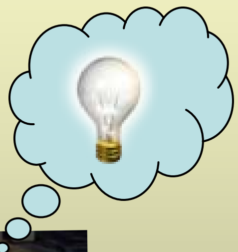
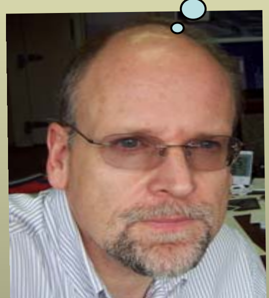
Corrugated Board Strength: effects of the localized buckling of linerboard facings – modeling, management and control





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*Yes, we are **still***
in business…

The stacking strength of boxes depends mostly on the **ECT** (edge compression strength) of the corrugated board

Boxes are often stacked in warehouses, shipping trucks, cargo holds…

Fun fact

- a ½ pound of paper can be made into a box that can hold a pair of shoes, will withstand a 1000 lb load - allow me to demonstrate

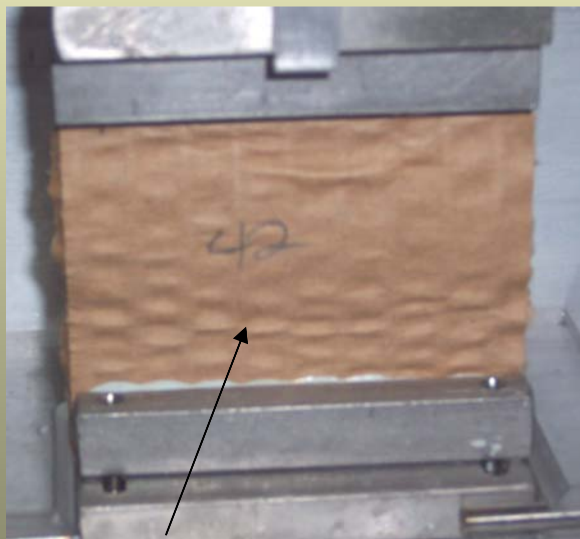
- Question: can we take ½ lb of any other material and do the same thing, at the same cost ? - ***no, not really…***

- Question: can we make the same box with ¼ lb of paper by doing something differently ??

  - ***well... maybe !!***

A corrugated board vertically compressed on an edge often displays a ***patterned buckling*** of the linerboard facings

load



An ECT creep test in cyclic humidity

load

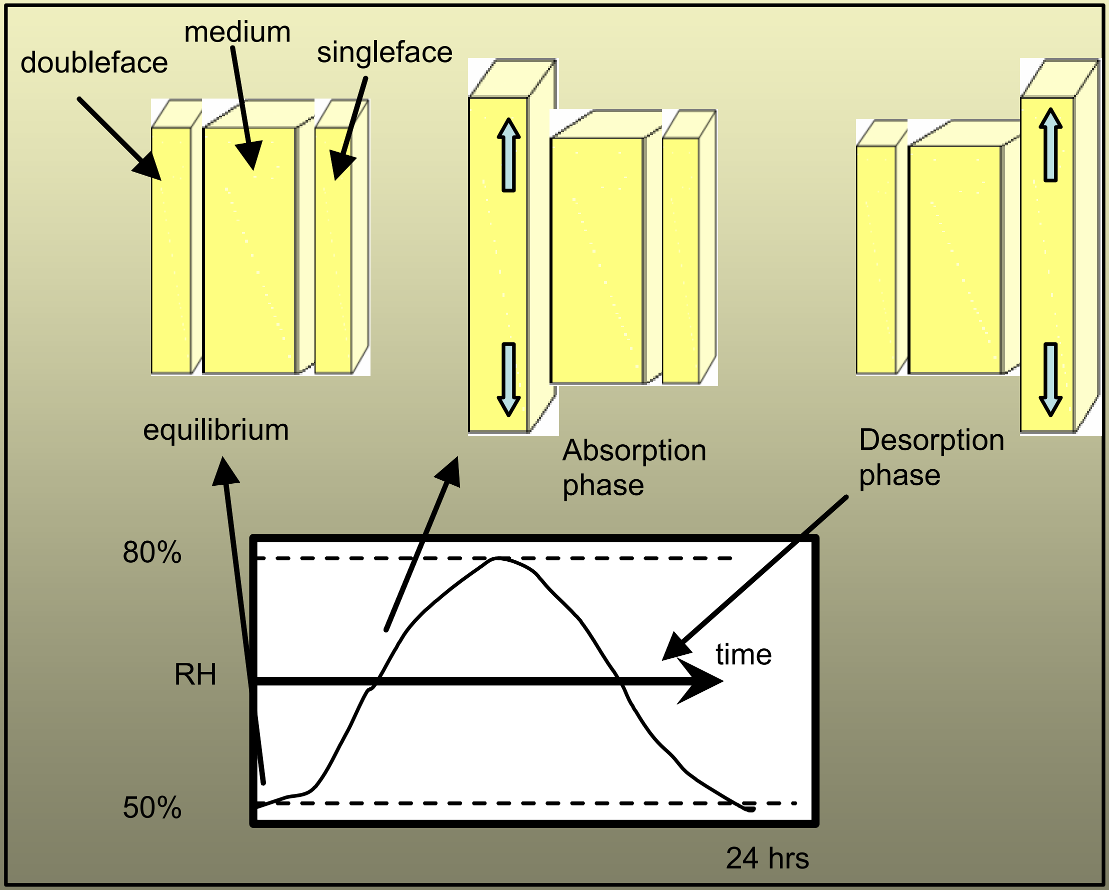
Test box in a cyclic humidity creep test

Fun fact

- Stacked boxes in a cyclic humidity environment e.g., 50 – 80 % RH last only about 1/5 th as long as the same boxes exposed to a constant high humidity

- Question: Why is that ??

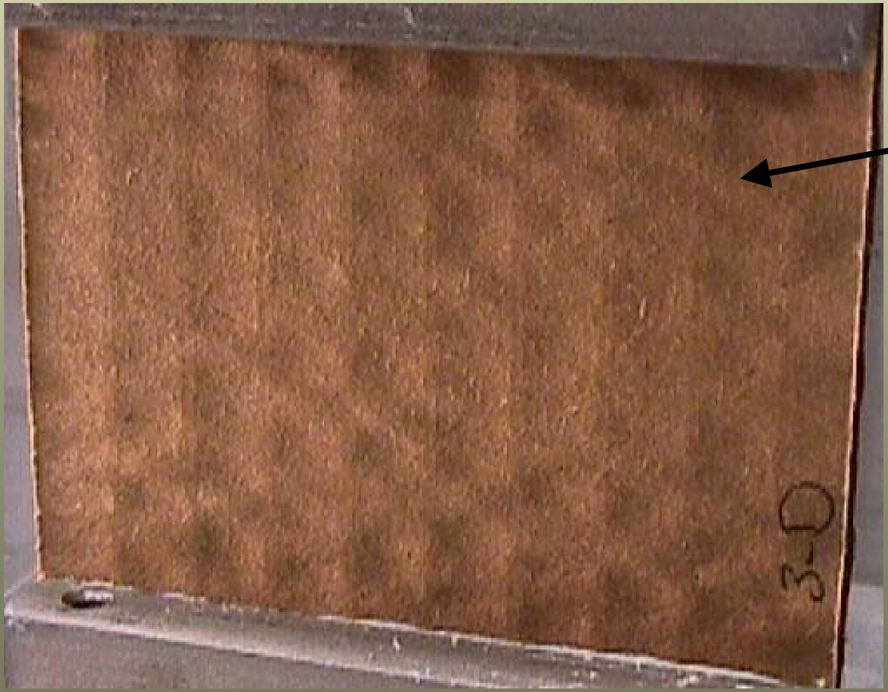
"Accelerated creep" is what happens in cyclic humidity



