The trouble with Ring Crush and how SCT and Autoline save the day

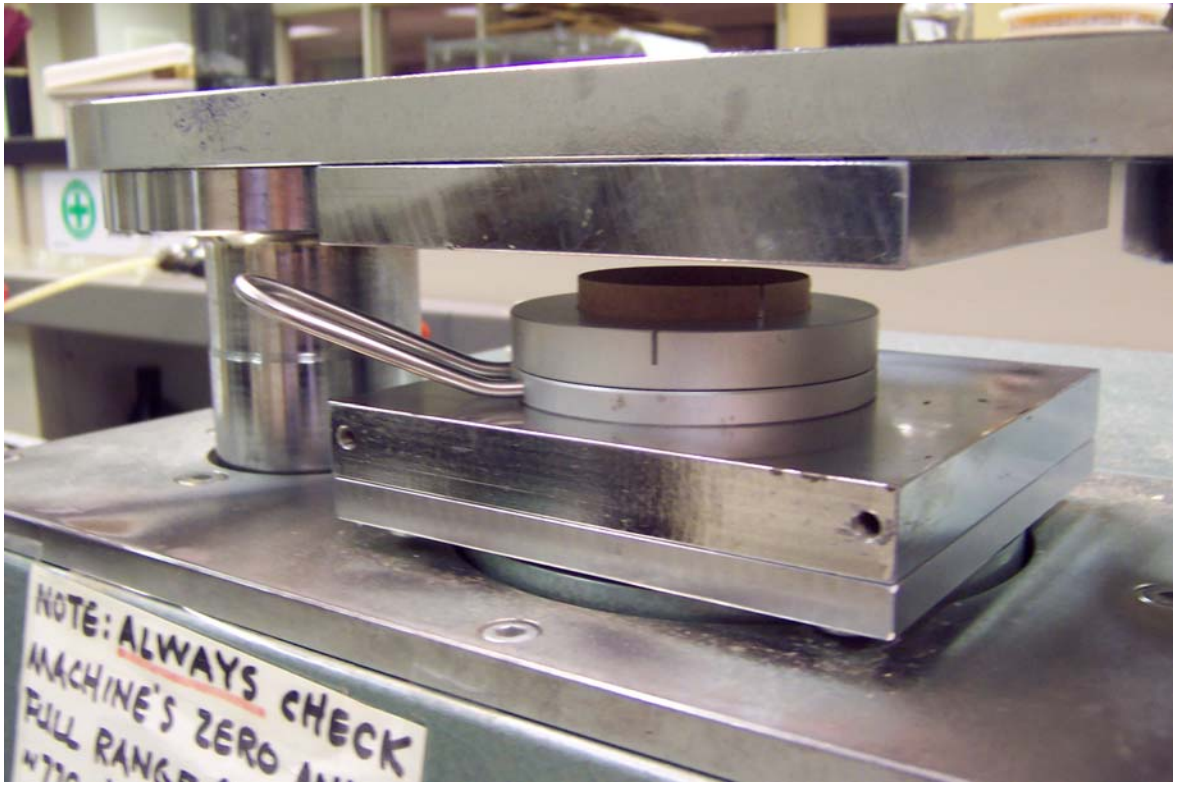
Who or what is Roman Popil ?

- Georgia Tech/IPST senior research scientist in Atlanta since 2002
- Principal Investigator of Engineered Packaging research consortium program
- Manager of IPST Paper Analysis lab for contract testing and research
- Been in paper industry R&D since 1986: MacMillan Bloedel, Honeywell-measurex
- PhD in plasma physics from University of British Columbia

What you will see in this talk ?

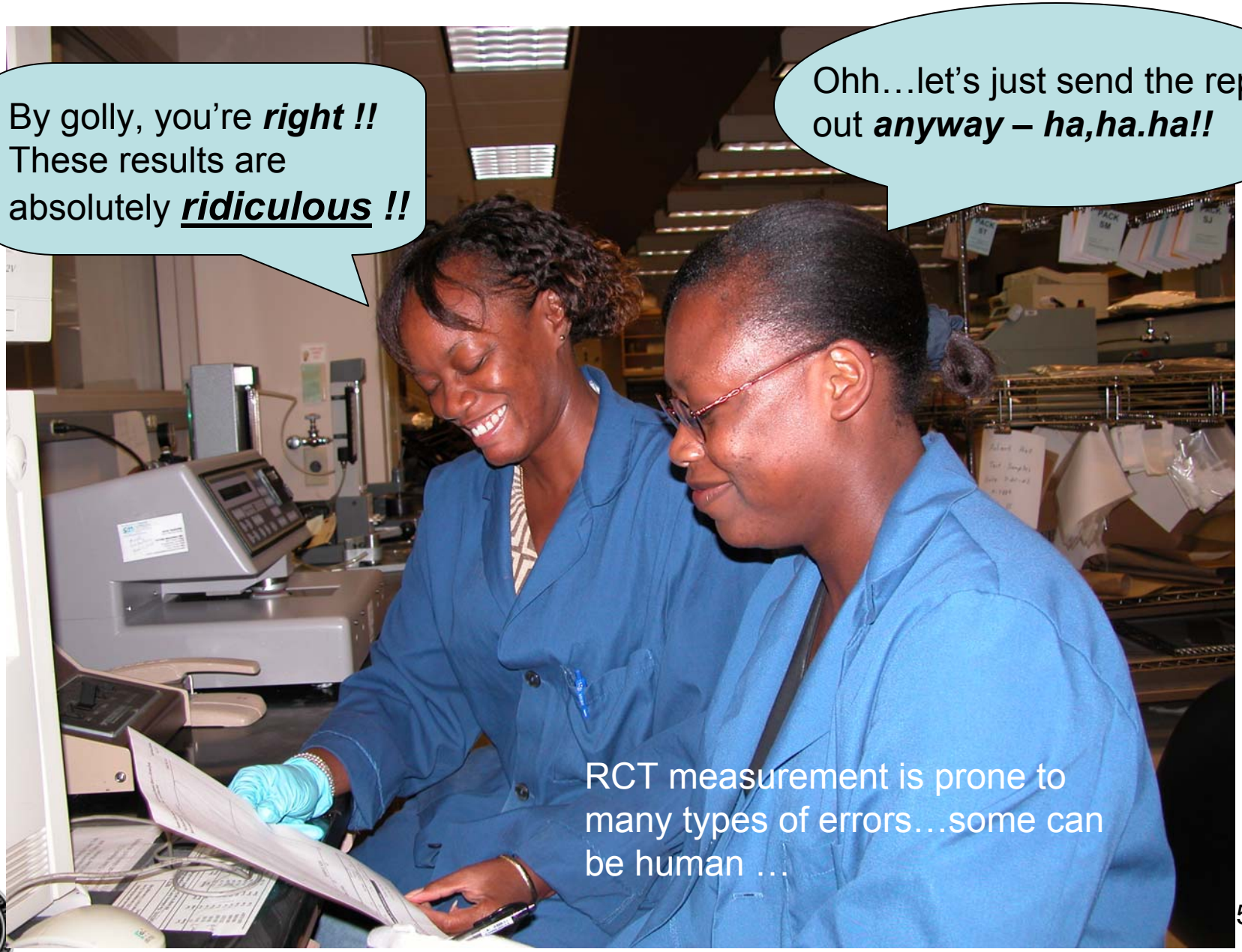
- quick look why RCT is a not a good measurement
- Why SCT is better for product optimization
- How to use the SCT for product development
- How the TSI with BW and SCT can be used to predict RCT anyway (if you must have RCT)
- How to implement in an Autoline to predict RCT

Ring Crush method



Sample and holder between compression platens – what could go wrong ??

The trouble of RCT measurement…



But…the linerboard industry still sells by the Ring Crush spec

- manual measurement, cannot be automated
- requires accurate cutting of sample – can't easily do handsheets
- handling of the sample
- measurement of sample caliper and selection of the correct fixture insert
- it is actually a combination of compression and…
- bending failure, this is not good for optimization programs

Ford Highland Park plant – Model T magneto assembly line

Why measure compression strength of medium or linerboard ?

A warehouse of stacked boxes, the customer wants the boxes to remain stacked and protect the contents

What happens instead….

ECT creep test →

Linerboard shows a buckling pattern from vertical applied load

BCT creep test →

Strains increase until box panels buckle,fold and collapse

Box performance is predicted based on strength of the components of the board

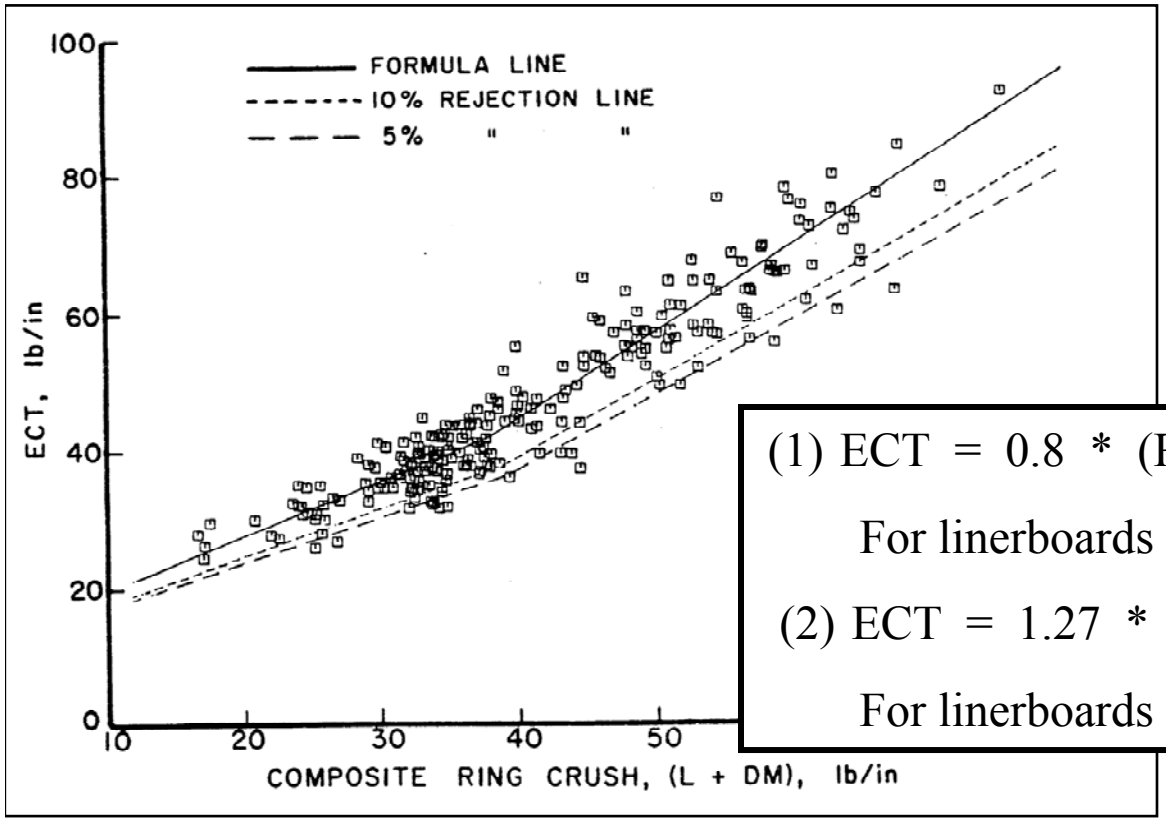


Figure 1) Whitsitt Relationship of ECT to Composite Ring Crush

Whitsitt 1983, IPC

Related ECT to RCT:

(1) $ECT = 0.8 * (RCT_1 + RCT_2 + \alpha RCT_{Med}) + 12$

For linerboards > 42 lb/msf

(2) $ECT = 1.27 * (RCT_1 + RCT_2 + \alpha RCT_{Med}) - 6$

For linerboards < 42 lb/msf

Different equations for different basis weights…

ECT predictive models based on SCT are simpler

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

$$C \approx 0.7$$

Simplified McKee equation for box compression:

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

$$BCT = C'ECT\sqrt{t \times Z}$$

$$C' = 5.87$$

Box footprint perimeter

Corrugated board caliper

RCT vs SCT

For RCT:


