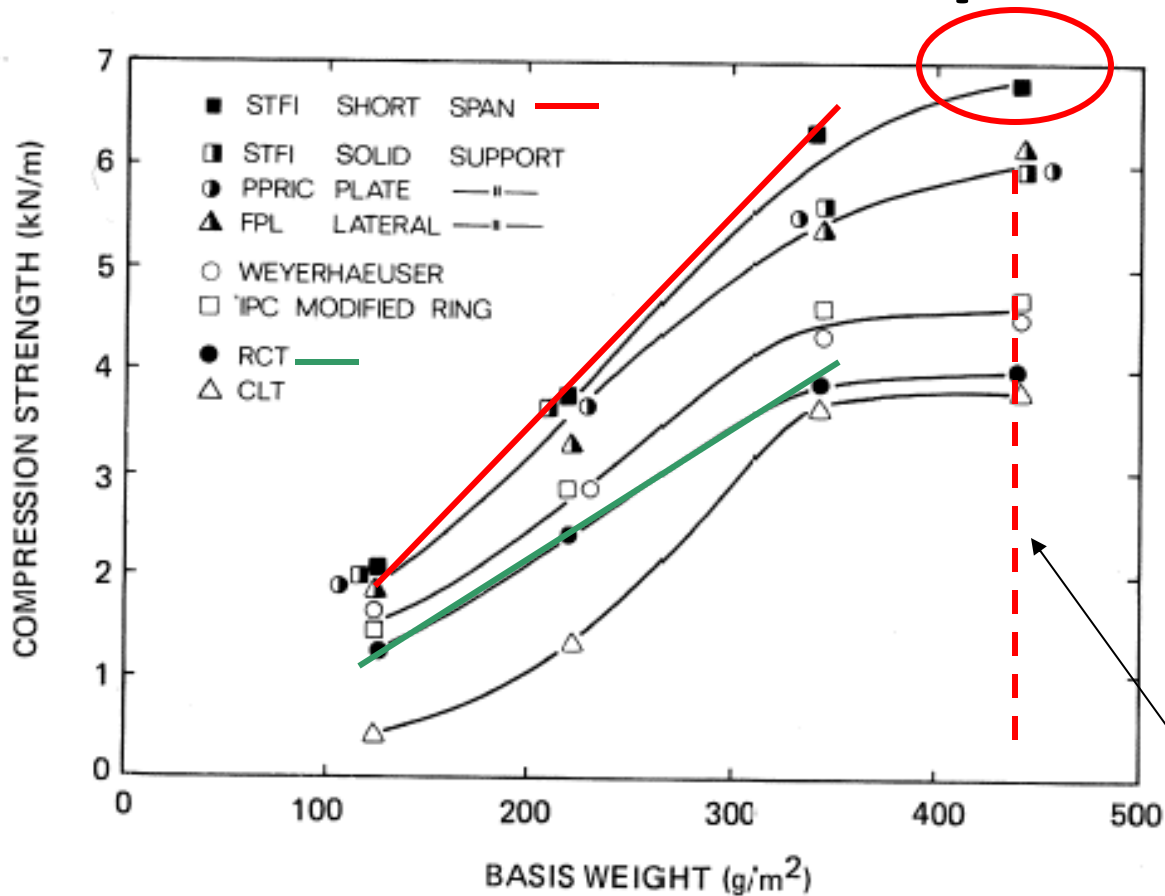
CD STFI and ring crush show different trends with increasing medium density.



Wet pressing medium to higher density increases the ECT of combined board.

ECT increased in accordance with SCT results.
RCT predicted an ECT decrease.

SCT and RCT comparison



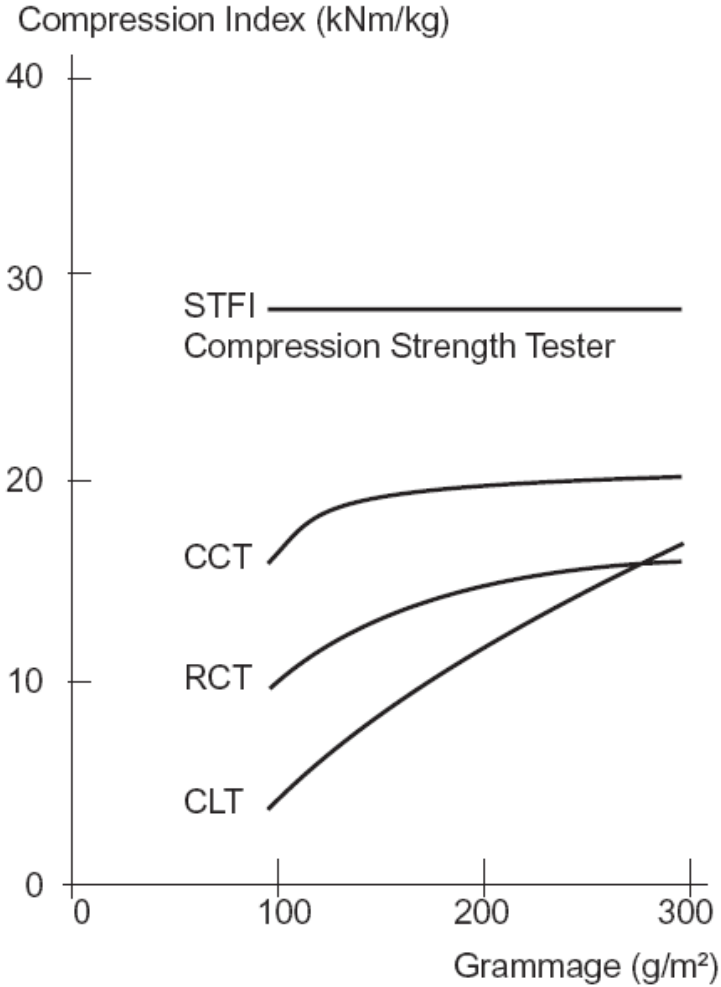
Note the difference between STFI and RCT (about 2 X)

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)

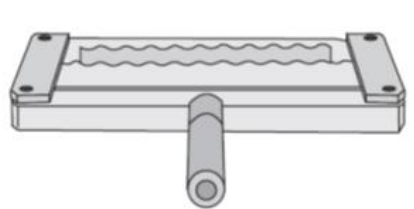
Fig. 31 Comparison between the compression strength of linerboard in the CD versus basis weight according to different test methods. (Courtesy of Christer Fellers, STFI, and Raj Seth, PPRIC, Stockholm, Sweden, and from Ref. 19.)