When the air becomes more humid, the outside of the box (the "double-face" side) expands and gets crunched by the vertical load. In reverse, if the outside air becomes drier, the outside of the box shrinks, so that the inside of the box (single-face) takes the load and gets damaged.

This buckling is a weakness… what if we could get rid of it ??

ECT strength is affected by both intrinsic compressive strength of the liners, medium and the bending stiffness of the liners – ECT is the leading component box compression strength and lifetime models



Typical buckling pattern "interflute buckling" of a combined board under a vertical load prior to compressive failure lowers the compressive strength of the board

At IPST, we performed a series of experiments to have a close look at buckling in ECT

We prepared 2 x 2” test specimens ends embedded in quick setting resin

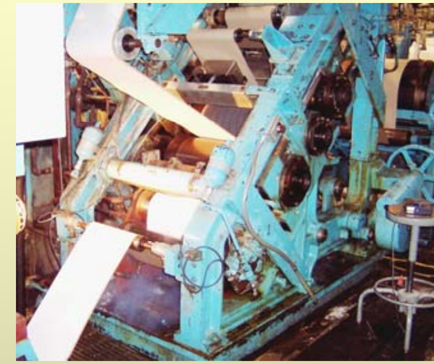
displacement

Used an Instron UTM and compression load cell

IPST Pilot Plant corrugating trials – we can make all sorts of corrugated board and test boxes - sequence:

Rod coating of 42# linerboard at Spectra-kote

Linerboard rolls coated with polymer or clay/polymer coatings



Rolls sent through IPST pilot single facer combined with WAM

Single facings manually combined with double facing

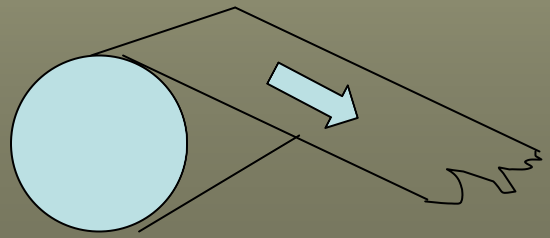
14 x 8 x 8” test boxes manually made

Test boxes put through performance tests, e.g. lifetime in cyclic RH

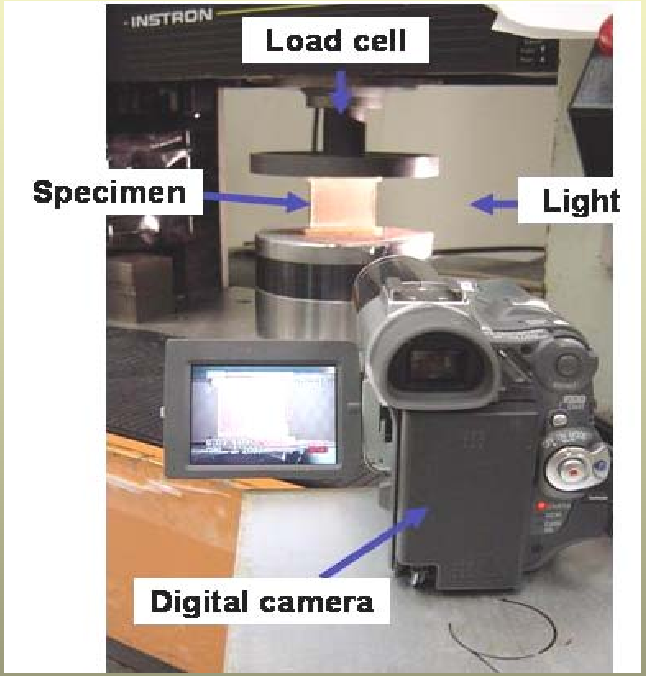
Fun fact

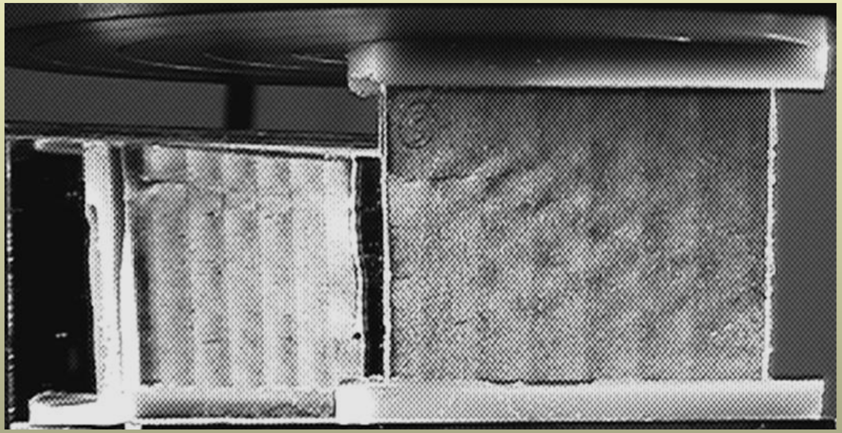
- Notice that paper is pulled from rolls in the machine direction (MD) – all machine made paper is oriented with its fibers (former wood cells) in the MD resulting in higher strength properties in the MD

- How to see that paper is oriented ? – Try tearing a piece of newsprint, usually MD is left to right so paper tears easily, up and down the tear will zigzag across paper layers - ***Try it !!***