Frank

1. Frank, Benjamin (Tappi Journal 2007) RCT has lower coefficient of variation, correlation with ECT is better because:

   test occurs over a larger test piece more averaging,

   Bending occurs in ECT and box failure

Against RCT:

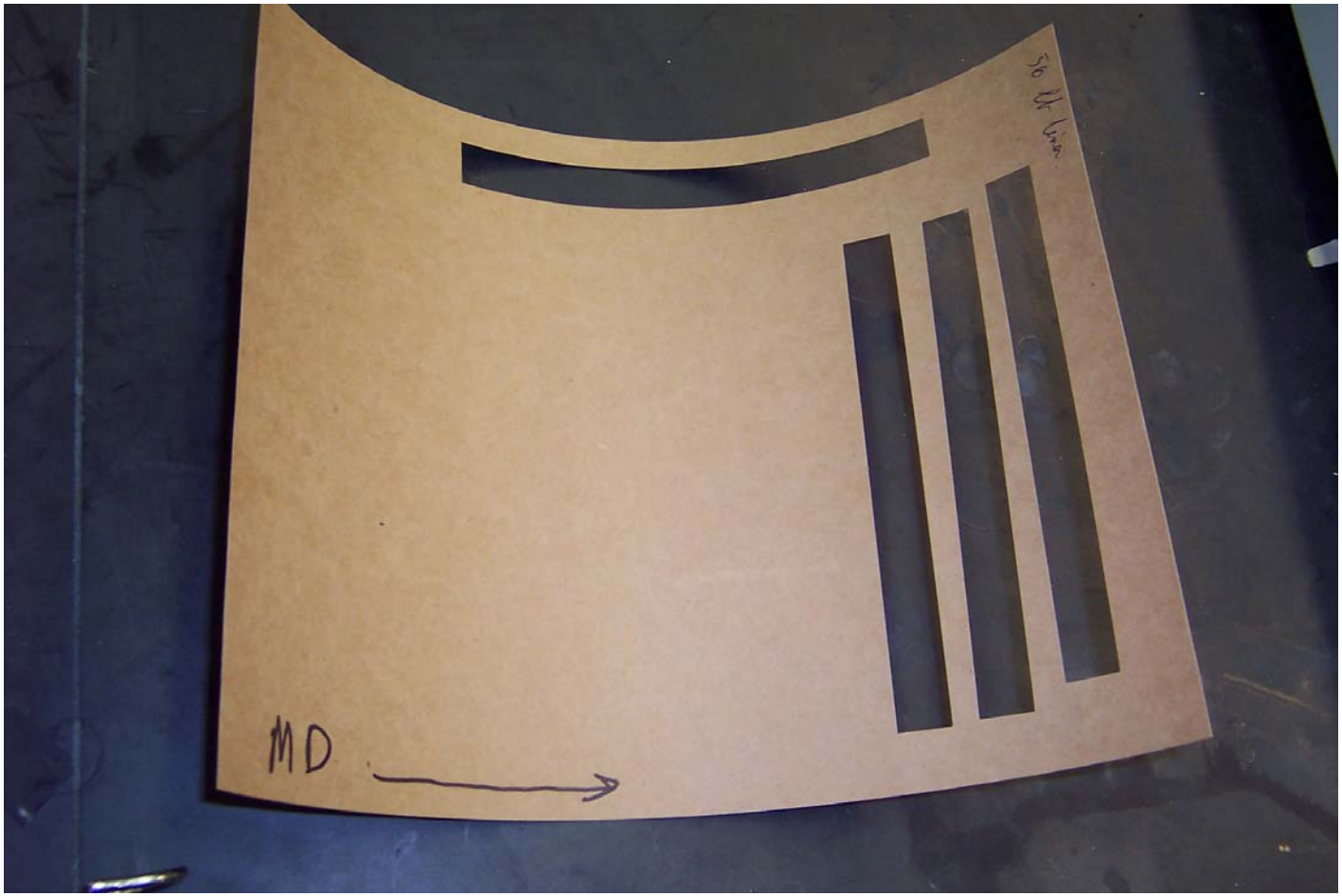
2. Seth, Fellers etc., SCT is the intrinsic compression strength of the linerboard,
3. Variability is inherent in the linerboard due to contaminants, defects, formation
4. SCT is more easily optimized through wet end deification, furnish changes or refining
5. RCT is not available on in-line automated testing machines.

RCT is supposed to predict BCT

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

BCT test

Then which way is the length of the test strip for CD and MD tests ?

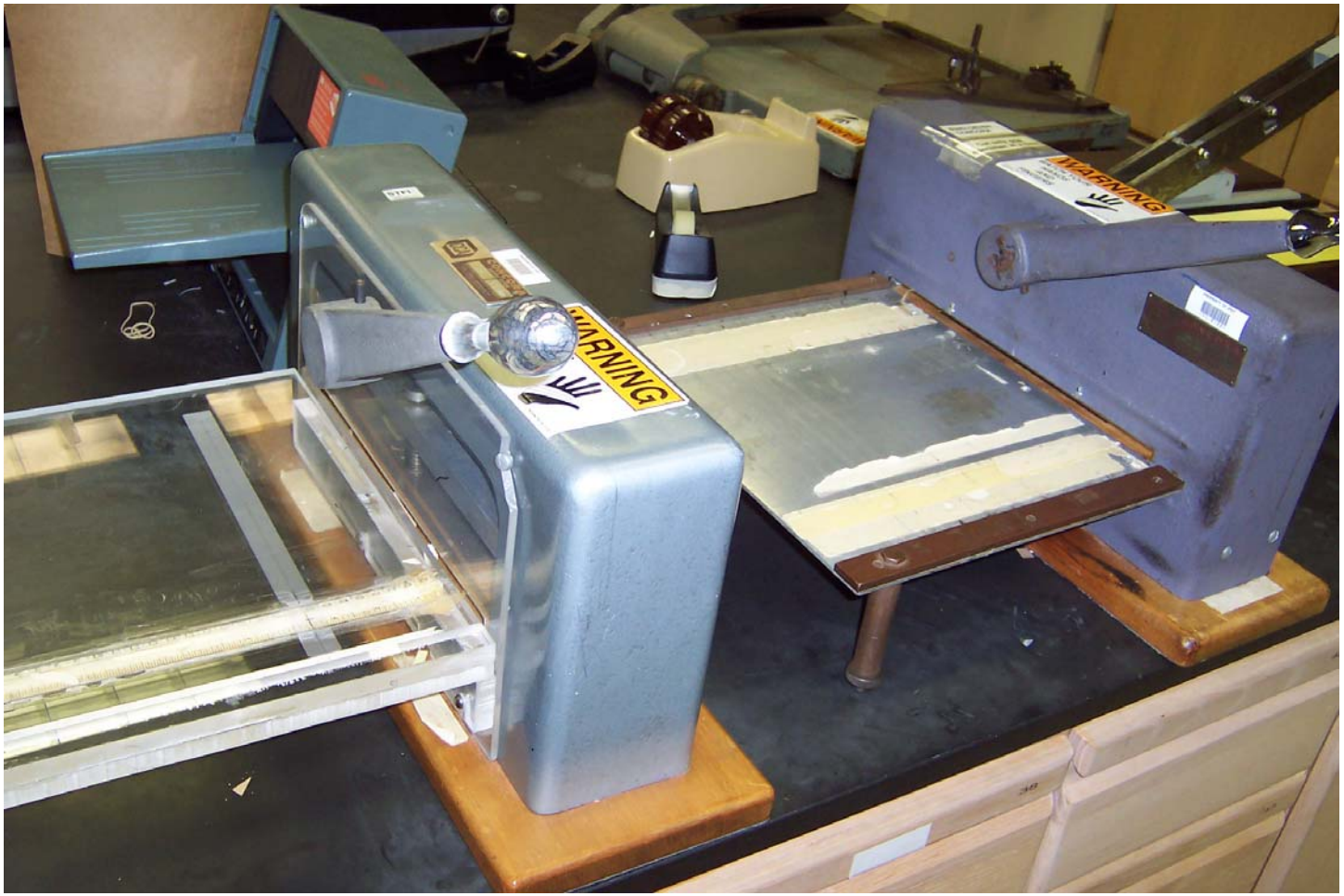


Can you cut the strips exactly along MD or CD, should they be together or spread apart ?

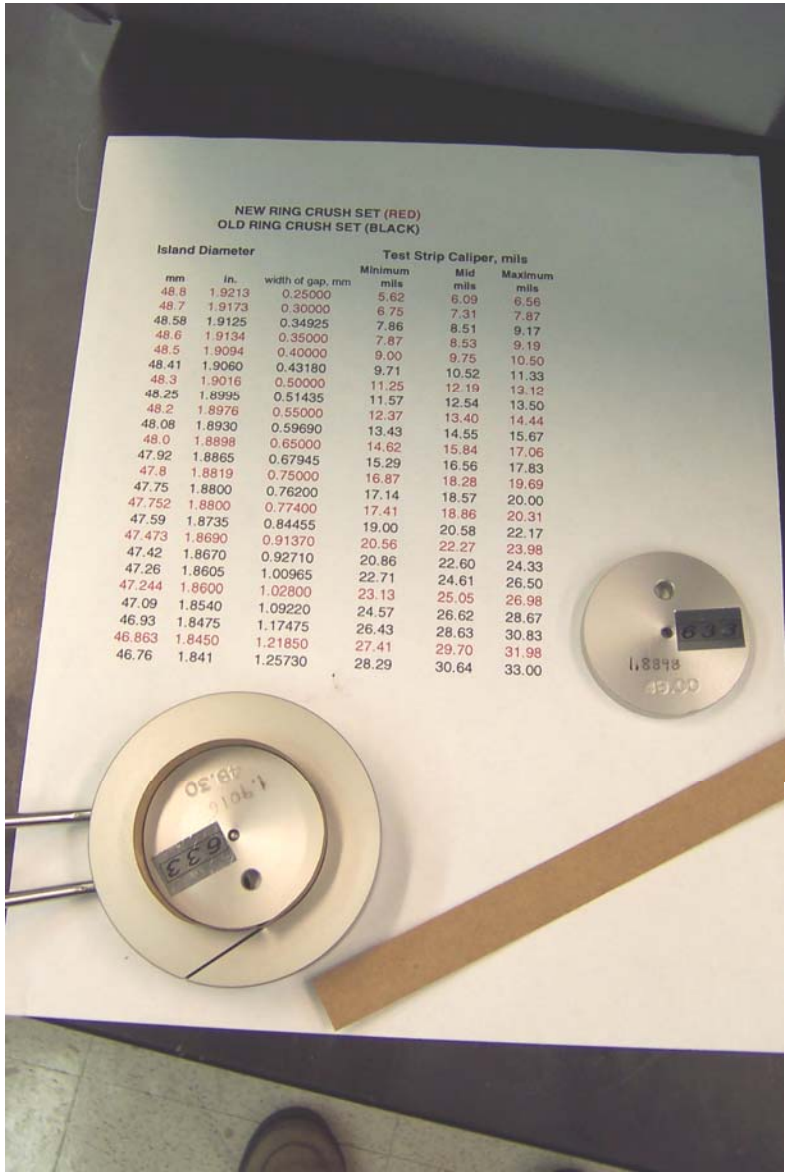
Cutter for 15 mm wide 4 inch span samples

However, parallel edges not so critical for SCT can use a ratchet cutter for consecutively adjacent strips handy for handsheet samples

Got to use a different cutter for ring crush though…



Both look the same – need to read the small label !



Ring Crush

Samples are 6 inches long and **12.5 mm (1/2”)** wide

Use different center “island” inserts depending on the caliper for the specimen

Calm cool technicians required with dry hands

IPST data ex Mike Schaepe

I sure hope you like my data !