Comparison of various compression tests – effect of basis weight

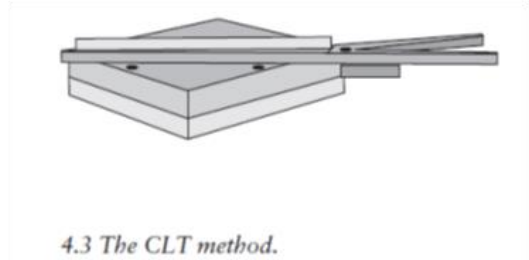


4.6 The compression index as a function of the grammage for the SCT, CCT, RCT and CLT tests.

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-



4.5 The CCT method.



4.3 The CLT method.

Excerpted from:
Malstrom, L&W handbook

Condebelt- Effects of higher density

Slide from: Christer Fellers, STFI

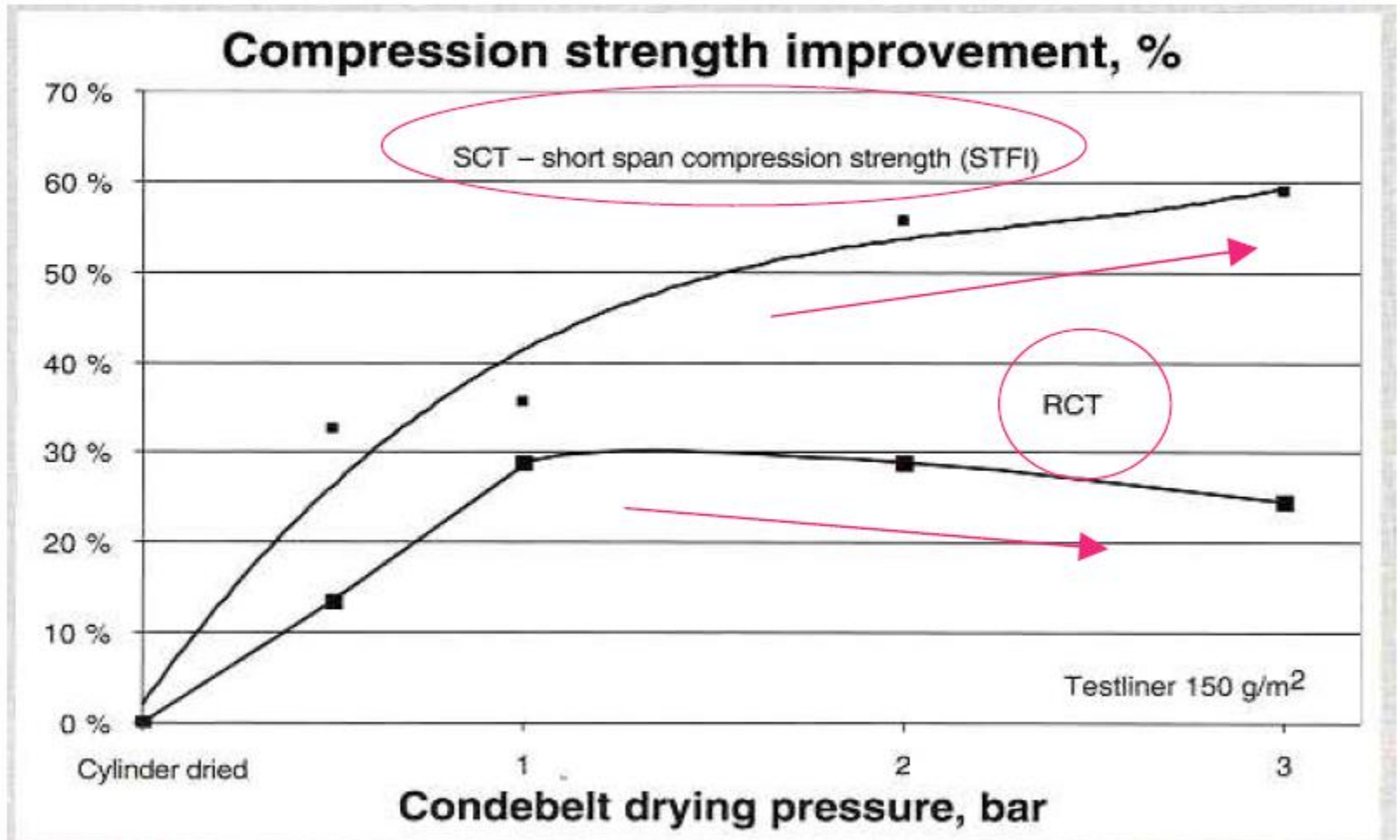


Figure 13. CD compression strengths improvement of Condebelt dried testliner compared with cylinder dried board¹⁰.

This data set shows the only way to change SCT is to change the furnish and beating of fibers