The ECT tests were video taped

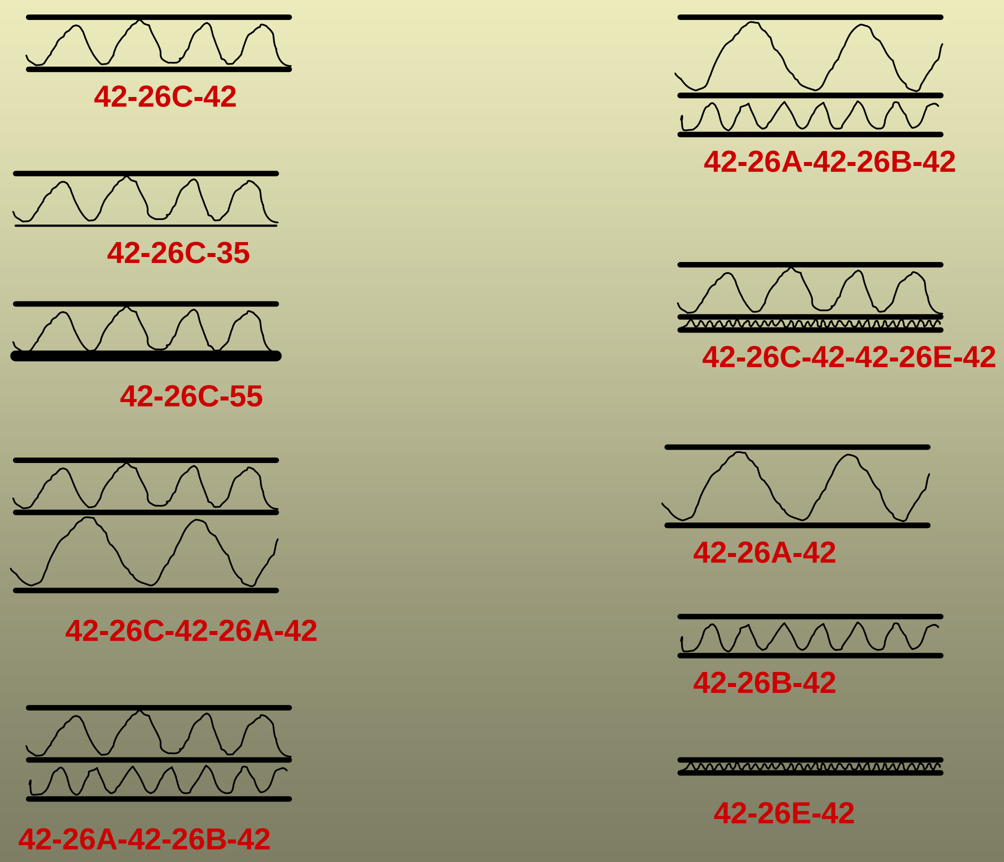




Instantaneous snapshot of an AC multi-wall board undergoing an ECT test. The A-flute side (in the mirror view, left) has already failed showing a crease across the rear facing while the C-flute side displays a buckling pattern.

Fun Fact

- Corrugated board comes in lettered flute sizes, the alphabetical order is chronological: A,B,C, E…



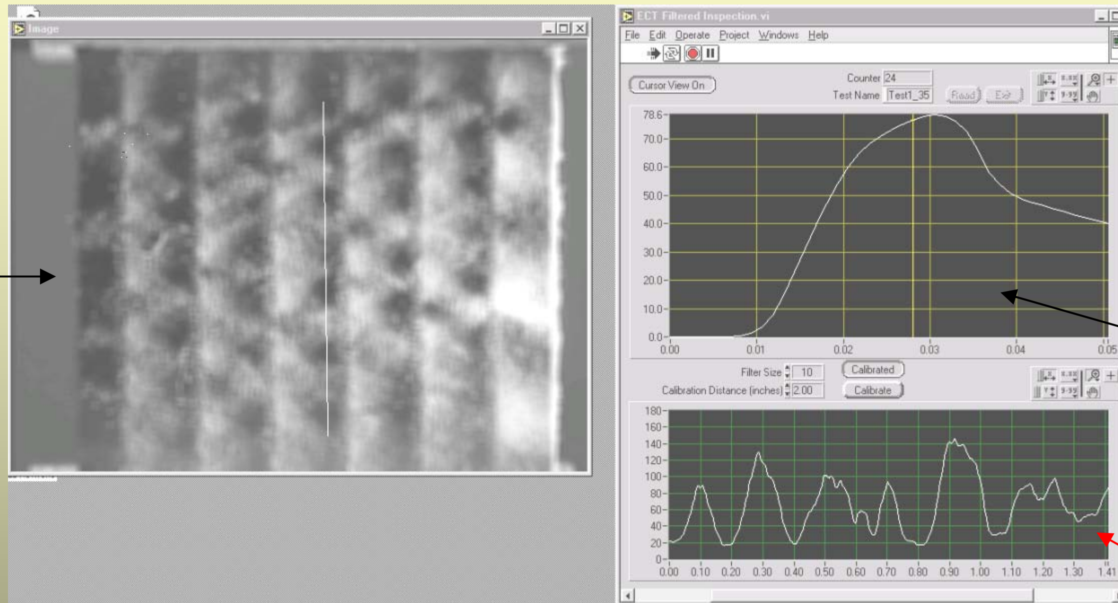
Most corrugated board is C flute designated as:

42-26C-42

meaning the linerboard is 42 lbs/1000 ft^2 (msf) and the medium is C flute size and 26 msf

We observe that liner buckling occurs in C and A flutes for linerboards 42# and lower

Low pass filtered image using glancing illumination

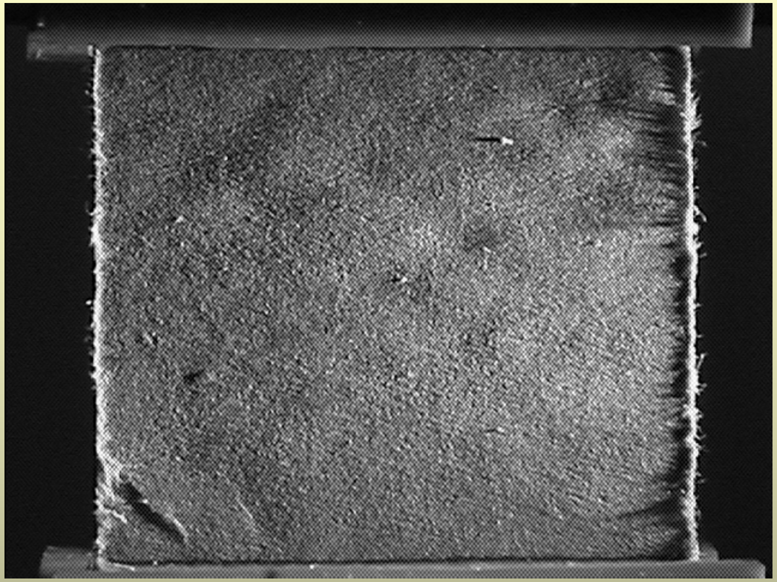


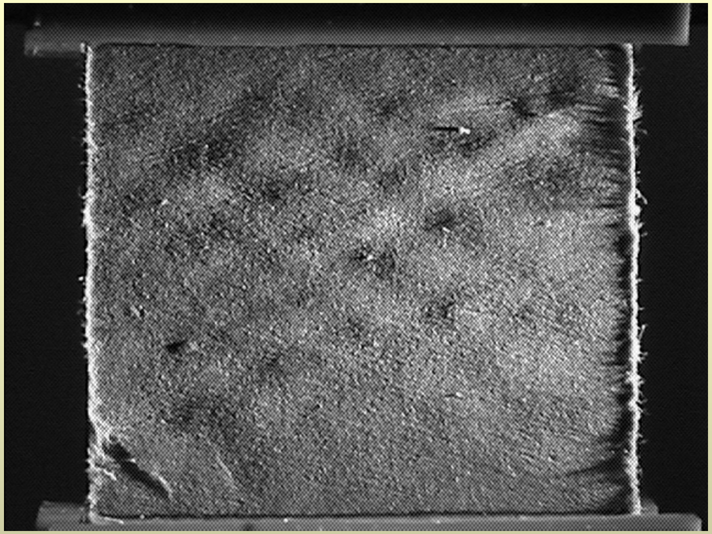
ECT load displacement - strain curve

Wavelength analysis

***<u>Result</u>*: Predicted ECT's are slightly lower than expected from component compressive strengths for <u>lightweights</u> especially when the caliper is reduced too much to gain STFI !**