This figure shows that at both the heavy weight and light weight ends of the graph RC and STFI diverge due to damage and buckling respectively

Short Span Compression Test is SCT

- STFI = SVENSKA TRÄFORSKNINGSINSTITUTET (Swedish Forest Products Research Laboratory , now renamed "*Inventia*")

Test method was developed by Christer Fellers in the late 1970's

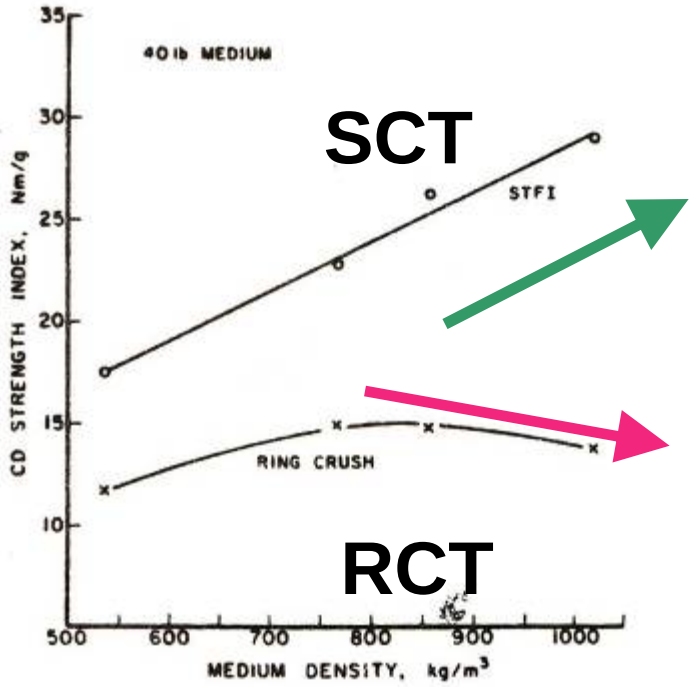
The short span compression test is **not** "STFI"

Christer gets another award from Jeffrey Suhling

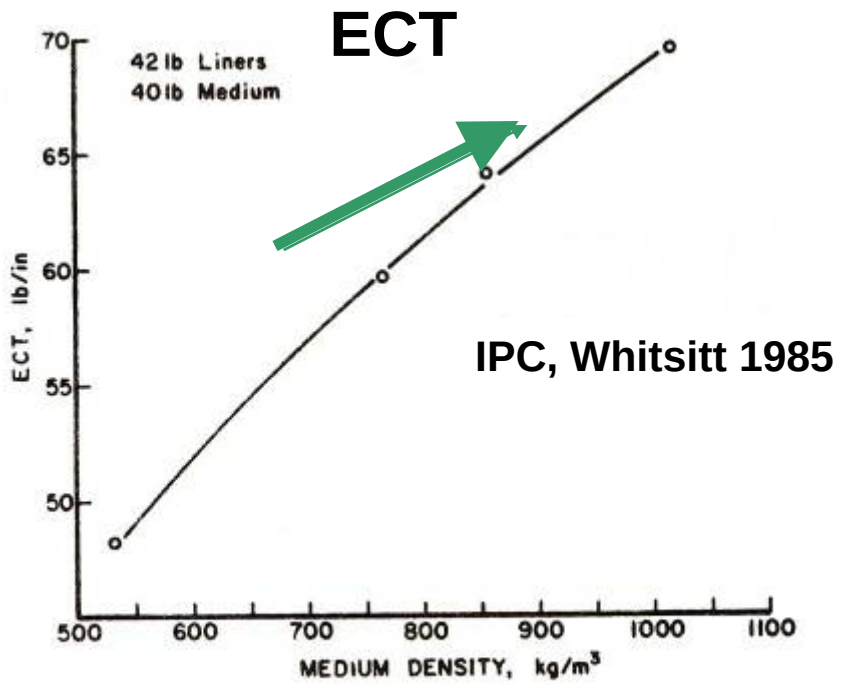
Fun Fact

- Compression tests are all called *CT, e.g. FCT, ECT, BCT, but SCT is rather new…
- Many call the short span compression test SCT as “STFI”, pronounced “stiffy”
- Why is this a ***bad*** idea ??
- Answer: _____

Corrugated medium comparison – SCT and RCT



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

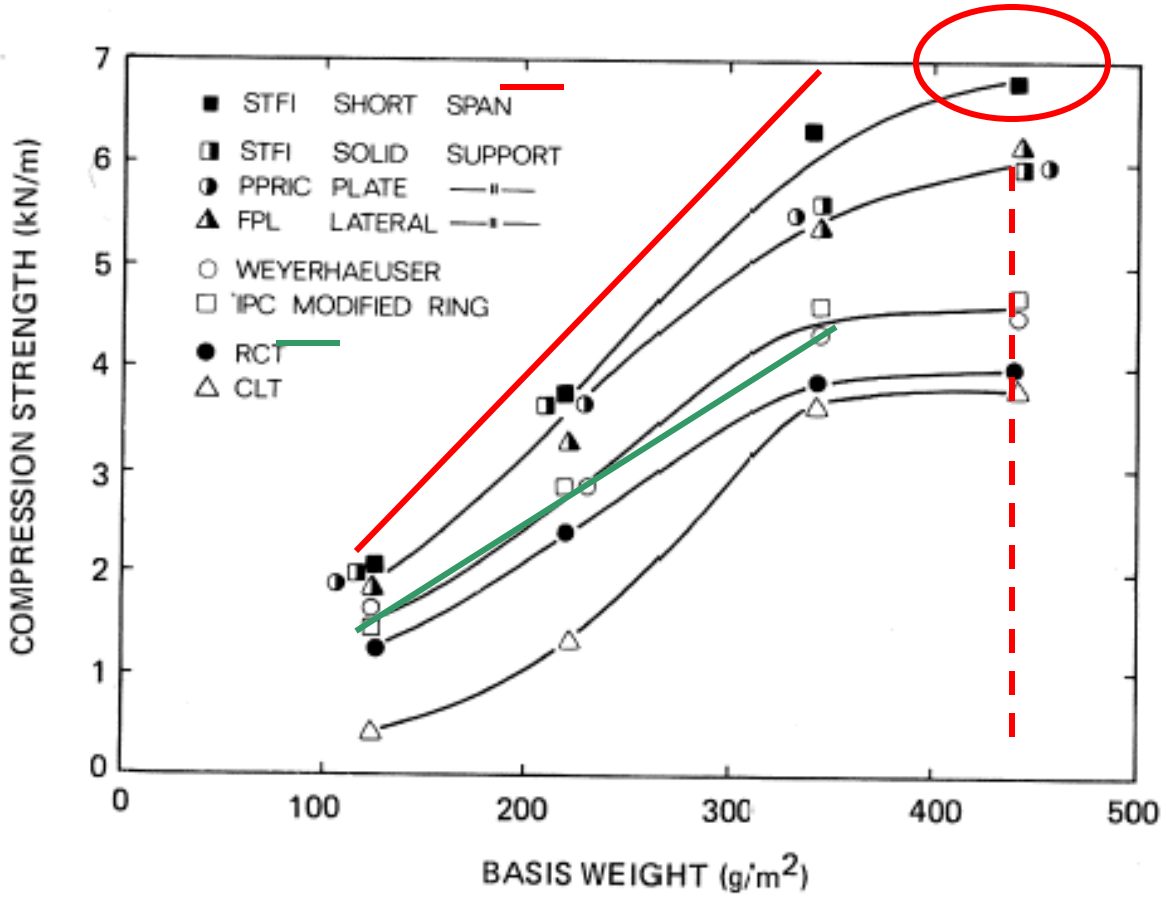


IPC, Whitsitt 1985

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

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

Conclusion:
SCT is better suited for low grammage corrugated medium than RCT.

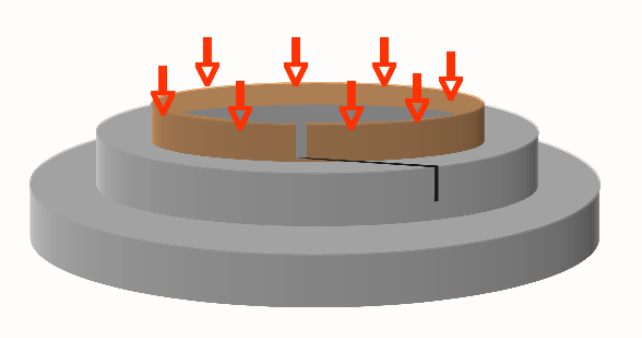


Note the difference between STFI and RCT (about 2 X)

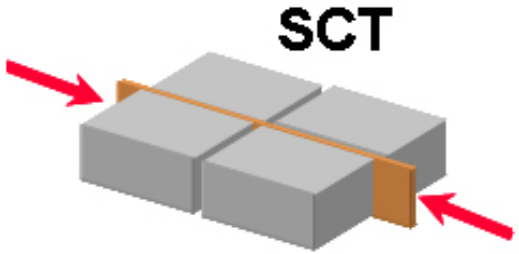
At very high basis weights and calipers, get slip: more surface compression

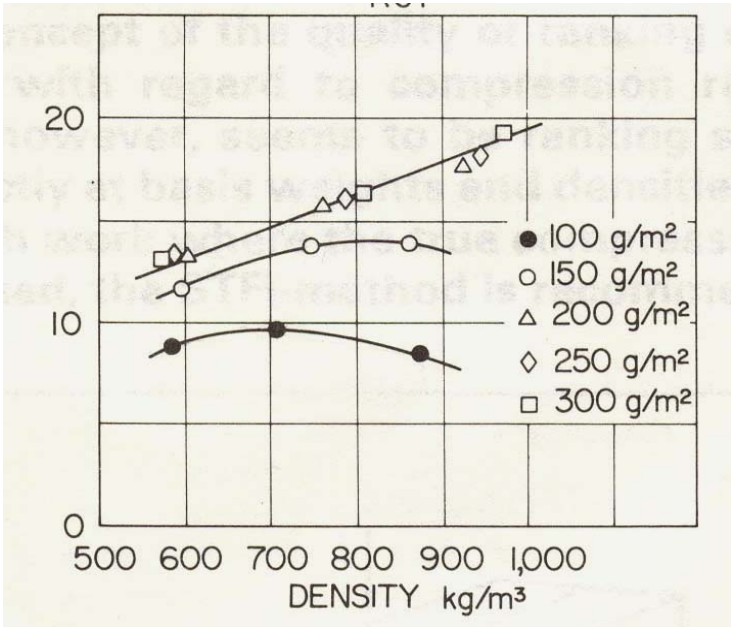
Fig. 31 Comparison between the compression strength of linerboard in the CD versus basis weight according to different test methods. (Courtesy of Christer Fellers, STFI, and Raj Seth, PPRIC, Stockholm, Sweden, and from Ref. 19.)

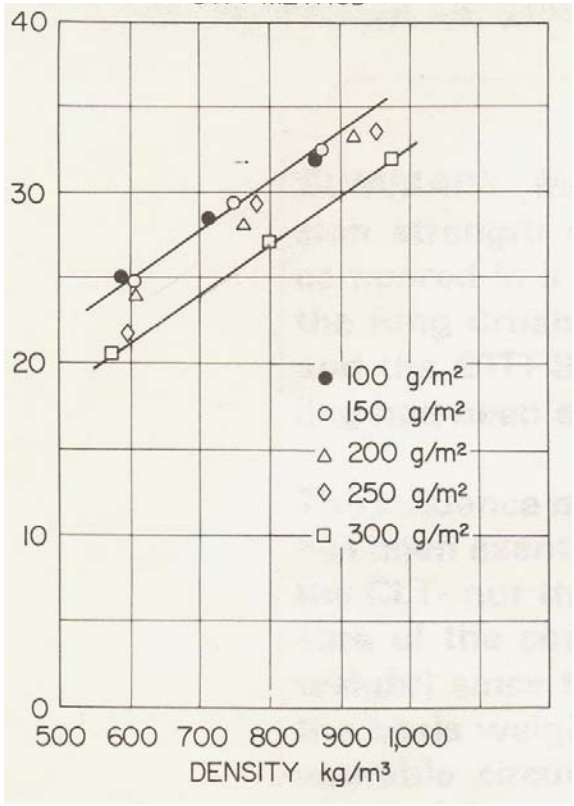
Effect of grammage and density



RCT







Christer Fellers' slide

T 826 pm-92

Short span compressive strength of containerboard

A test specimen, 15 mm wide (0.59 in.), is clamped in two clamps, 0.7 mm (0.0276 in.) apart. The clamps are forced towards each other until a compressive failure occurs. The maximum force causing failure is measured.