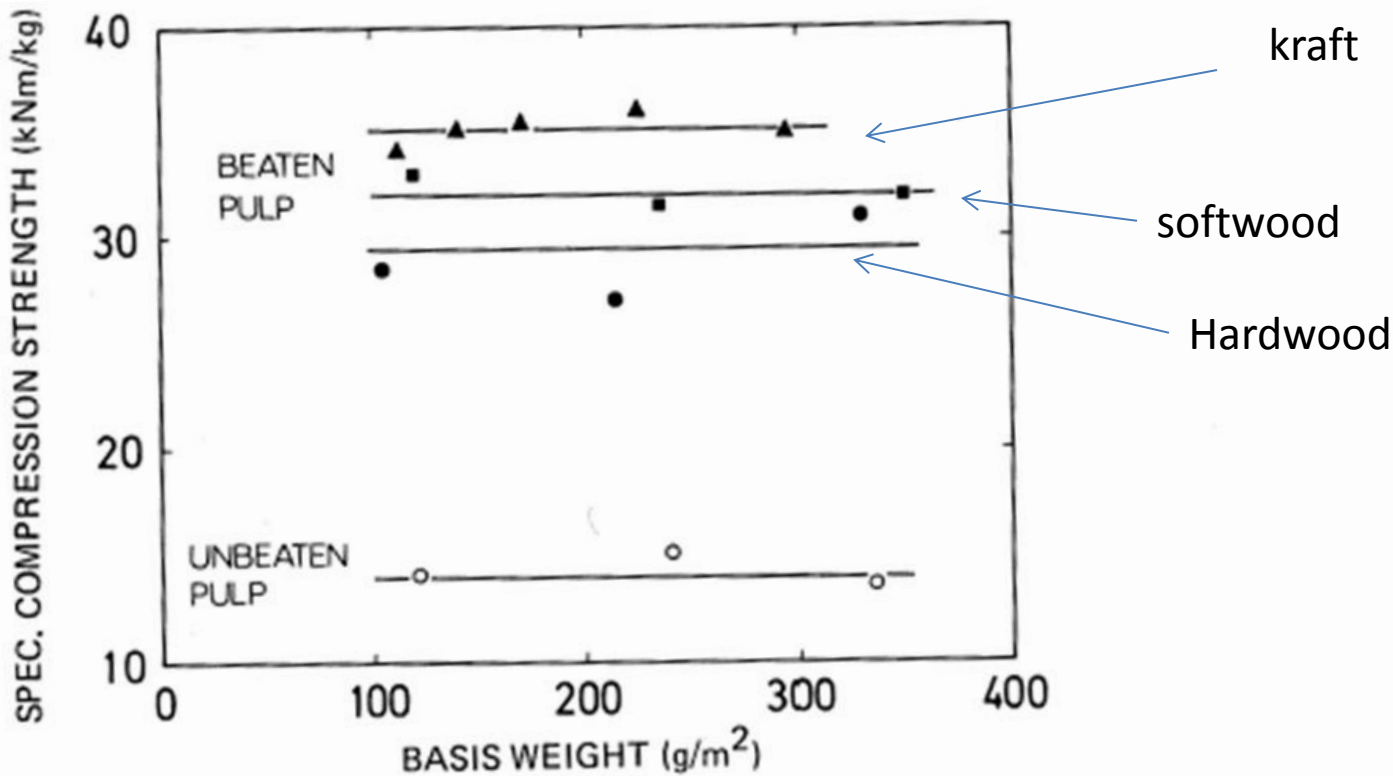


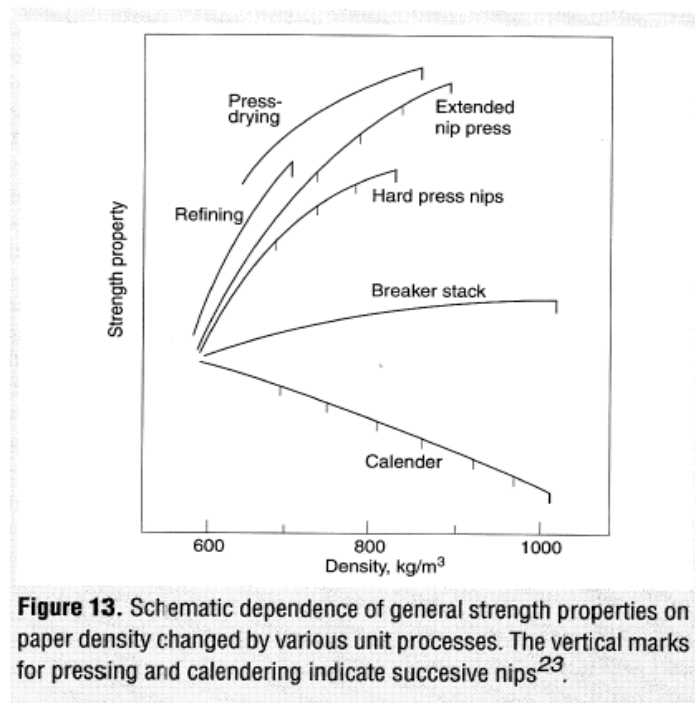
Fig. 16 Specific compression strength versus basis weight for handsheets according to the STFI short span test: ▲ kraft; ■ bleached softwood; ●○ bleached hardwood.

Effects of Processes on Compressive strength using SCT

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

	Compressive strength	Tensile strength
Beating	+	+
Fiber orientation	+ in MD - in CD	++ in MD -- in CD
Felted sheet	+ or ± 0	-
Wet pressing	+	+
Drying shrinkage	--	-
Humidity	--	-
Sizing	++	++

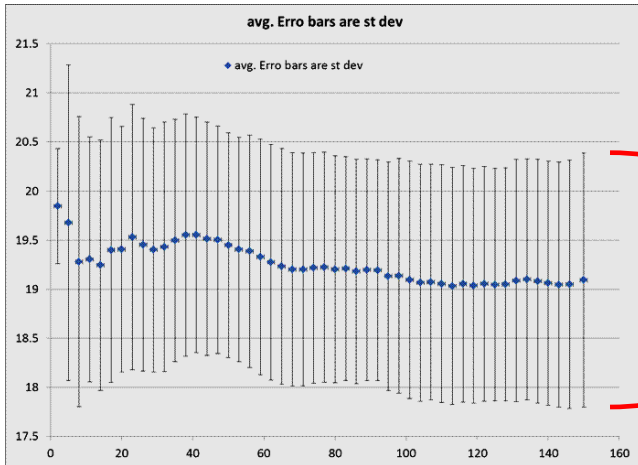
Table 5 compares the qualitative effect of some process variables on tensile and compressive strength. Beating and wet pressing improve compressive strength¹⁸. The



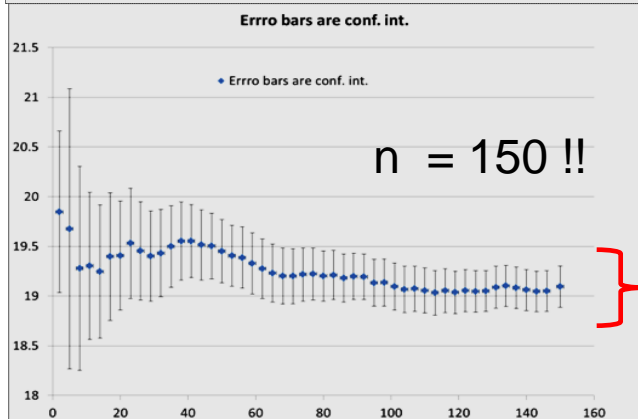
Excerpted from
“Paper Physics” by
Niskanen

Measuring SCT on the same sample on 2 different labs, an example, IPST Paper Analysis lab data

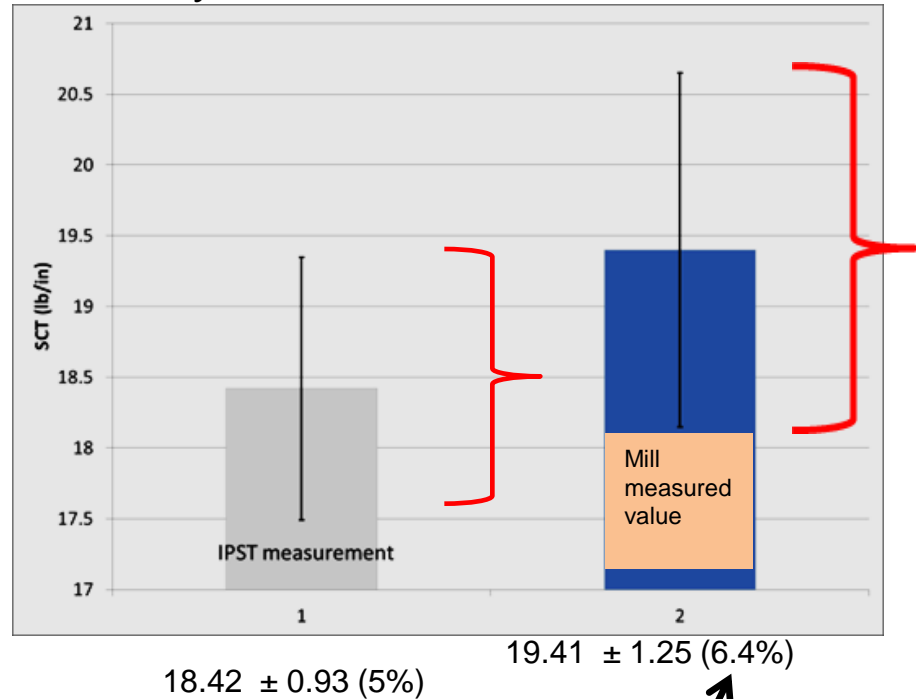
A mill measured the same sample 150 times in an attempt to improve accuracy !