Typical ECT video history



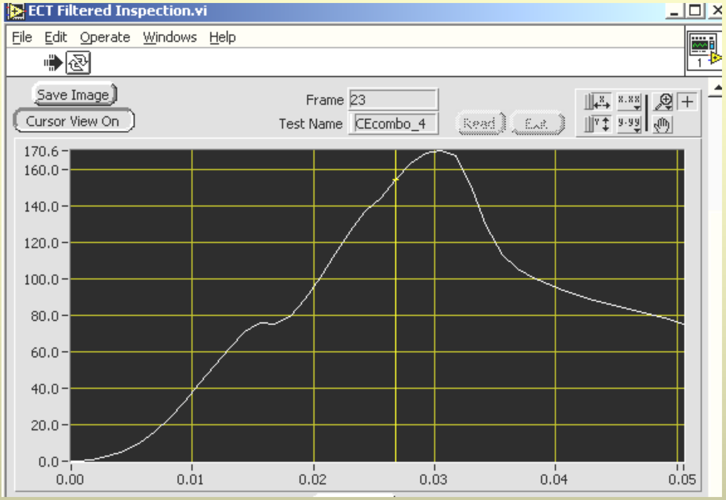


2) Peak load: 38.5 lb, strain: 1.6%

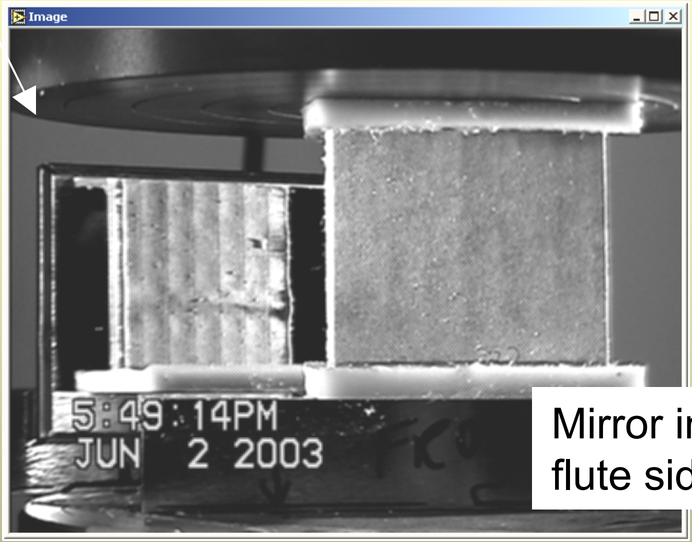
1) 35-26-35 liner, onset of buckling, stress: 32.8 lb, strain 1.3%

3) Cross face crease at 25.9 lb, strain: 2.1%

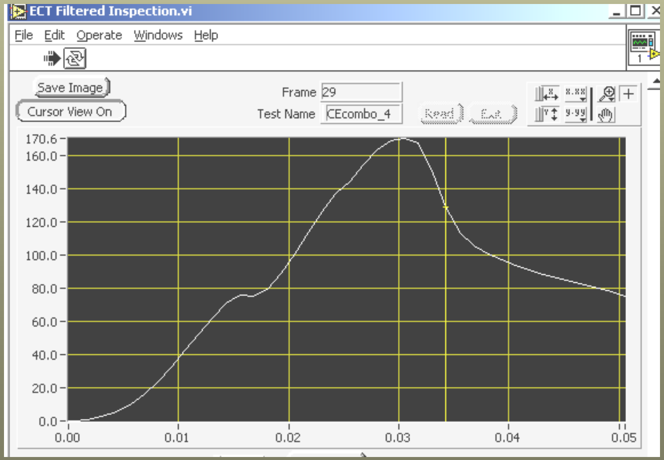
Video observation of CE double wall ECT, load/displacement data on the left, still frames on the right



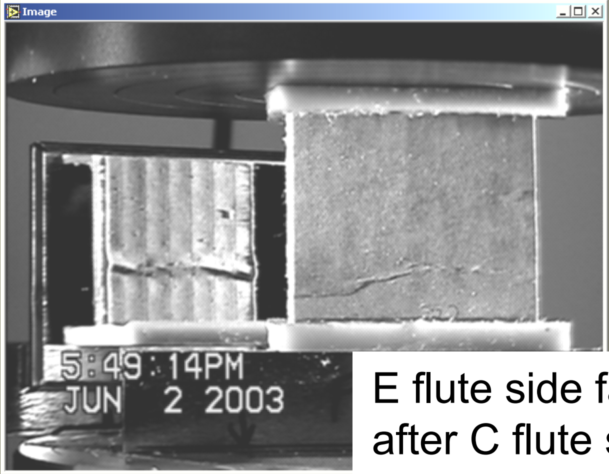
85.3 peak load, onset of C flute failure