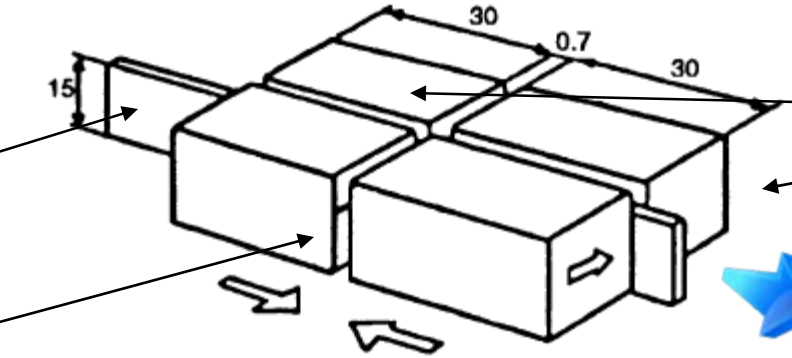


Fig. 1. Clamping arrangement; all measures in mm *(4)*.

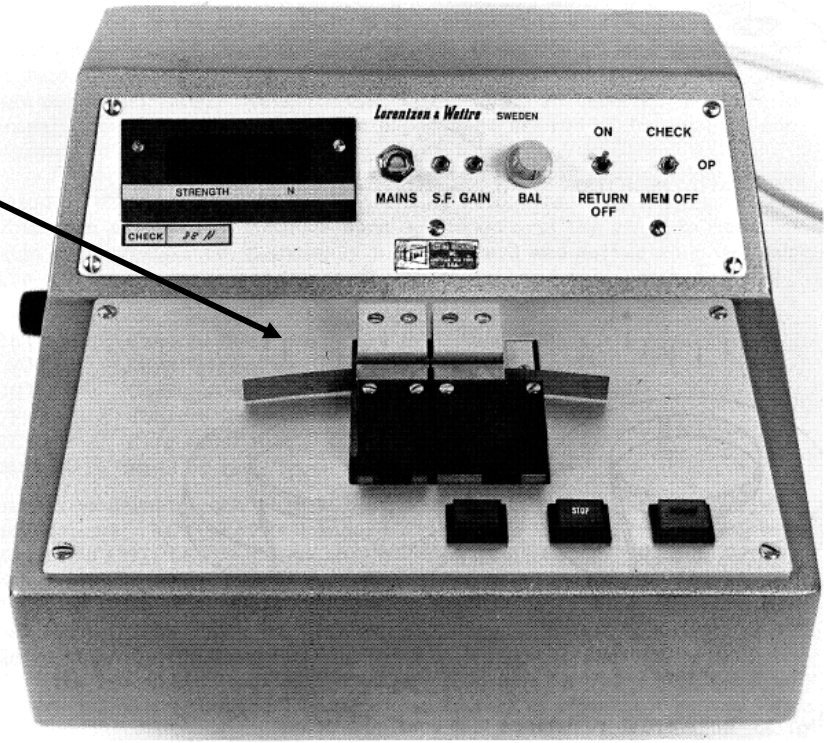
4.1.2 The clamps shall be able to grip the test specimen with a constant clamping force of 2300 ± 500 *N* (517 ± 112 lb).

4.1.3 A means for indicating the clamping pressure exerted by the clamps.

4.1.4 At the start of the test the free span between the clamps shall be 0.70 ± 0.05 mm (0.0276 ± 0.002 in.). After the test is started, the clamps shall move toward each other at a speed of 3 ± 1 mm/min (0.12 ± 0.04 in./min), the

The L&W SCT

Simple strip insertion, one button operation



On-board test sample moisture correction is available, based on resistance measurement requires calibration that is furnish dependent – unused at IPST

Instrument is checked periodically using a selected standard paper sample kept in a drawer with its data history fro instant comparison

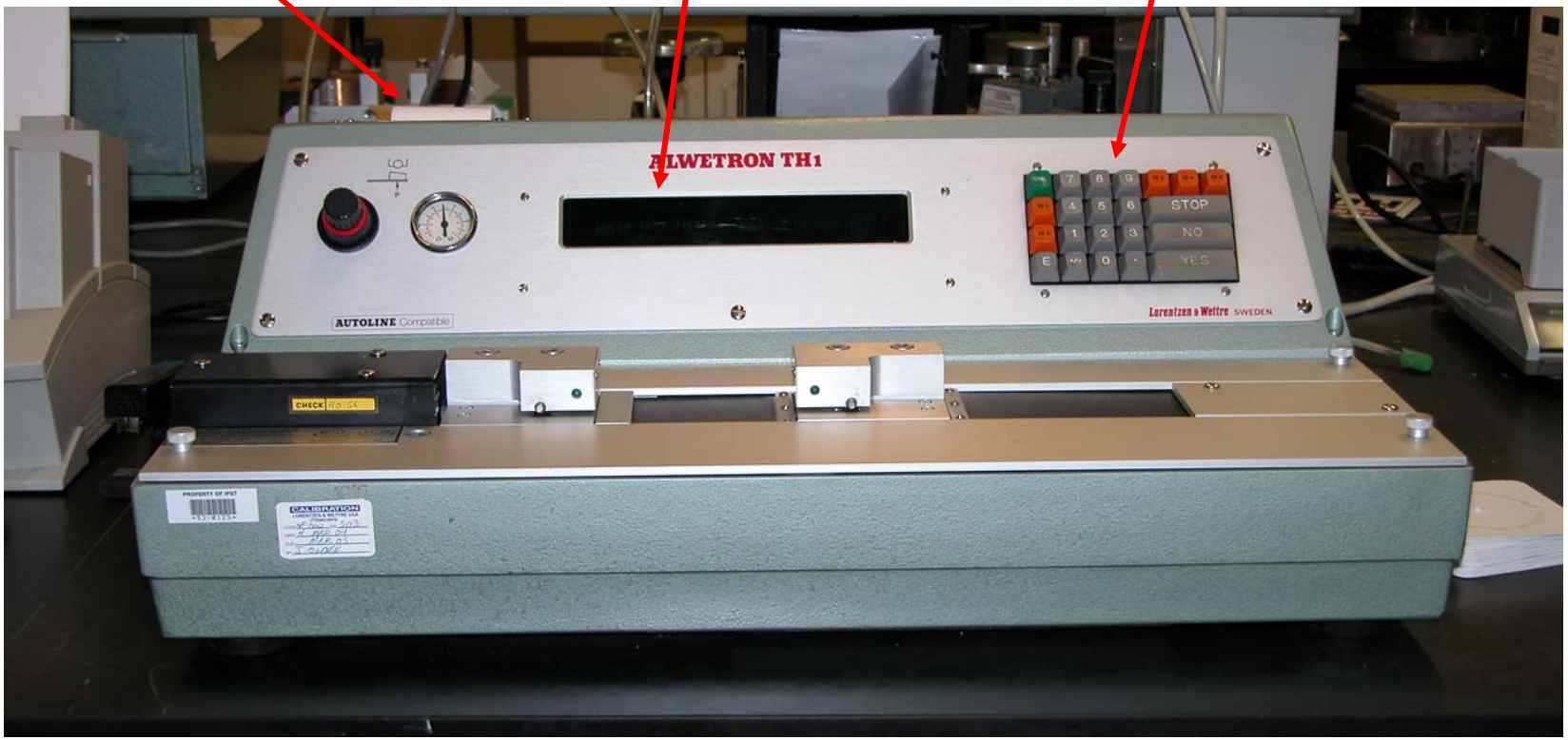
For mill QC use – samples must be conditioned to 50% RH equilibrium…fastest way → cut 6" x 15mm strips, place in microwave oven for 10 seconds, hang *separated* strips in a draft for 2 hours, ***then*** test

After many years of service…

Thermal dot matrix printer dots fades, rollers wear out

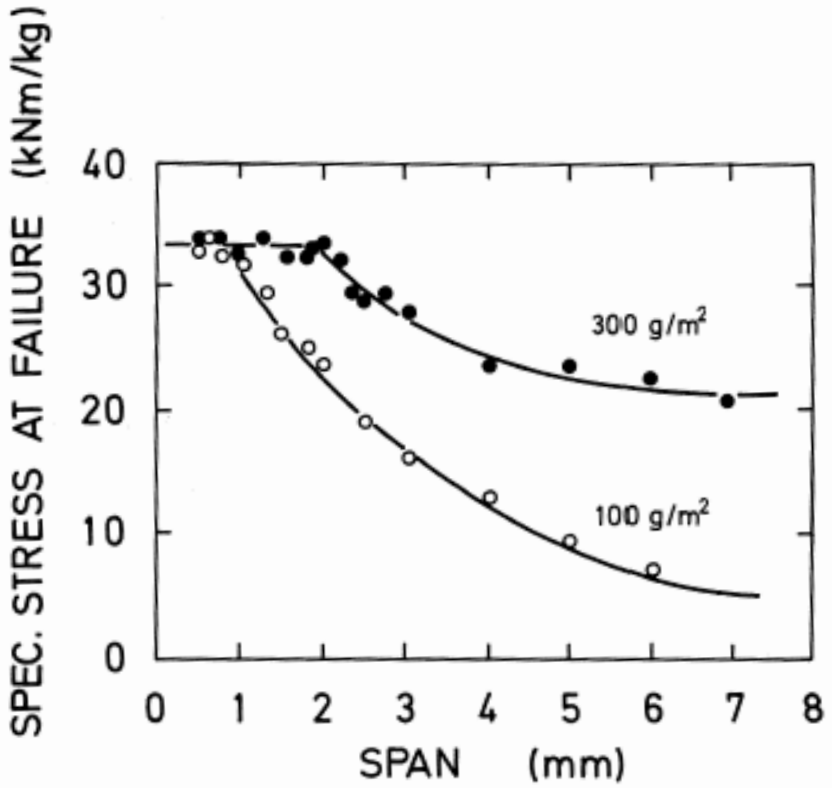
Green LED read-out fades, missing dots

Keyboard button contacts become erratic or fail



Unit must be in a conditioned lab, use in humid environments (e.g. mill floor) will affect electronics

SCT works because over the 0.7 mm test span there is *no* bending



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

Euler buckling curves

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-

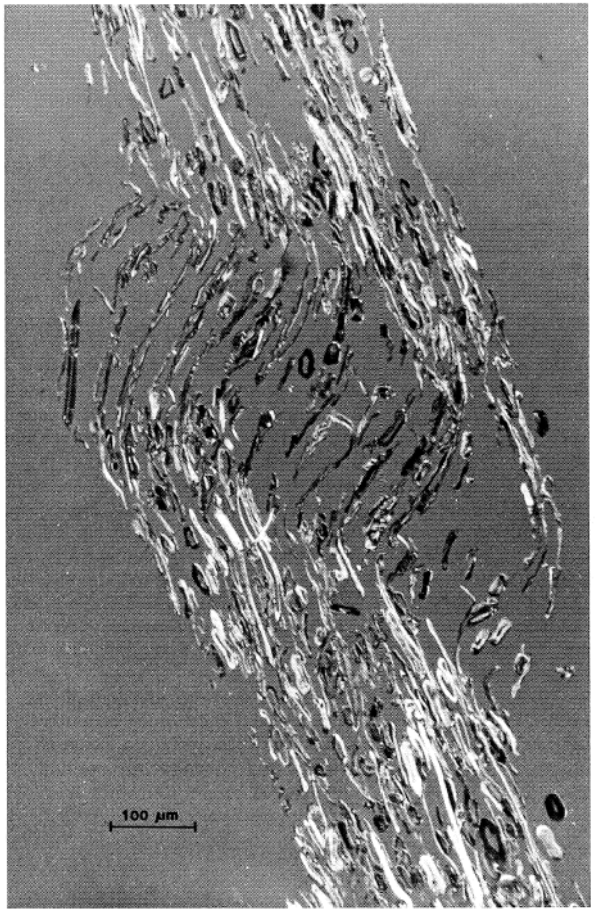


Fig. 32 Characteristic microstructural damage of an edgewise compression failure in paper. Photographed in partially polarized light. (Photomicrograph courtesy of Amin Eusufzai, Empire State Paper Research Institute.)