Std. dev.



c.i.

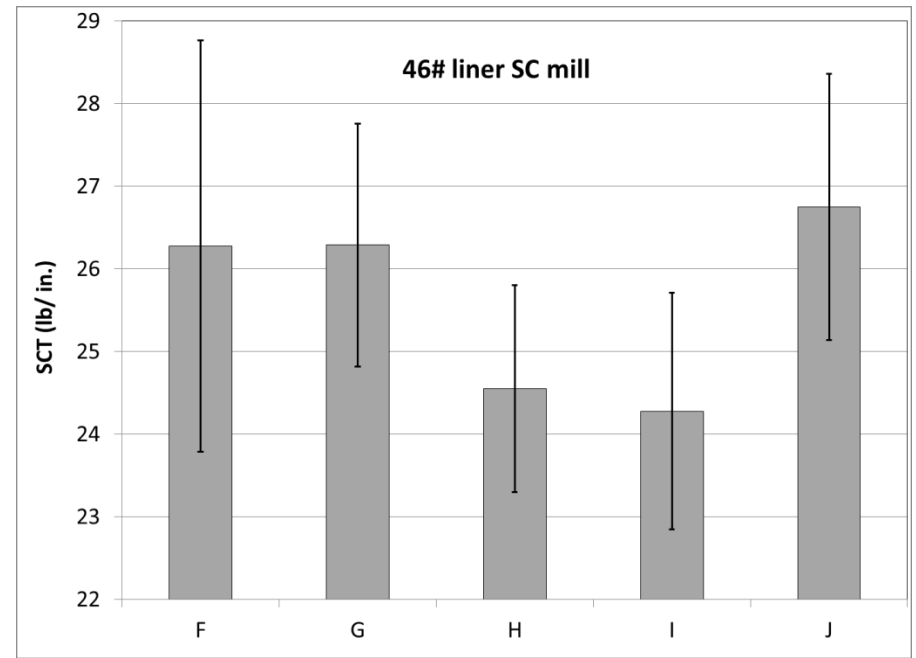
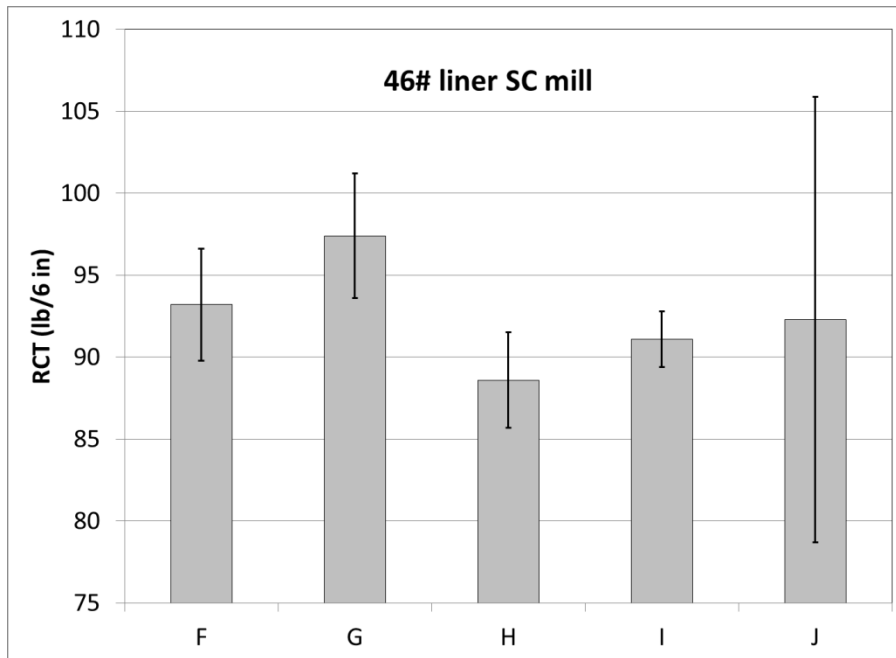