Mirror image C flute side



Onset of E flute failure, happens post peak load

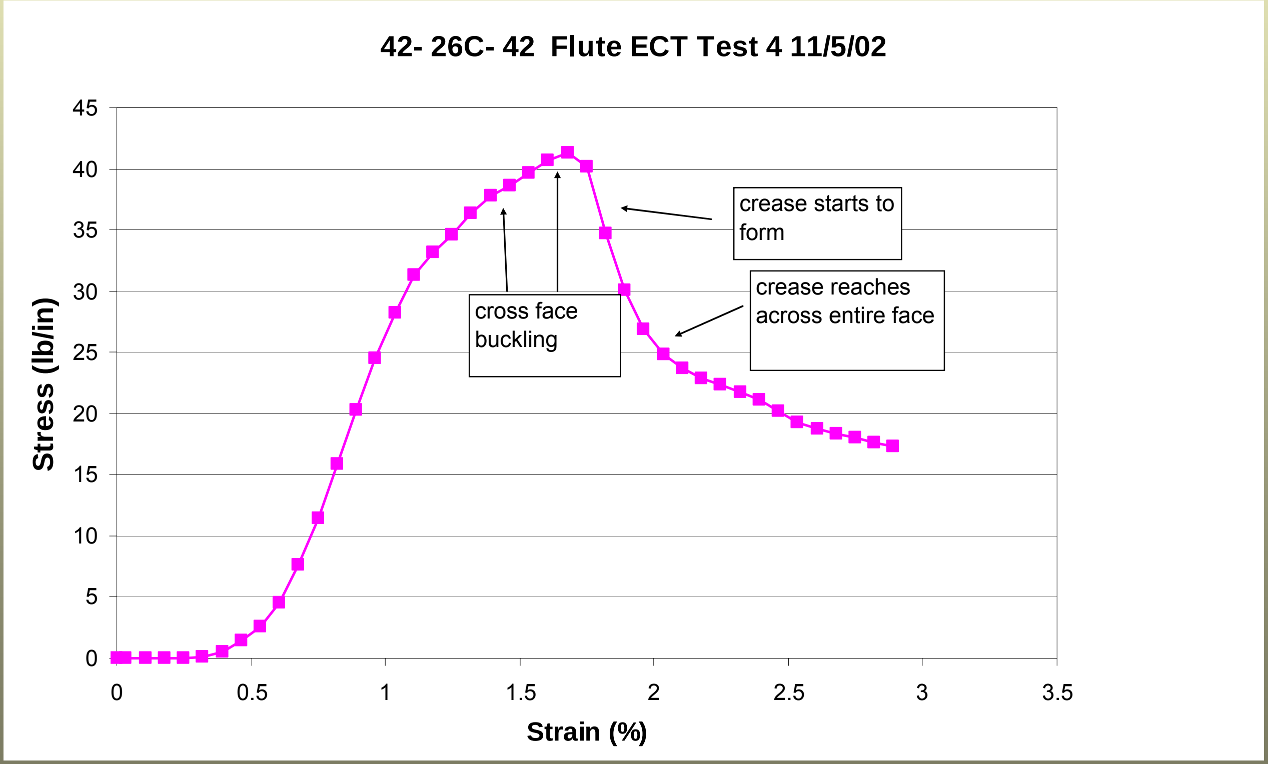


E flute side fails after C flute side

Typical Load-Strain Curve ECT test at IPST

Instron set-up:

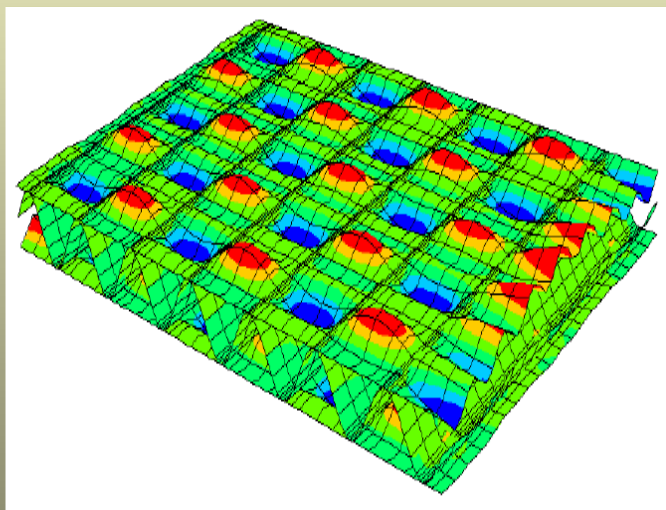
1. **0.5”/min strain rate, Instron stress-strain data output to video digitizing PC, 0.1 sec resolution**
2. **2” square samples Billerud cut edges embedded in Alumilite plastic resin pedestal mounts**



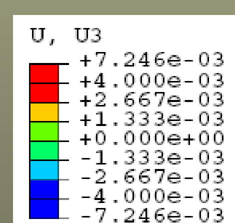
FE modeling of ECT, 1.75” free span, buckling wavelength predictions done by Civil Engineering group at Georgia Tech

- Simulations use measured elastic properties and stress strain data of components, non-linear elastic-plastic model and non-linear geometry, ABAQUS™ code – written up in Composite Structures 2008.

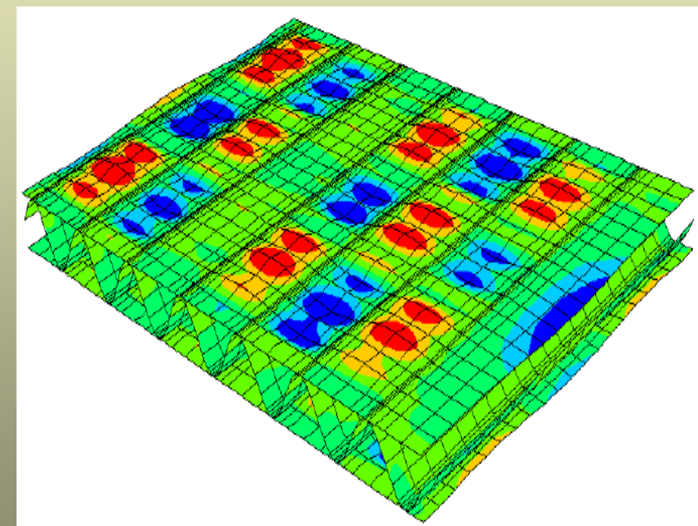
- Results correlate with experiments, A and C flute buckle, B flute does not buckle, there is no buckling of the medium , data support the buckling load formula