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

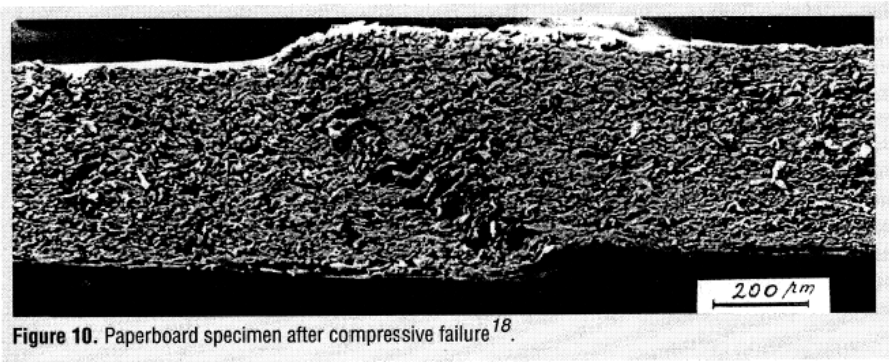


Figure 10. Paperboard specimen after compressive failure[18].

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

STFI or SCT (Short Span Compression Test) is considered to be the intrinsic compression test strength for linerboard – this is ***how you can understand*** what affects it through a "Page equation" model for SCT:

A MODEL FOR SHORT-SPAN COMPRESSIVE STRENGTH OF PAPERBOARD

Paul Shallhorn, Shuohui Ju, and Norayr Gurnagul

Pulp and Paper Research Institute of Canada, Pointe-Claire, QC, Canada

Can affect this by low consistency refining

$$\frac{1}{\sigma_c} = \frac{1}{\sigma_0} + \left[\frac{Cw}{(2\alpha E_f t^3)}\right]\left(\frac{\rho_f}{\rho} - 1\right)^2$$

Note the dependence on fiber modulus (fibril angle,species)

and sheet density (wet pressing)

where σ_c is the sheet compressive strength, i.e. short-span compressive strength, σ_0 is the sheet compressive strength at limiting high density (the mean fibre compressive strength), C is fibre coarseness, w is the fibre width, α is an efficiency factor, E_f is the average fibre modulus, t is the collapsed fibre thickness, ρ_f and ρ are the fibre (cellulose) and apparent sheet density respectively.

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 MD
	- in CD	-- 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 strength[18]. The

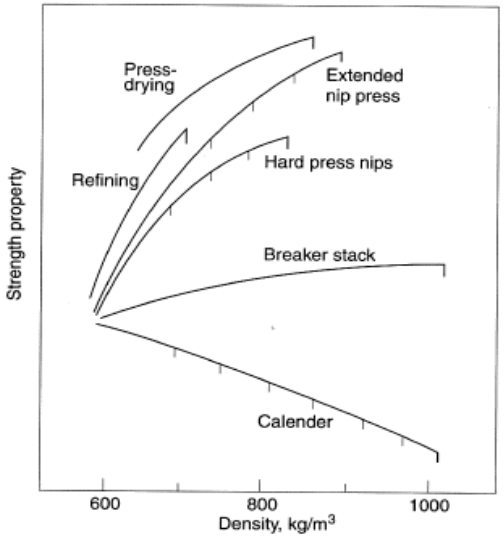
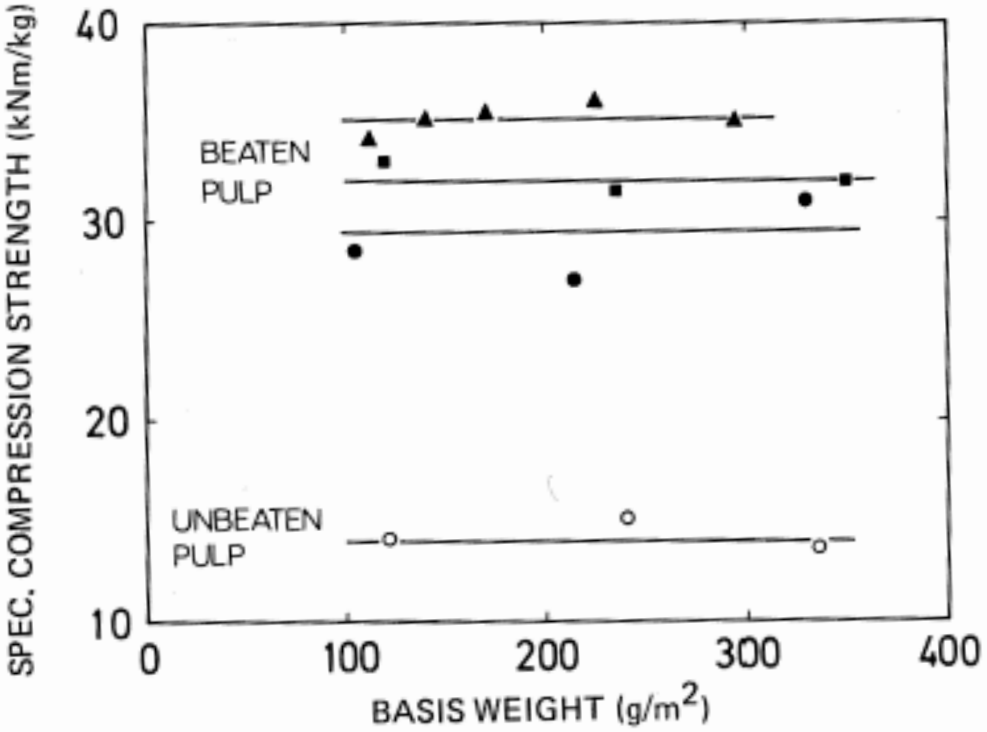


Figure 13. Schematic dependence of general strength properties on paper density changed by various unit processes. The vertical marks for pressing and calendering indicate succesive nips[23].

From Paper Physics by Niskanen

Using SCT



Shows the only way to change SCT is to change the furnish and beating level of fibers

Recall the Shallhorn Gurnagul model for SCT

From the Handbook of Physical Testing

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

Ring Crush is affected by the bending stiffness and the caliper of the test specimen so is not a true compression test

Tappi Journal 1998

George S. Rennie

ABSTRACT: Ring Crush Test and Short Span Compression Test are two methods to measure the stiffness of linerboard. Experimental work has led to an empirical formula relating the two properties. The correlation coefficient for the equation is good in both CD and MD.

linerboard. Using data collected from tests on recycled and kraft linerboards in the 127–337 g/m^2 range, it is possible to derive a very simple empirical formula:

$$SCT = RCT + 0.005T/t^2 \qquad (1)$$

where

SCT = Short Span Compression, kN/m

RCT = Ring Crush Test, kN/m

T = Taber stiffness, mN·m

t = Apparent thickness, mm.

The value of t comes from the TAPPI Test Method for thickness *(4)*.

Note the dependence on Taber and caliper in this empirical relationship

Note that Taber is a bending stiffness measurement

How can RCT and SCT be related ?
(current IPST ongoing research)

- RCT is a combination of bending and compression failure
- SCT is compression failure only
- McKee reasoning for plate failure as a combination of compression and bending takes the empirical form:

$$Compression\ \ failure\ load\ =$$

$$(Compressions\ \ strength)^{b} \times (Buckling\ load)^{(1-b)}$$

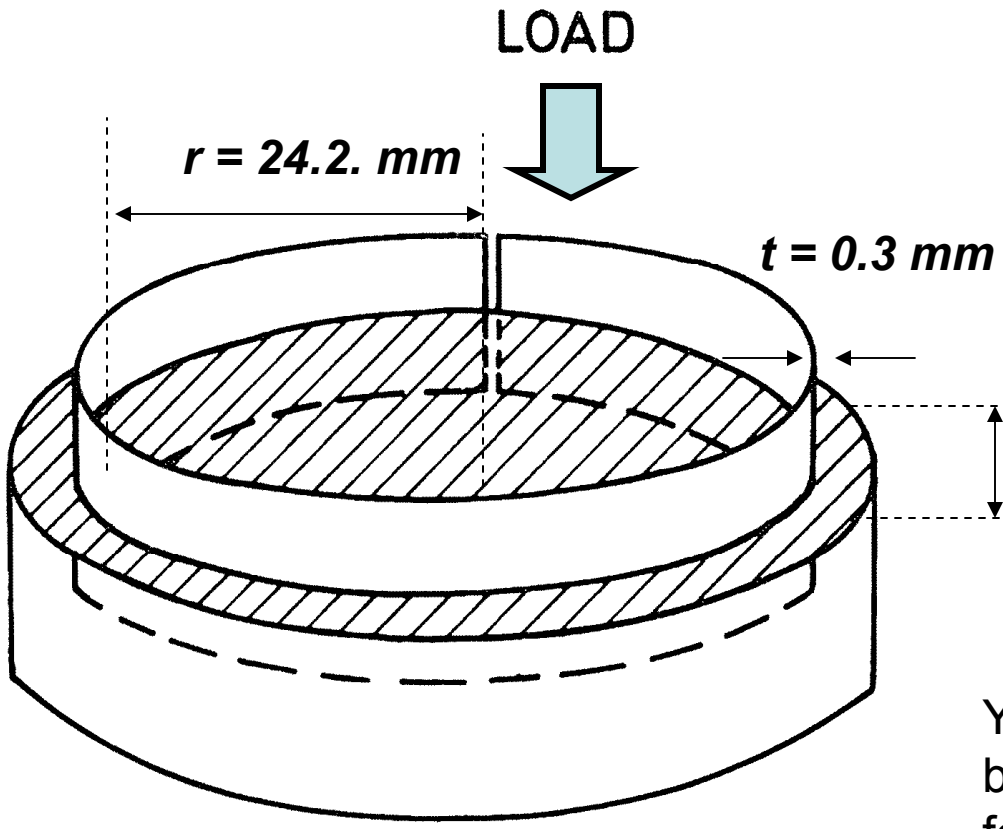
Related to the bending stiffness which depends on the structure e.g, round tube, plate, flute shape, etc

Buckling load for a thin walled tube:

From Timoshenko and Gere:

$$\sigma_{cr} = \frac{E}{\sqrt{3(1-\nu^2)}} \times \frac{t}{r}$$

"E x t" is tensile stiffness



For this formula to hold need to fit one half wave:

$$\frac{l}{m} = 1.72\sqrt{r \times t} = 4.7mm$$

Yep, specimen is high enough to buckle - we can use this formula

We can get a measure of the ring buckling load using the L&W TSI

By measuring the speed of sound in paper, basis weight and the caliper we can estimate the tensile stiffness

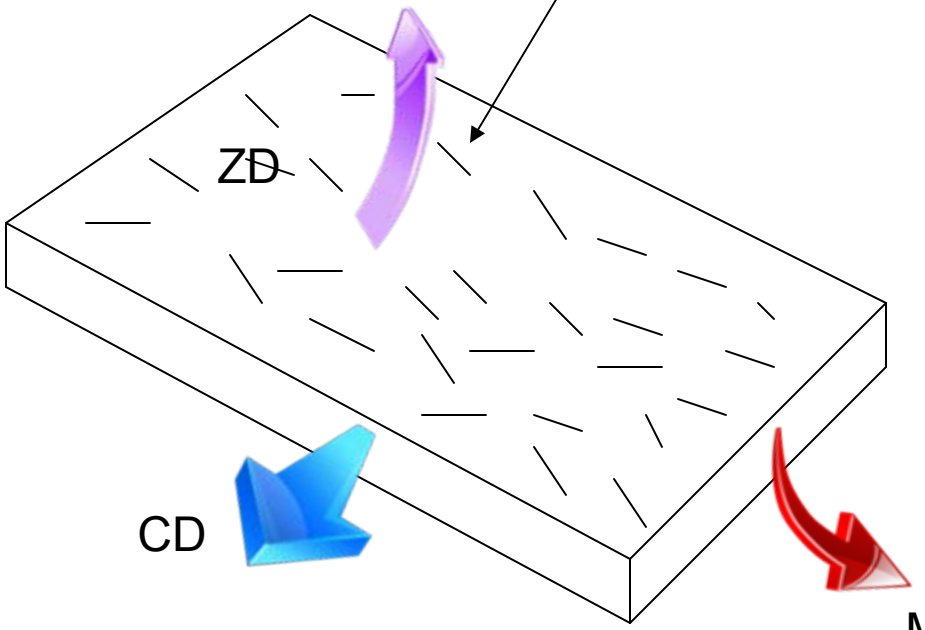
The tensile stiffness is directly proportional to the buckling load of a thin walled tube.