Error bars in c.i. decrease as $1/\sqrt{n}$, Tappi standard is **n = 10**

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

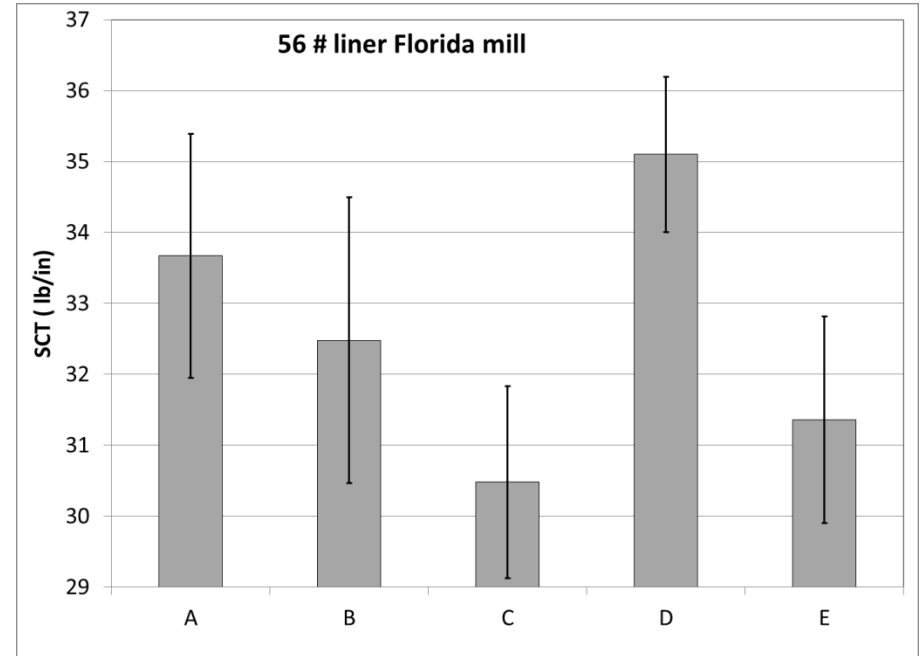
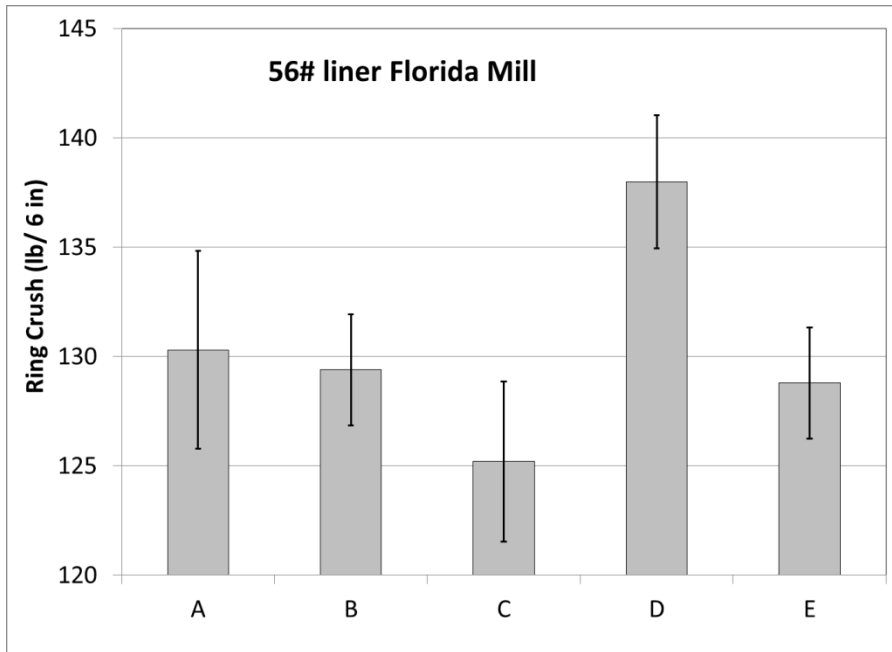
46# liner, same mill, same machine, different reels



RCT says Sample G > H, I SCT says they are all equal in strength

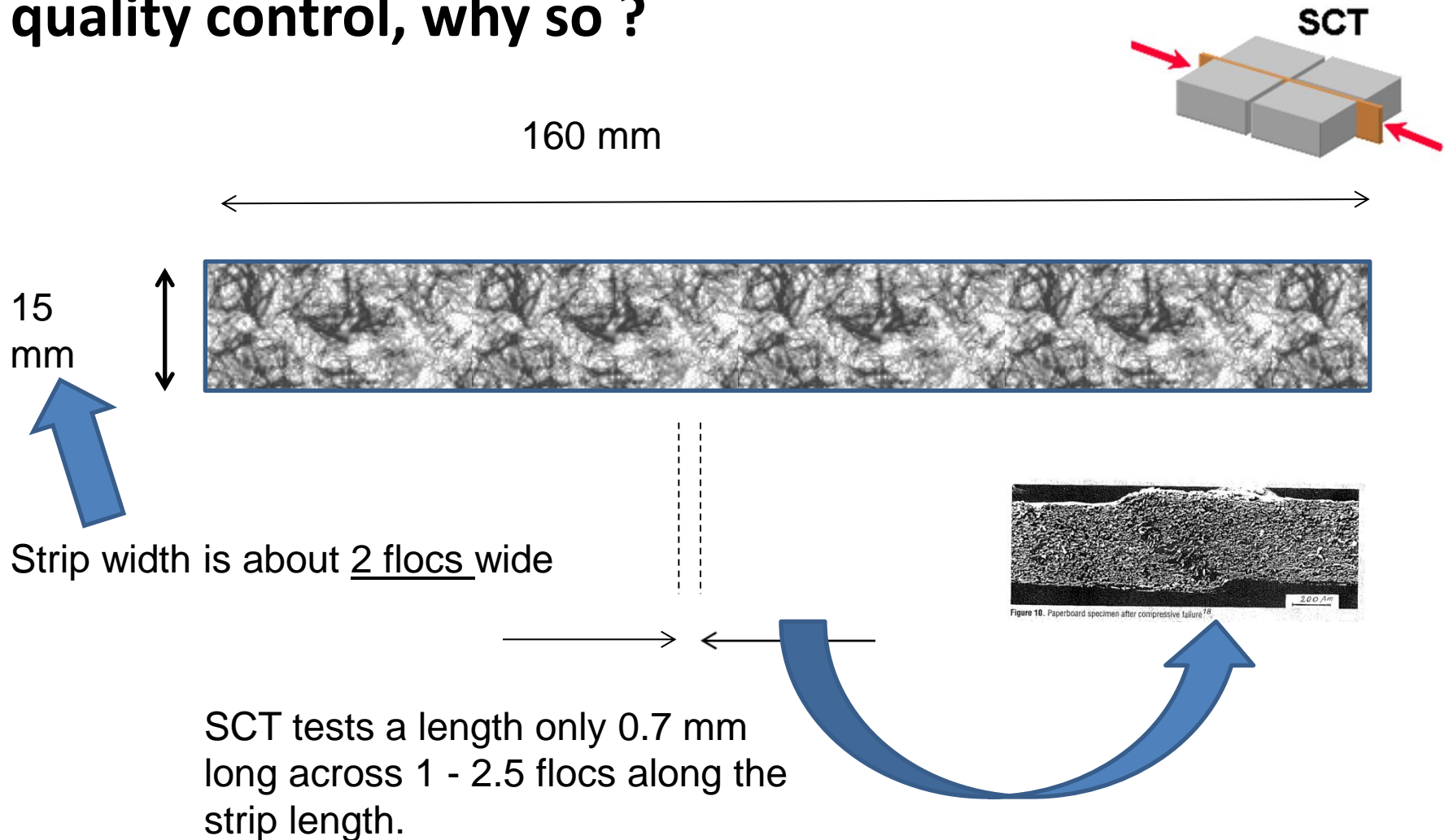
RCT vs SCT for quality control – “real life” examples 2

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 $\sim 7\%$, is still too high for quality control, why so ?



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

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

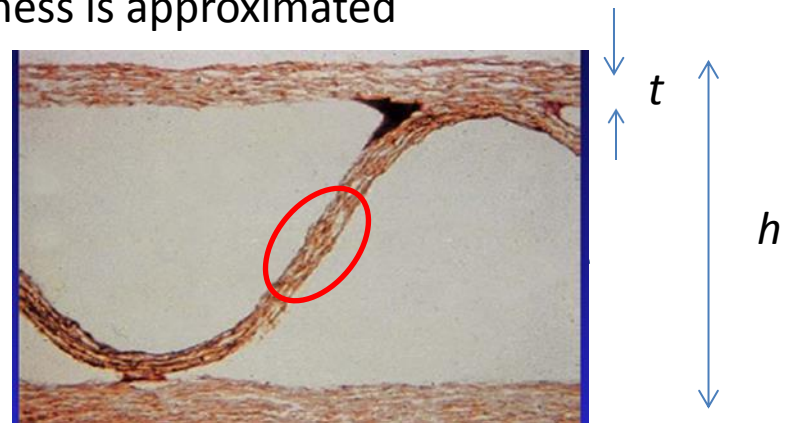
(“b” exponent forms here ensure units correctness)

Bending stiffness measurement may not be available so...