“Pinned” connection between liners and medium, λ = 2b



Out of plane displacement -inches



“Rigid” connection between liners and medium, λ = 0.5b

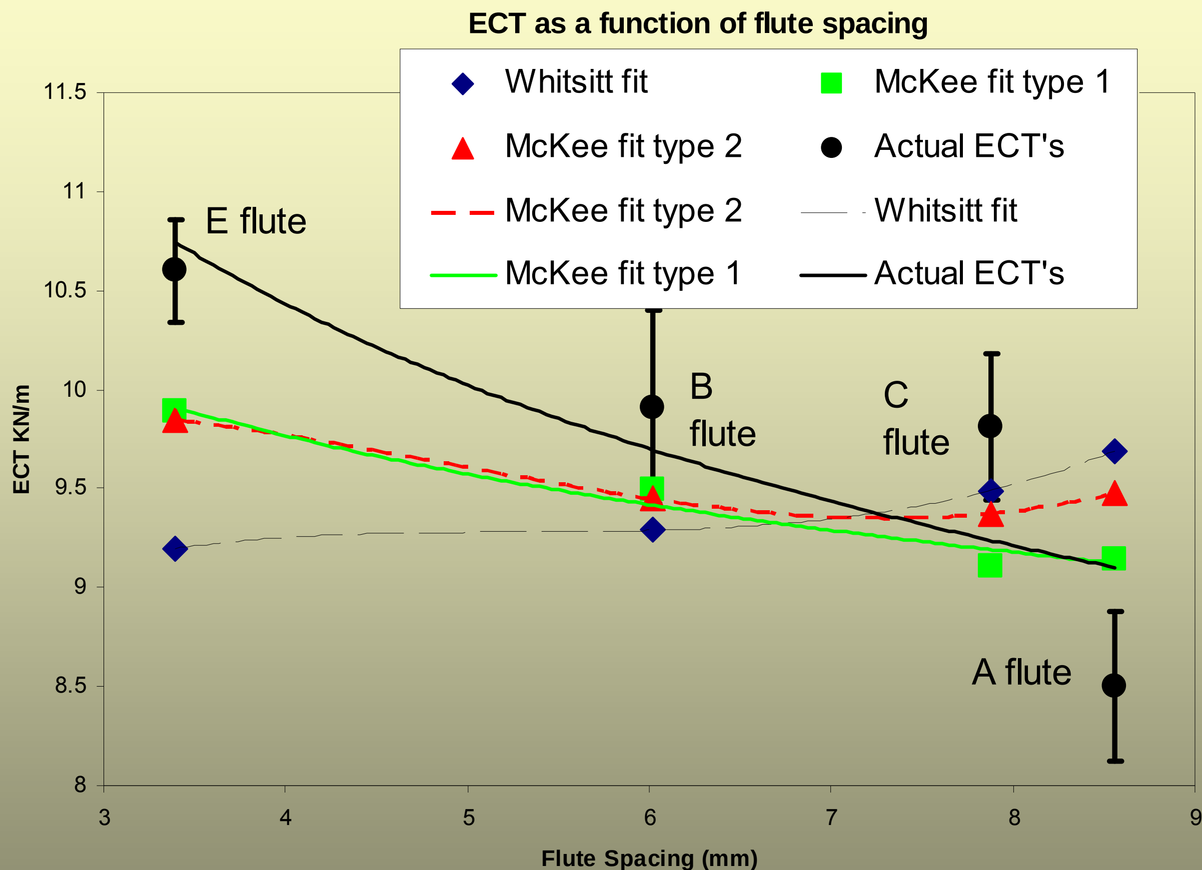
Since we have buckling in ECT – what can we do about it ?

$$ECT \propto 2\,x\,SCT_{liner} + \alpha\,SCT_{medium}$$

This is the conventional “Whitsitt” model for ECT relates compressive strengths (short span ***SCT***) of components to ***ECT***, suggests an optimization strategy…based on SCT – but there is no buckling on this model…

Can substitute Ring Crush for STFI (SCT) but then you get linerboard buckling failure in addition to compression failure – the “pro” debate here is that with RC you get lower variability – but the “con” debate is that it is harder to optimize – like Mullen burst

The problem with the Whitsitt model: ECT as a function of flute size all same medium and liner:



Whitsitt model is a summation of the SCT's weighted by the take-up factor for the medium length – no liner buckling in this model !!

"McKee" fits use SCT with Bending Stiffness to fit the data accounting for buckling

Boards here are all made from the same liner and medium, different flute sizes, buckling of the liners is thought to cause the observed ECT order

Larger flute size lowers the buckling load and hence the ECT

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: _________

Interflute buckling in ECT model: linear summation of liner and medium McKee terms originated with Whitsitt in 1963

191 - 43

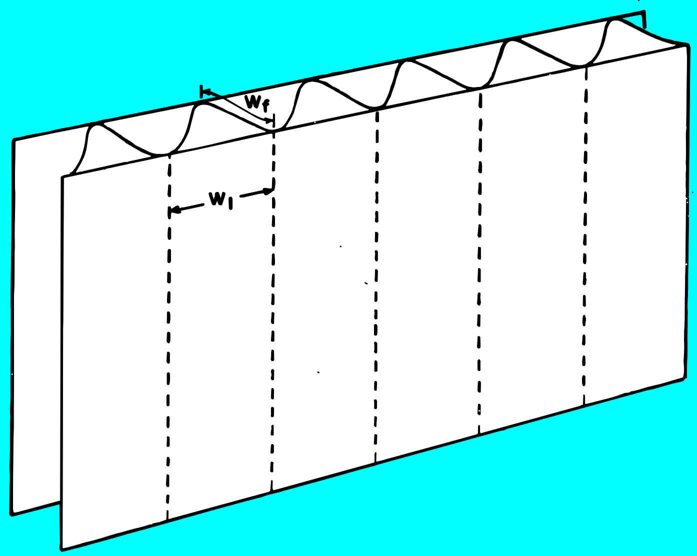


Figure 19. Corrugated board showing miniature liner and medium plate elements.

Following this approach the liner and medium contributions to ECT are formulated as follows:

Liners $$P_\ell = a\, P_{r\ell}^{\,b} \left(\sqrt{D_{x\ell} D_{y\ell}}\right)^{1-b} w_\ell^{\,2b-1} \quad (2)$$

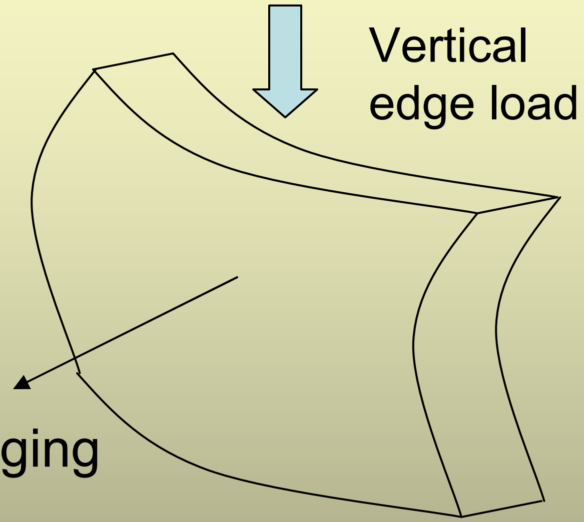
Medium: $$P_c = c\, P_{rc}^{\,b} \left(\sqrt{D_{xc} D_{yc}}\right)^{1-b} w_f^{\,2b-1} \quad (3)$$

W.J. Whitsitt, IPC Progress Report, "Optimization of Machine Properties for Compressive Strength: Survey of Factors Affecting Compressive Strength" March 15, 1982

Reference to a June 18, 1963 Preliminary Report "Relationship between edgewise compression strength of combined board and component properties":

linear summation of "Institute top load box compression formula" is a 5% accuracy prediction versus 7% using compression strength only

Consider the failure of a vertically loaded panel – we introduce the buckling load



The load to buckle a panel of width b, free to rotate at the edges, MD and CD bending stiffnesses D_1 and D_2 is:

$$P_{cr} = 4\pi^2 \frac{\sqrt{D_1 D_2}}{b^2}$$

A panel sustains an increasing load until it fails through a combination of compression and buckling:

ECT or BCT = (compression strength)^{b}(buckling load)$^{1-b}$

The above is the starting point for the McKee equation

We can put the linerboard buckling into a model for ECT

$$P_z = cP_m^{\,b} P_{cr}^{\,1-b}$$

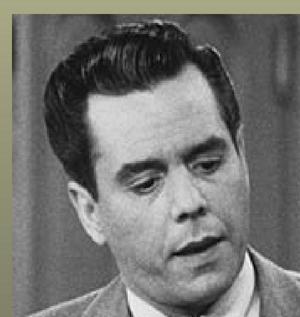
Failure load

Compression strength

Buckling load

Eeew!!... ***equations !!***

Ay, yay ,yay caramba…but hey, y'know Lucy… I tink eets really ***seempol***…



Buckling load for a loaded panel of width b_f :

$$P_{cr} = \frac{4\pi^2\sqrt{D_{11}D_{22}}}{K b_f^{\,2}}$$

K ~1 if the edges are able to pivot

We can calculate the buckling load P_{cr} using MD and CD Bending Stiffness D_1, D_2

We did a lot of work with an L&W 2 point stiffness tester, a more straightforward design, cross calibrated instruments with stainless steel shims.

Taber has historically been used for 2 point bending stiffness of liners and medium, Taber measures **bending *moment*** M **<u>not</u>** stiffness EI/b !

From linear elasticity theory, the conversion factor from Taber moment M to stiffness D is:

$$D = \frac{EI}{b} = M\left(\frac{L}{3\theta b}\right) = M \times 1.67$$

This means that Taber x 1.67 → bending stiffness !!

So buckling happens in ECT and BCT – we can put it into a model

An 1963 IPST report mentions a "McKee equation"- like approach to incorporate lightweight liner interflute buckling during ECT:

$$ECT \propto 2(SCT_{liner})^{b}(\sqrt{D_{MD}D_{CD}}/b^{2})^{1-b} + \alpha\, SCT_{medium}$$

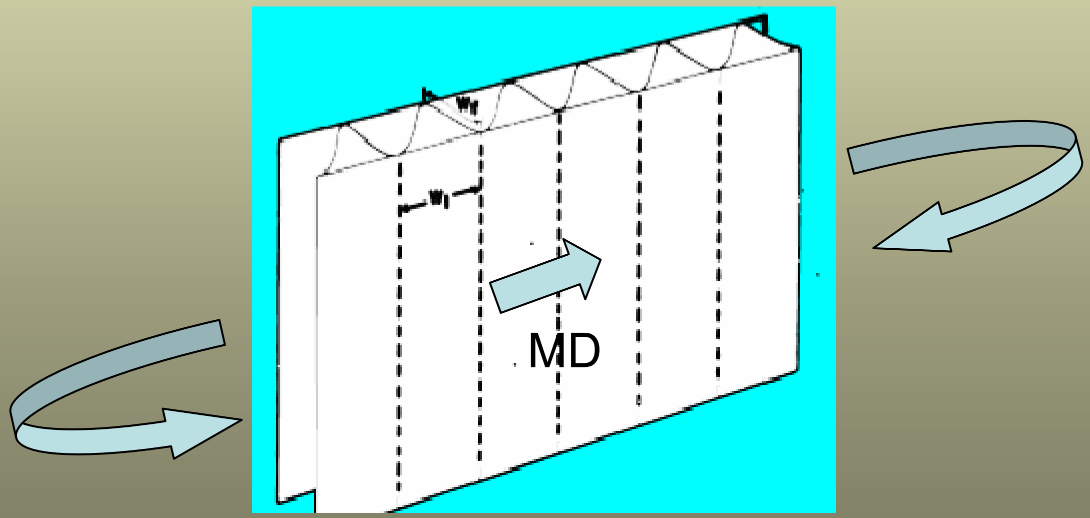
The premise behind this equations is the same as used by McKee in deriving the BCT failure load equation:

1) Use the model of a vertically loaded panel
2) A panel fails mostly by compression failure and in part by buckling

The model says you can optimize ECT with SCT but *not* at the expense of bending stiffness

Fun Fact

- Machine made paper has the paper fibers oriented in the along the machine direction MD



So, because of this, it is actually harder to bend corrugated board along the flutes than across the flutes

Try it !!

Criterion for Buckling in ECT

Liner compression strength (SCT) > Buckling load

Expressed as:

→ SCT (kN/m) > P_{cr}

→ SCT (kN/m) > $4\pi^2(D_1D_2)^{1/2}/b^2$

This occurs for 42# and lighter linerboards on A and C flute, borderline on B flute

How to do the calculation for P_{cr}:

Get MD and CD bending stiffnesses either from Taber (note: for Taber, ***must*** multiply Taber output by 1.67 to convert from moment to stiffness) or use L&W 2 point tester (set to 15 degrees or use a shorter span to get more sig figs on readout → use the mN readout and convert to stiffness using the 2 point bending formula)

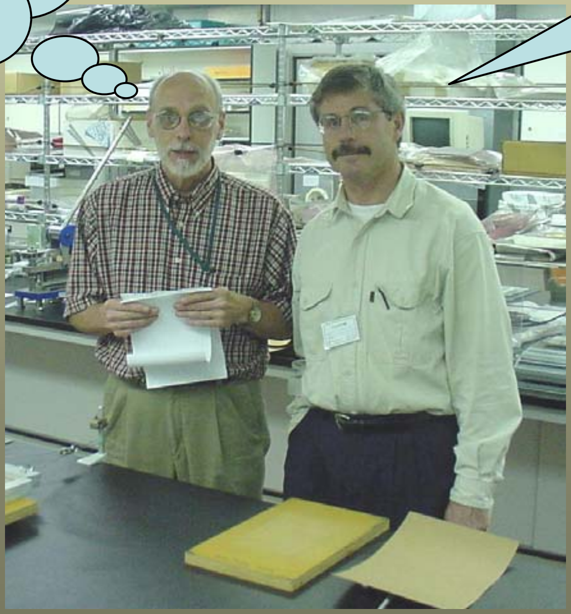
ECT buckling model summarized

$$ECT = C'\left\{2\times(SCT_l)^b(P_{cr})^{(1-b)} + \alpha(SCT_m)\right\} \ \textit{if} \ \ SCT_l \ge P_{cr}, \textit{ liner buckling occurs}$$

$$= C\left\{2\times(SCT_l) + \alpha(SCT_m)\right\} \ \textit{if} \ \ P_{cr} \ge SCT_l, \textit{ "Whitsitt" formula holds}$$

Hmm…why did we let this guy in here again ??