Combining measurements to predict RCT

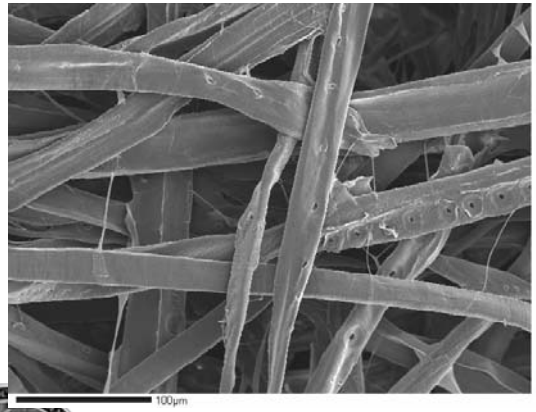
The Autoline for linerboard will have SCT, caliper, basis weight, and a TSI – these measurements can be combined to fit an RCT model, the model can be programmed into the Autoline software to provide a calculated estimated equivalent value for RCT

PAPER STUCTURE - OVERSIMPLIFIED

Fibers: former wood cells, typically 1 – 3 mm long, 50 microns wide



SEM x-section

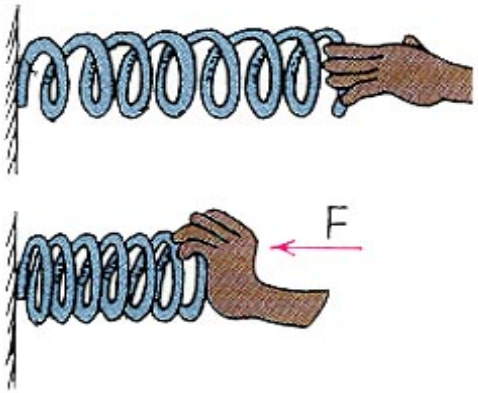


SEM surface

Paper consists of 50 to 30% air and a network of bonded fibers aligned predominantly along the MD – machine direction

For box making applications, only CD compression is considered

Paper as a 3D spring:



In 1D we have Hooke's law for the Force F to move a spring distance x

$$F = k\,x$$

For a 3D solid slab such as paper , we have by analogy, the pressure or stress ***σ*** required to displace the solid by a strain ***ε*** for each principal direction:

$$\sigma_{MD} \approx E_{MD}\varepsilon_{MD} \quad \sigma_{CD} \approx E_{CD}\varepsilon_{CD} \quad \sigma_{ZD} \approx E_{ZD}\varepsilon_{ZD}$$

The ***E***'s here are the **elastic moduli** for each of the 3 directions

The ***ε***'s are the strains i.e. relative changes in displacement : $\Delta\ell\,/\ell_{\,0}$

E's and sound speed

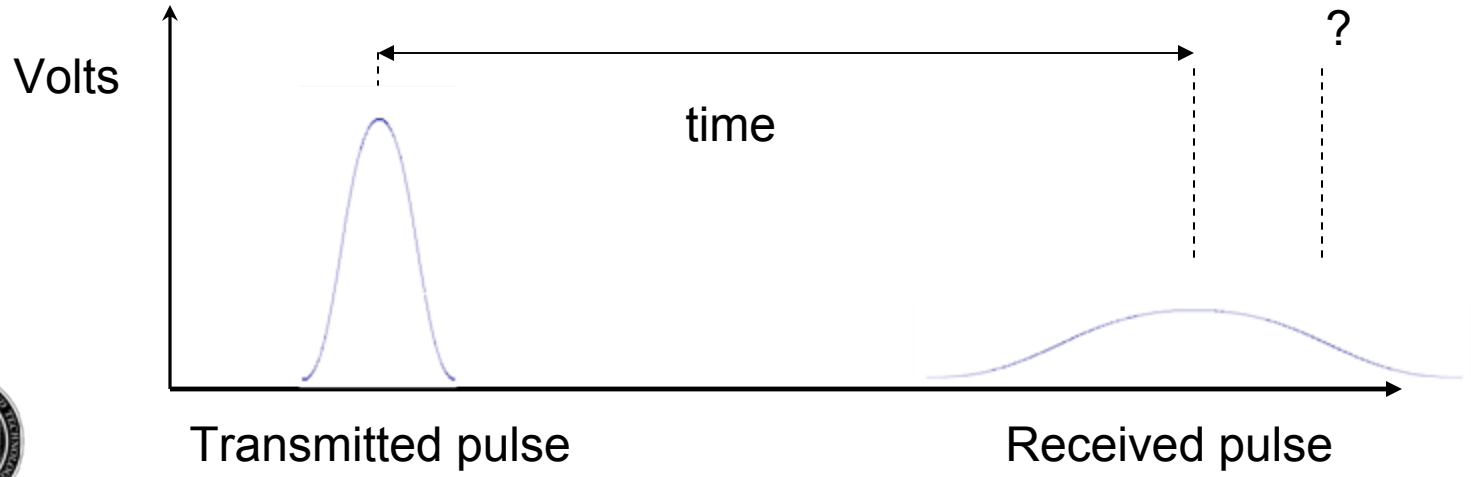
To a good approximation:

$$E_{MD} = \rho V_{MD}^2 (1 - \nu_{12}\nu_{21}) \approx \rho V_{MD}^2$$

$$E_{CD} = \rho V_{CD}^2 (1 - \nu_{12}\nu_{21}) \approx \rho V_{CD}^2$$

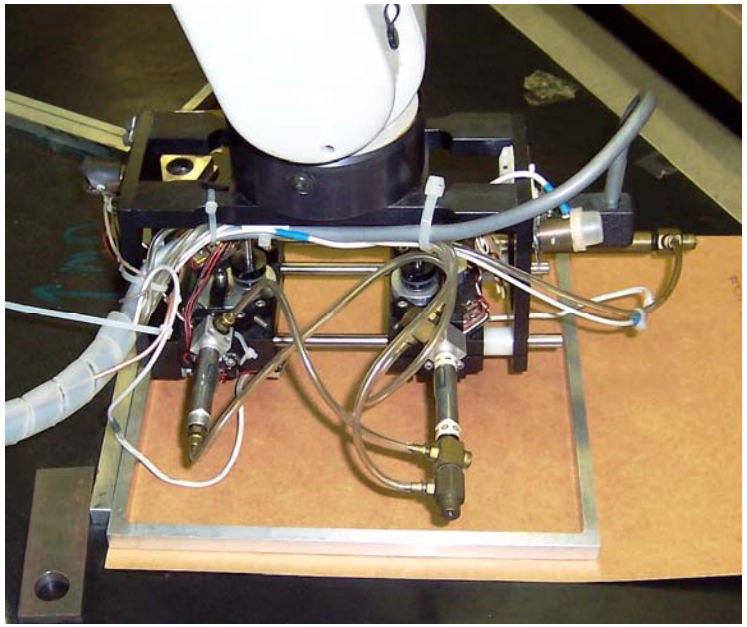
⇨ Moduli (MD or CD) = apparent **density** x **velocity squared**

We can measure the speed of sound propagating along the plane of the sheet using a pair of transducers:

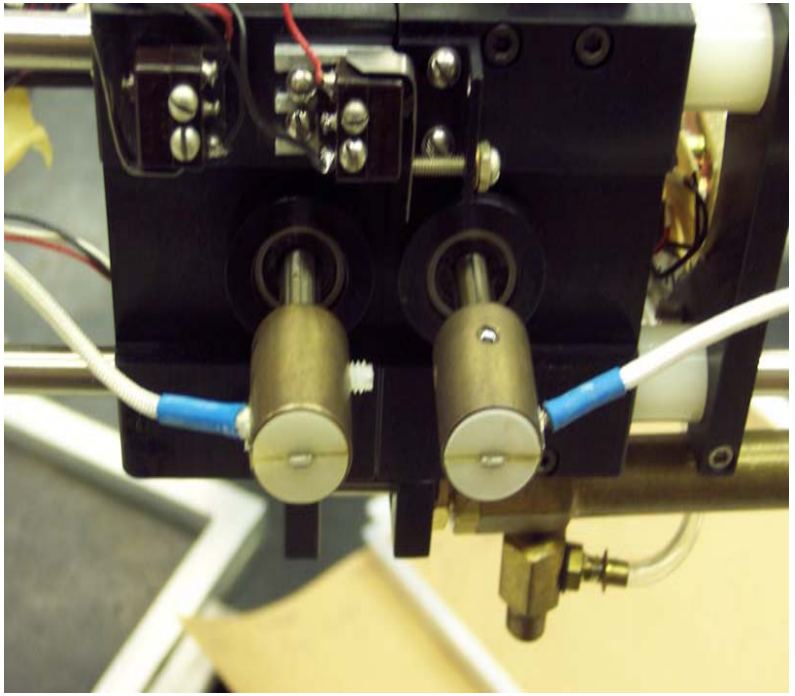


Measuring sound speed in paper

IPC 1970's Robot Arm difference method technique



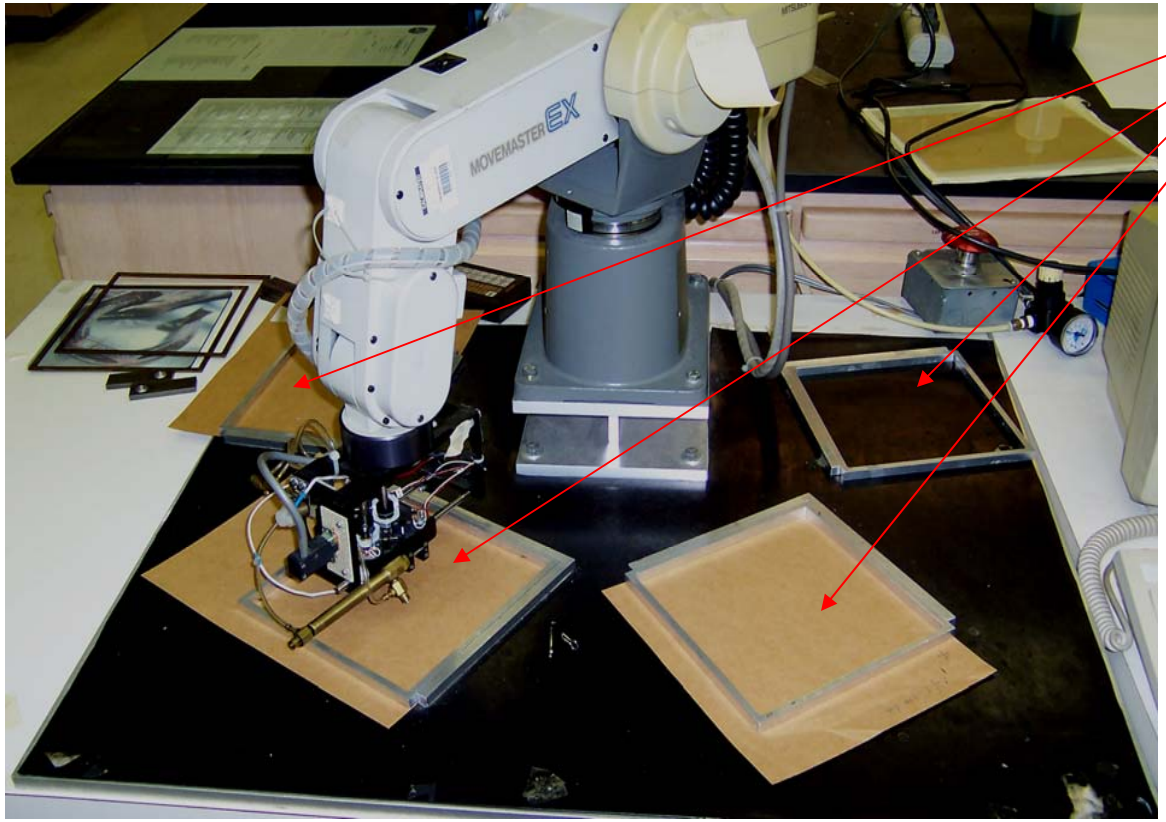
Bimorph "paddle" transducers apart for "far" reading



Close up of transducers for "near" reading in shear mode, transducers are rotated for longitudinal mode

From successive pairs of measurements a 2 distances get Poisson ration, and shear modulus – 15 minutes per test