For a corrugated board the bending stiffness is approximated as a sandwich beam:

$$D_{MD,CD} \cong \frac{E_{MD,CD}th^2}{2}$$

The medium contributes to D less than 5% :



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

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

Simplified McKee equation derivation

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

$$\sqrt{\{D_{MD}D_{CD}\}} \cong ECT h^2$$

Note: Measurement of D is more sensitive to board crush than caliper h

Assume the typical $b = \frac{3}{4}$

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

$$\cong C' ECT^{3/4} (ECT h^2)^{1/4} Z^{1/2}$$

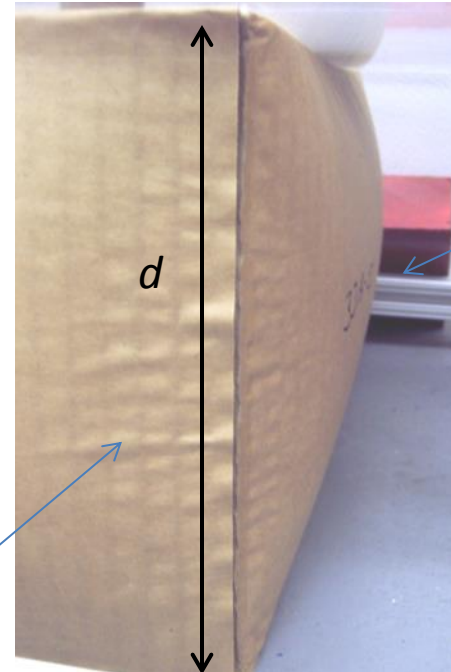
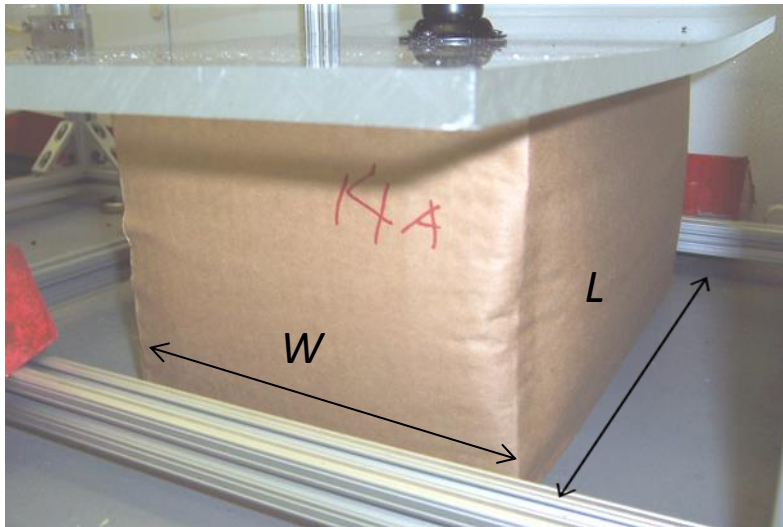
$$= C' ECT \sqrt{hZ}$$

Chalmers' DST (gaining popularity) measures MD twisting stiffness (by twisting board strips) which is also a sensitive indicator of **crush damage**



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

A box under vertical compression



Note how the panels bulge outward whenever d is high enough

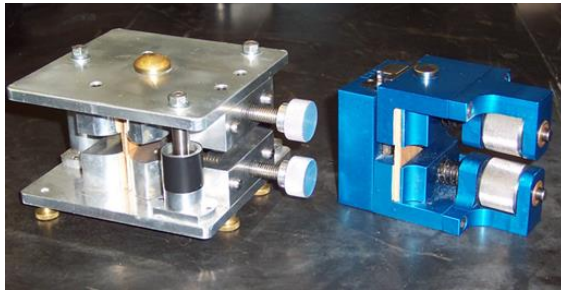
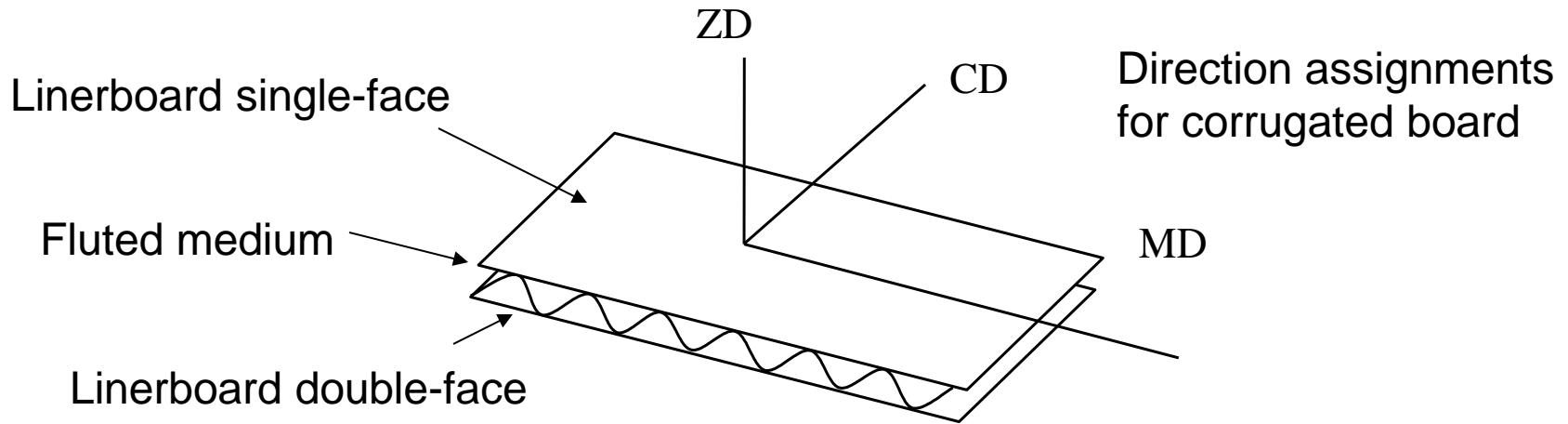
Note the interflute patterned buckling of the linerboards