IPST Robot Arm – from the 1980's



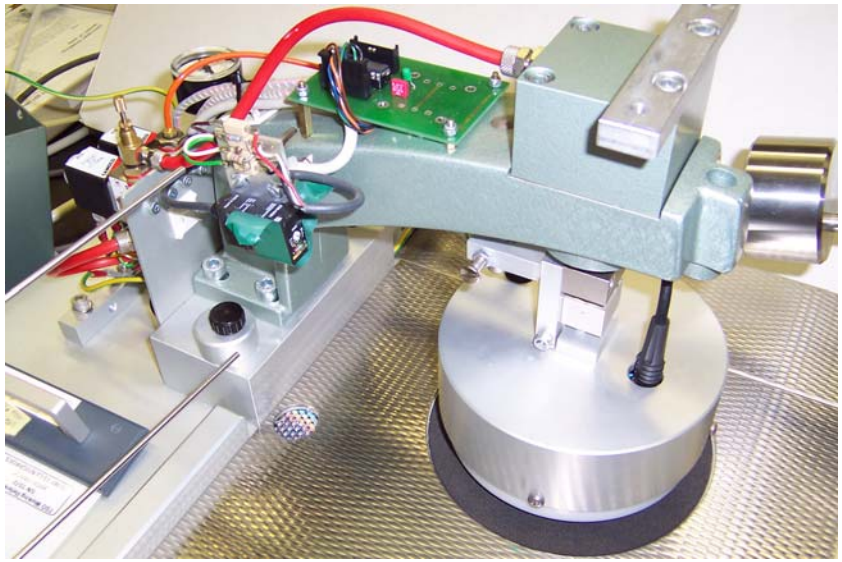
4 user selectable measuring stations

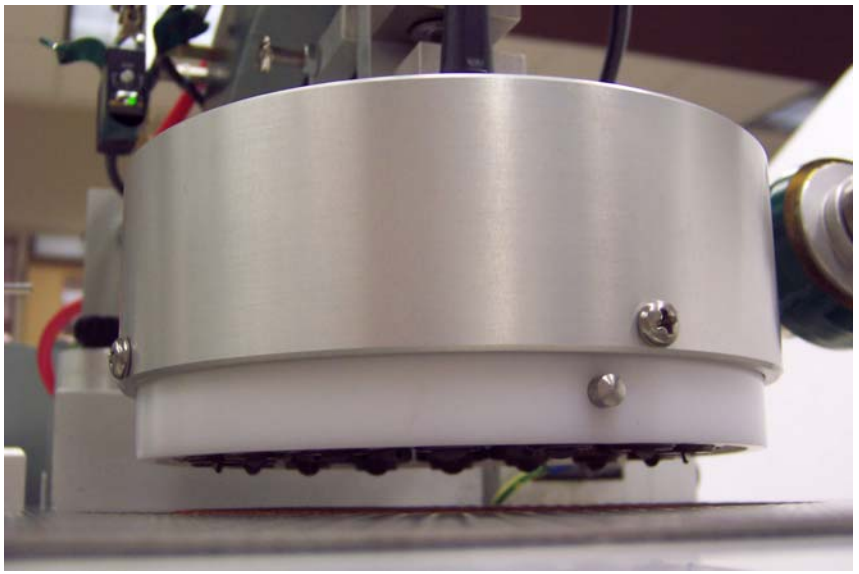
Robot arm end effector rotates for polar plots

Takes an hour for a 2 degree resolution plot

A typical lab tech's response

L&W TSI comes to the rescue





8 pairs of transducers fixed distance, head comes down at a higher pressure for basis weights > 100 gsm

Polar plot and V^2 produced in 6 seconds but:

Might be influenced by low density and high roughness to produce underestimates of V^2

So…correlation of V^2 from TSI vs tensile stiffness has to be verified for particular sample sets

L&W TSI measures V_{CD}^2 = TSI_CD

For the buckling load part in the RCT model we need $\boldsymbol{E}$ **x** $\boldsymbol{t}$

This is the same as:

$$E_{CD}t = \rho V^2 t = \frac{BW}{t} V^2 t = BW \times TSI\_CD$$

So the buckling load in an RCT model becomes:

$$\sigma_{cr} = \frac{E}{\sqrt{3(1-\nu^2)}} \times \frac{t}{r} = C''\{BW \times TSI\_CD\}$$

With C'' being constant since r and Poisson ratio's do not change appreciably

Modeling RCT in terms of combined compression and buckling strengths

The model for ring crush is proposed as:

$$RCT = C(SCT)^{b}(Et)^{1-b}$$

•Based on McKee reasoning for the compression strength of a plate but instead replacing the buckling load of a plate by that for a thin cylindrical ring (e.g. Roark's formulas) where:

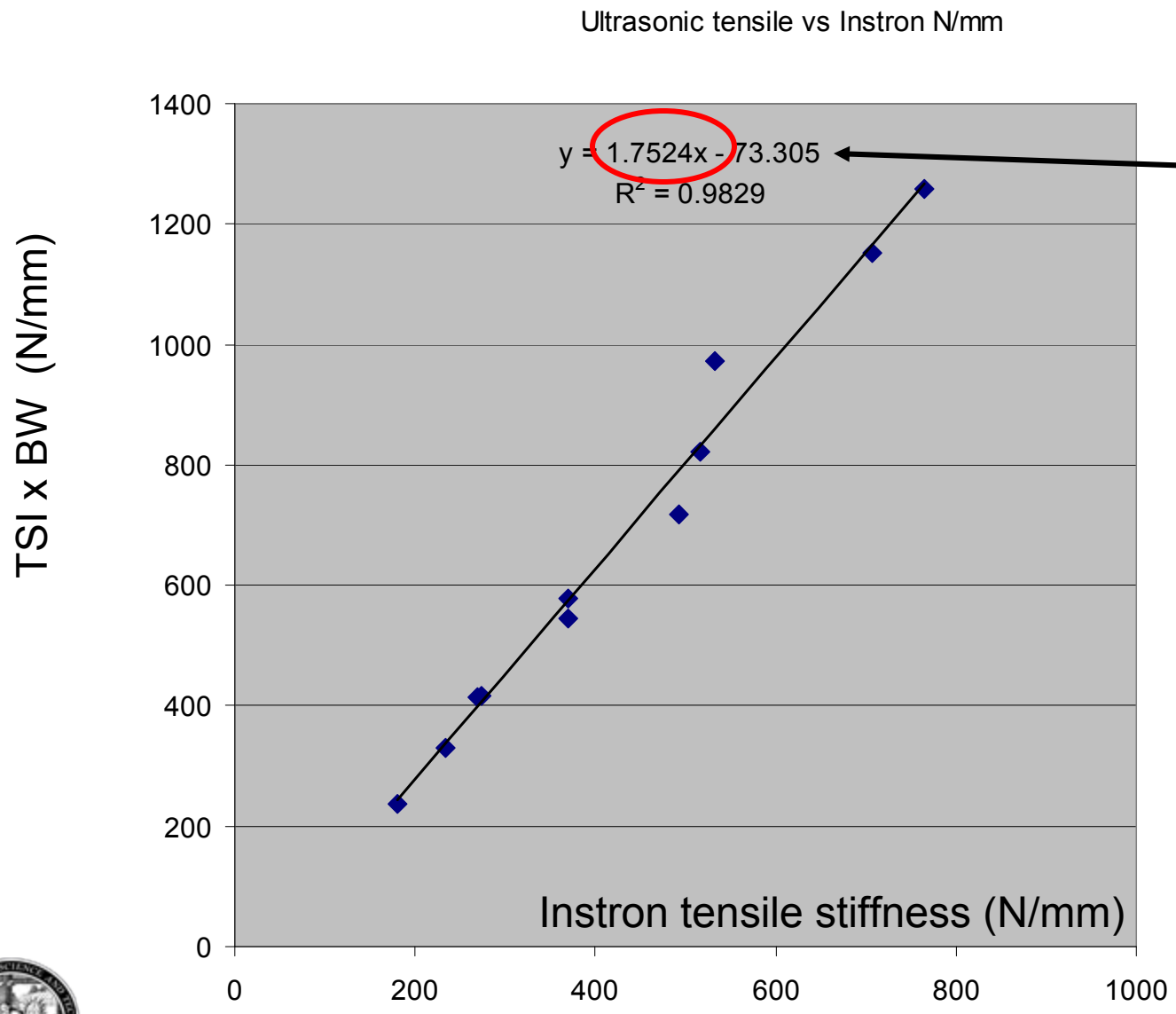
•P_{cr} is the buckling load for a ring is proportional to Et

•Et = tensile stiffness (modulus E times sheet thickness t) = constant x (v^2) x basis weight

•Can get v^2 (specific stiffness) from L&W TSI output

• so… can now get an RCT value by measuring SCT, BW and TSI_CD

This shows that TSI * BW = Et when E x t is measured by the Instron as tensile stiffness

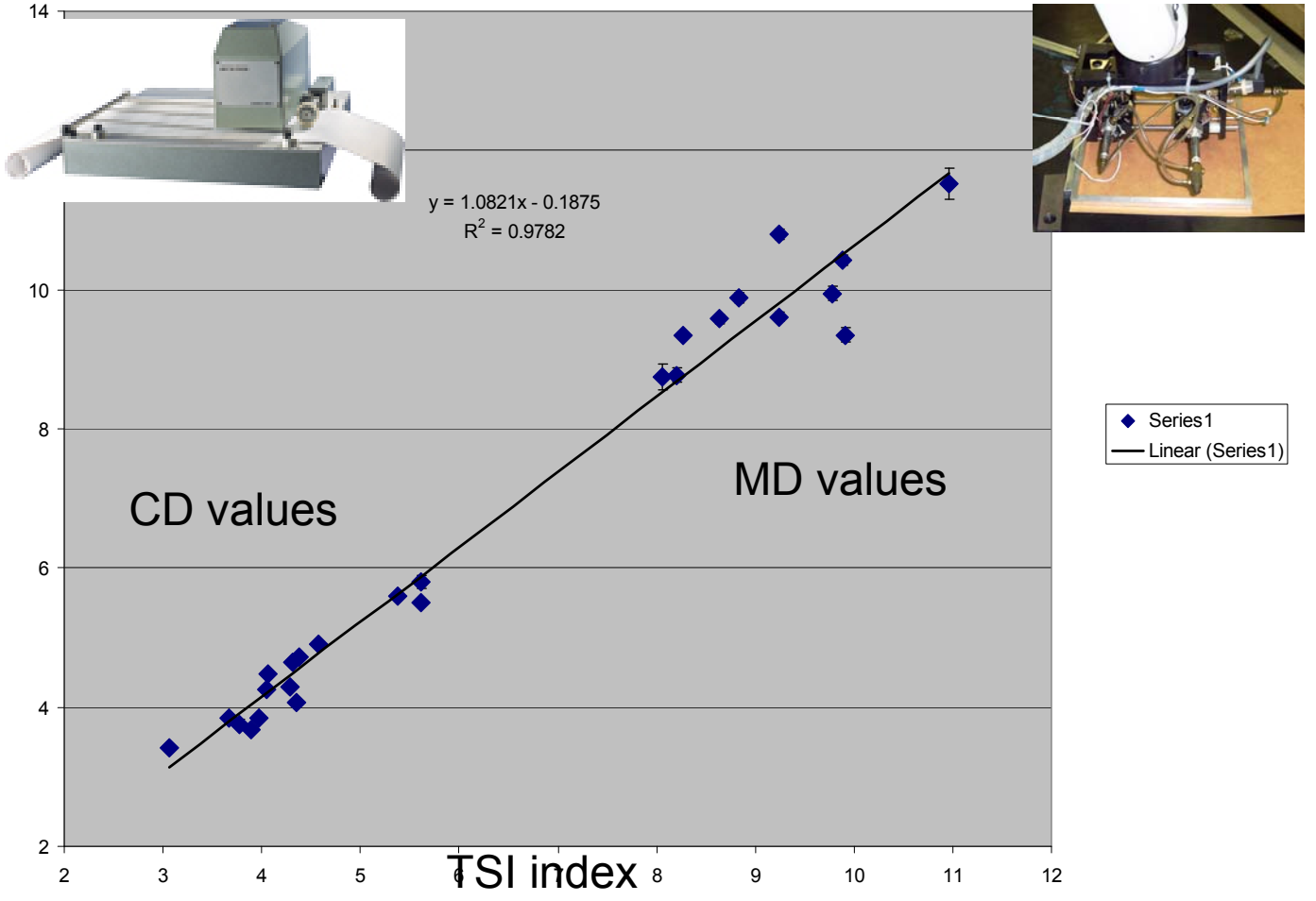


Ultrasonically measured values are always higher than mechanical equivalents

TSI checkout with IPST Robot

)2

Sample ID
42 lb kraft liner
33 lb medium
26 lb medium
56 lb liner WC
16 lb medium
18 lb medium
OCC 42lb liner
20 lb medium
3m mylar
yellow copy
inkjet mylar
WAM 33#
blotter