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

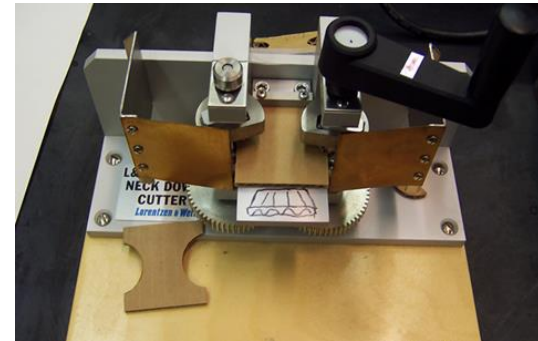
$$d \geq 2 \times (L + W)/7 \text{ or } d \geq Z/7$$

$$\text{Otherwise: } BCT \approx C'ECT \times Z$$

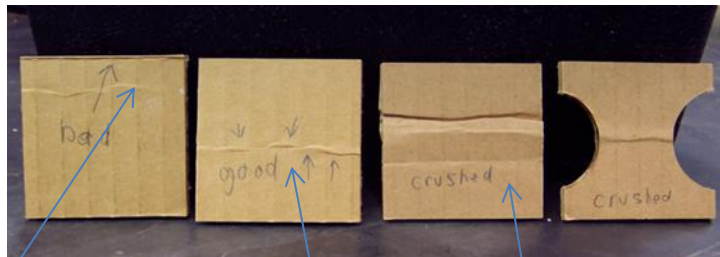
Corrugated board, ECT basics and problems



ECT test clamping fixtures (T 839)



“Neck down” sample cutter (T 838)



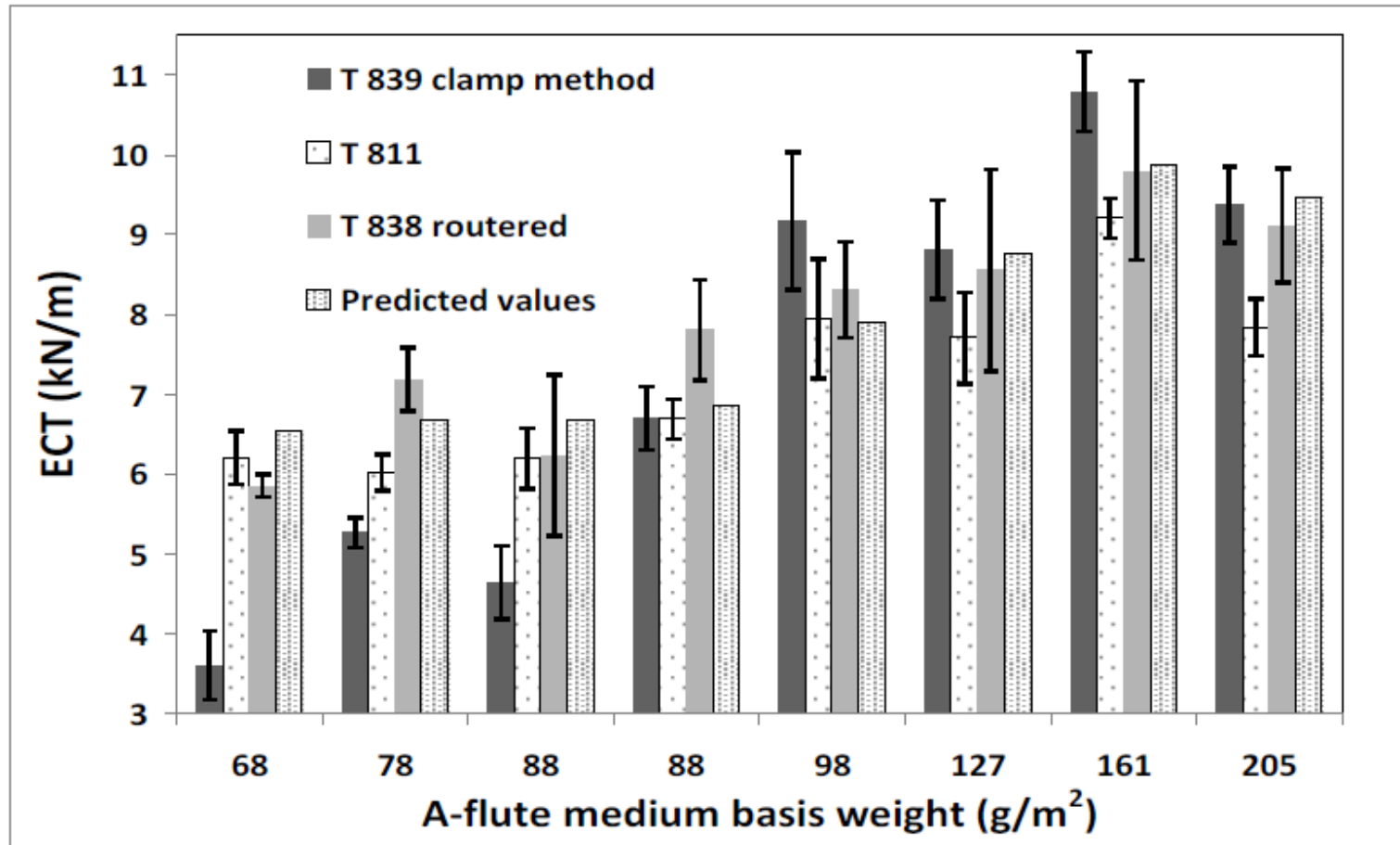
Rolled edge

OK, middle crease

Bowling liners

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

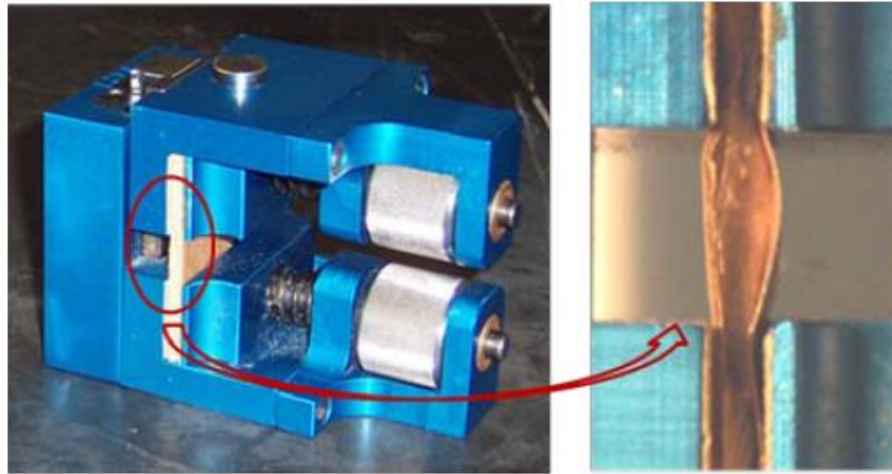
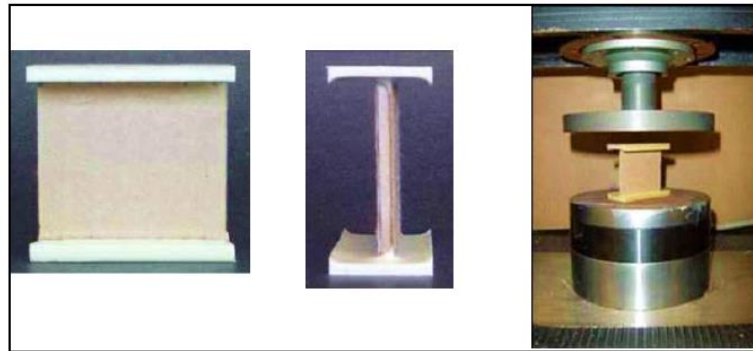


Figure 2. A common version of the T 839 ECT clamp fixture (left) with a close-up (right) of the unclamped region showing the convex bowing of the facings of a previously crushed 112 g/m² C-flute corrugated board undergoing vertical compression

Video studies at IPST have characterized interflute buckling during ECT



← Experimental set-up

When buckling occurs, we can have a *better* predictor than: $ECT = C\{2 \times SCT_{liner} + \alpha SCT_{medium}\}$

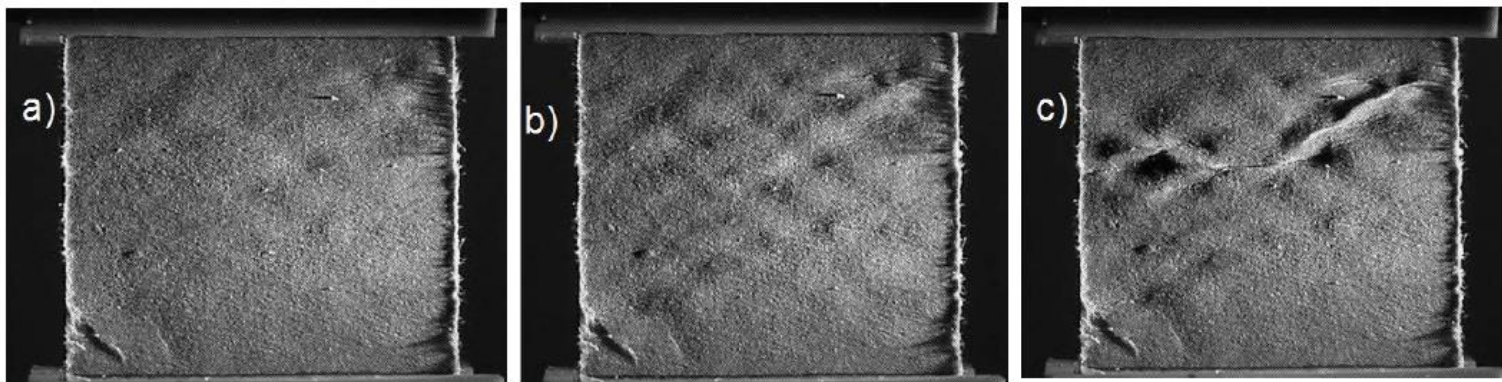


Figure 13. Excerpted time sequence video snapshots of a glancing angle illuminated ECT test of a 35-26C flute board: a), 5.7 kN/m load, 1.3% strain, some buckling is evident b), peak load 6.7 kN/m, 1.6% c), post failure 4.5 kN/m, 2.1% , crease forms joining micro-plate buckling crests

How to fit the McKee equation constants:

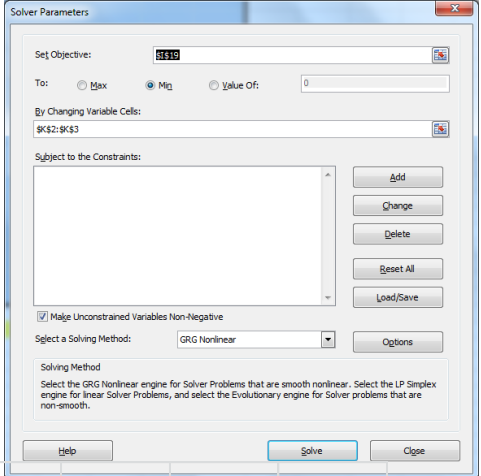
1. Get BCT , ECT , Bending stiffness D_{MD} and D_{CD} and perimeter Z data for a set of similar boxes of interest. At least 6 data points are required covering a range of BCT values. Enter as data in separate columns into Excel.
2. Keep values for the McKee \mathbf{C} and \mathbf{b} in a separate area of the spreadsheet.
3. Assume the usual McKee constants for $\mathbf{C} = 2.028$ and $\mathbf{b} = 0.75$, calculate in a separate column the predicted McKee BCT using:

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

4. Calculate in a separate column, ΔBCT = the absolute value of the differences between actual and predicted McKee BCT's.
5. Calculate the sum of the ΔBCT errors in a separate cell.
6. Use Excel® *Solver* function to Minimize the sum ΔBCT error by changing the cells containing the McKee \mathbf{C} and \mathbf{b} → function returns new \mathbf{C} and \mathbf{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

1	A	B	C	D	E	F	G	H	I	J
2									McKee C =	1.87028
3									McKee b =	0.791213
4										
5	Sample ID	BCT	ECT	D MD	D CD	Z	McKee	error	original McKee	
6		lbs	lb/in	lb -in	lb -in	in	prediction	ΔBCT	values	
7										
8	Box 1	956	42	141	94.0	48	924.25	31.75	759.31	
9	Box 2	1150	56	135	90.0	48	1150.00	0.00	931.97	
10	Box 3	1100	47	136	90.7	48	1002.68	97.32	818.72	
11	Box 4	975	48	163	108.7	48	1058.81	83.81	870.27	
12	Box 5	967	44	148	98.7	48	968.65	1.65	795.85	
13	Box 6	836	41	136	90.7	48	899.98	63.98	739.01	
14	Box 7	1039	45	157	104.7	48	998.25	40.75	821.41	
15	Box 8	856	47	146	97.3	48	1017.65	161.65	833.37	
16	Box 9	1078	53	143	95.3	48	1114.29	36.29	907.23	
17	Box 10	1234	57	140	93.3	48	1175.11	58.89	953.05	
18										
19							sum of errors =		576.0885757	

McKee fit constants kept in these cells, start with 2.028 and b = 0.75, these become changed by Solver

absolute value of difference between predicted and actual BCT values = ABS(predicted -

McKee prediction is calculated using the constants in the box :
 McKee pred. =

$$\$J\$1 * C7^{\wedge} \$J\$2 * (\text{SQRT}(D7 * E7)^{\wedge} (1 - \$J\$2) * F7^{\wedge} (2 * \$J\$2 - 1))$$

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
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