Correlation looks ok for a variety of various liners medium, copy paper and plastic film

This is the spreadsheet analysis using Excel “Solver” to fit the model RCT = C x $(SCT)^{b}$ x $(Et)^{(1-b)}$ i.e., a “McKee” style equation for RCT using a combination of compression strength (SCT) and buckling load (~ Et which in turn, is TSI x BW)

model:

RCT = (STFI)^b(Et)^(1-b)

Et = TSIxBW

C = 0.35, b = 0.36

q38

C = 0.349467355

b = 0.362403921

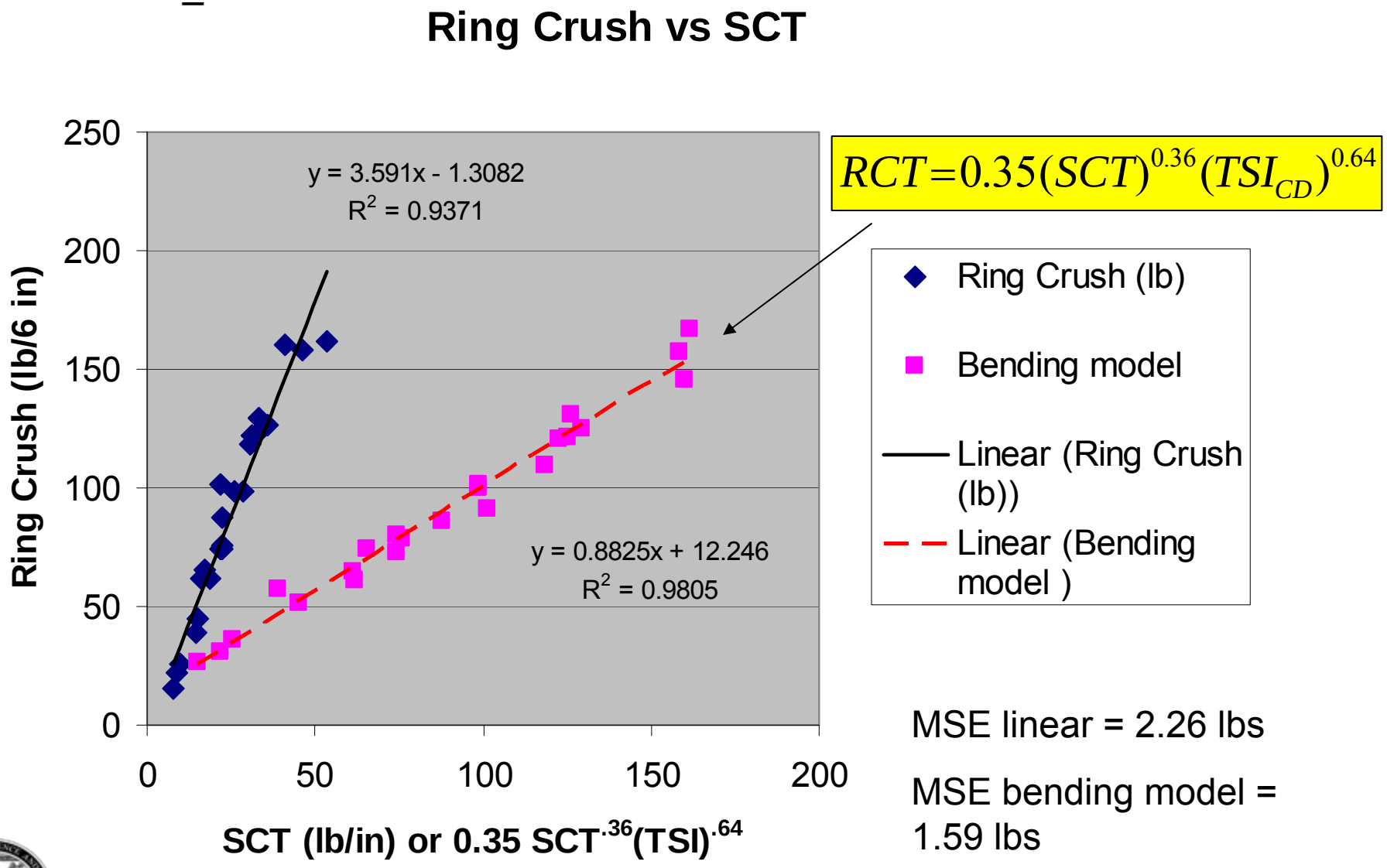
STFI (lb/in))	Ring Crush (lb	ET	Model	error^2
18.6	61.48	688.8574233	65.02243389	12.54883787
22.43	76.06	837.696652	78.83173899	7.682537056
22.069	101.15	1066.474227	91.41300701	94.80903252
30.813	118.4	1172.550736	109.5963138	77.50488992
31.231	122.4	1350.911968	120.5385411	3.465029404
33.467	129.6	1378.359952	125.192706	19.42424044
46.08	158.41	1640.9707	157.1106897	1.688207376
35.829	126.49	1421.312619	130.8608967	19.10473791
53.631	161.49	1652.173551	166.7145053	27.29545532
26.209	98.46	1136.489074	101.3153034	8.152757588
40.786	160.2	1556.65121	145.3418956	220.7632653
21.702	74.34	875.2949972	80.10608446	33.24773006
34.443	125.36	1285.666476	121.0113364	18.91087478
16.051	61.98	680.5922305	61.16781024	0.6596522
28.64	98.77	1063.086323	100.264588	2.233793158
22.178	87.82	961.1309916	85.70075308	4.491207499
14.288	39	661.461174	57.58578752	345.4314977
17.155	65.7	882.722197	73.96061475	68.23775609
7.539	15.15	281.03	26.46449812	128.0178676
8.599	21.9	331.8952	30.86274479	80.3307942
9.981	25.47	394.284	36.35707584	118.5284204
14.975	44.99	534.2069	51.11413764	37.5050618
22.193	74.09	747.9719	73.05644945	1.068226737
				1331.101873 sum error
		RSQ=	0.980453481	

$$RCT = 0.35(SCT)^{0.36}(TSI_{CD})^{0.64}$$

Model to calculate RCT

Data is for a series of linerboards and medium of a wide range of basis weights

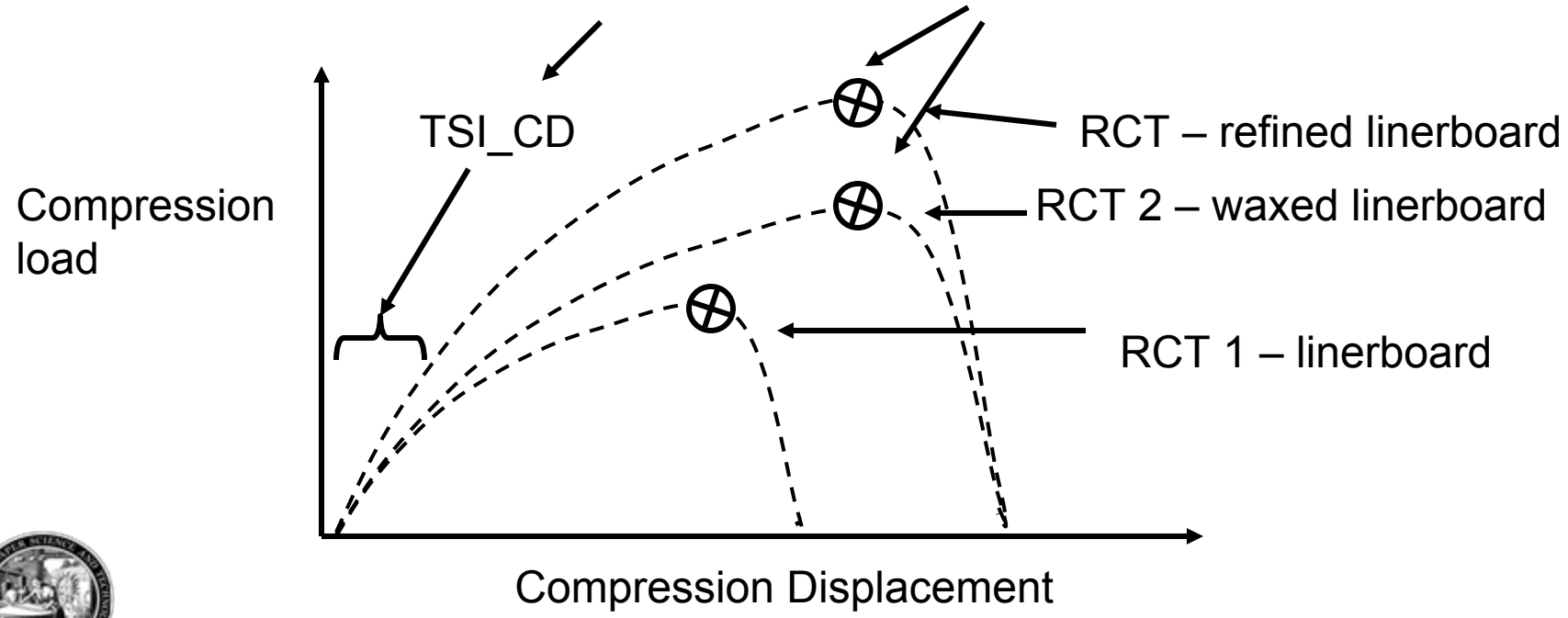
This shows that the r^2 improves from 0.94 to 0.98 if we use a non-linear bending model for RCT: the value is that we get a better prediction for RCT using SCT, BW and TSI_CD



Will this always work ?

- If just using Et = D x (TSI_CD) x BW the assumption of stiffness being proportional to failure may not hold if:
    1. stress-strain curve is changed by increased or decreased ductility of paper
    2. addition of filler, starch, impregnation with polymer, radical change in fiber species

Comparable stiffnesses but different failure loads can occur…

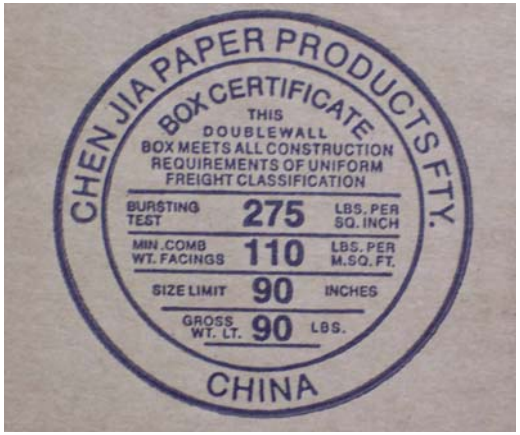


Relevance to Industry, you, me, the world and everything else..

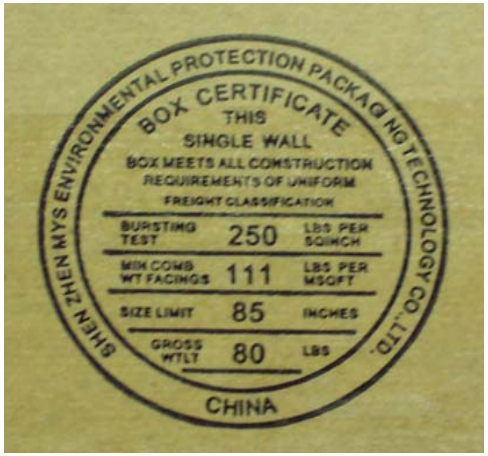
Current requirement to address the manufacture of recyclable boxes for food and produce transport meeting FDA specs must be produced **locally** –demand cannot decline with a growing population.

Chinese corrugated production volume surpassed US already in 2008

Overseas product and shipping containers are not a threat to this market: food transport and packaging



Doublewall BC box for furniture shipping



Single wall B flute box for PC monitor

Mullens here are ***bogus***

Corrugated is not going away

Awwright !!
*Let's make **boxes** !!*
Yeeaahh!!

Hasta la Vista, RCT !!

Thank you:

L&W

IPST Member Companies

TIP3 grants