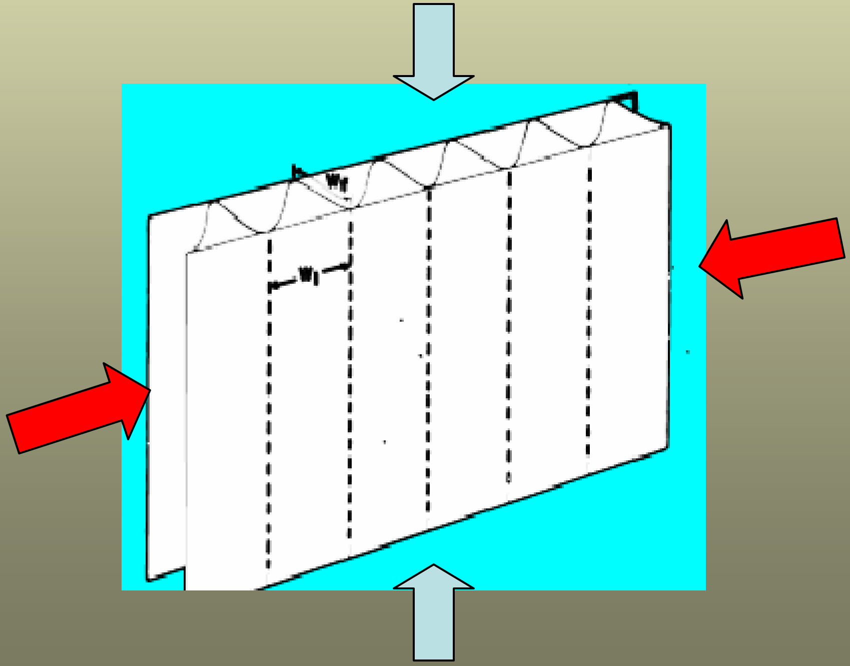
*Oh,oh oh… yeah, yeah..,sure sure, oh there's **buckling** in there alright …*



Keith Bennet and Chuck Habeger (scientists) at Weyerhaeuser R&D August 2002 checking out interflute buckling

Fun Fact

- <u>Question</u>: If fibers are aligned in the MD shouldn't ECT of corrugated board be also larger in the MD



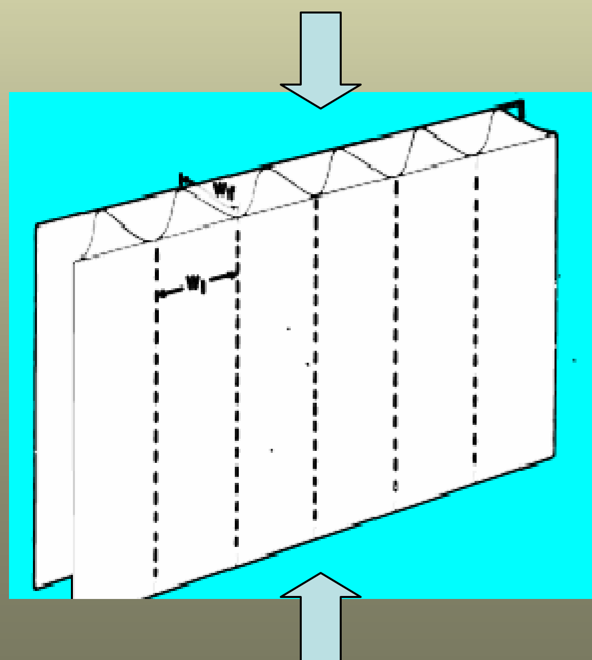
Which way will the board be stronger ?

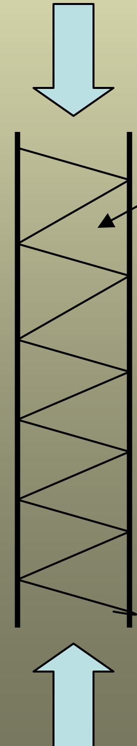
a) Red arrows MD or…

b) Blue arrows CD

Fun Fact

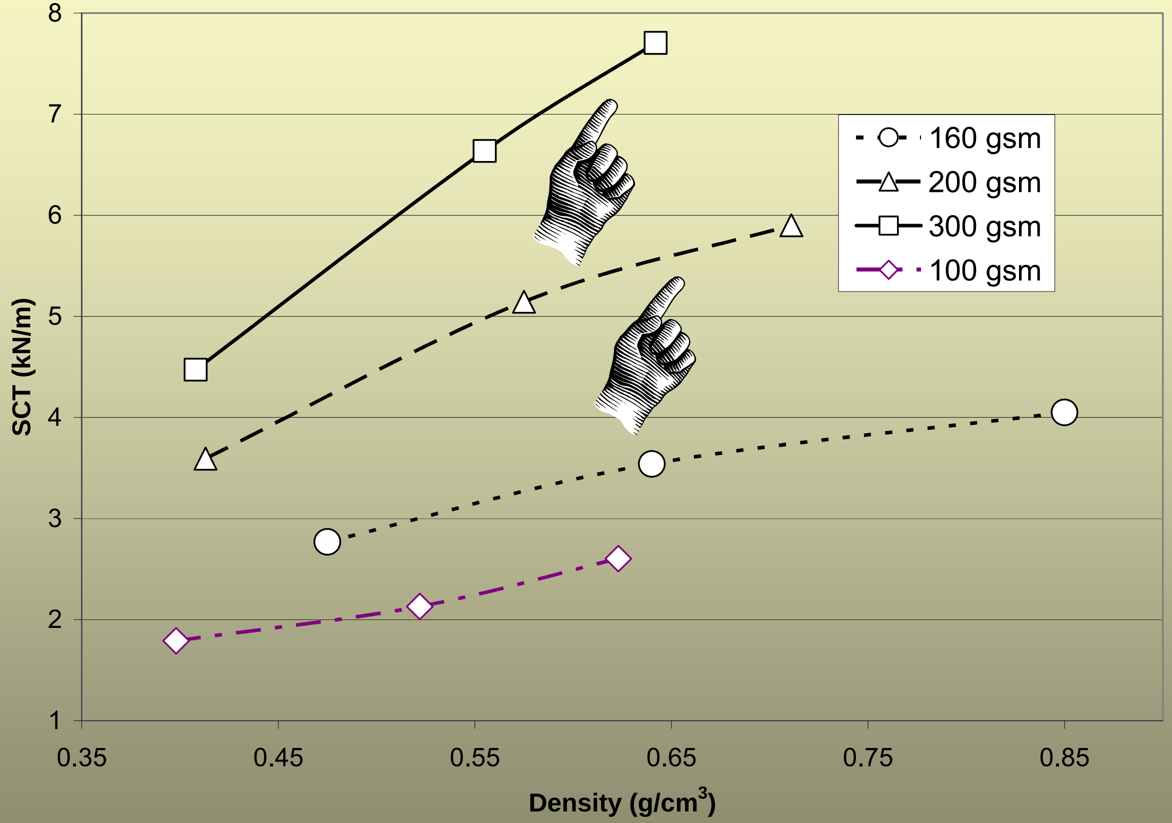
Answer: Corrugated board is stronger in the CD because of the contribution of the medium





Along the MD, SCT is larger, but the fluted medium does not contribute to compression strength

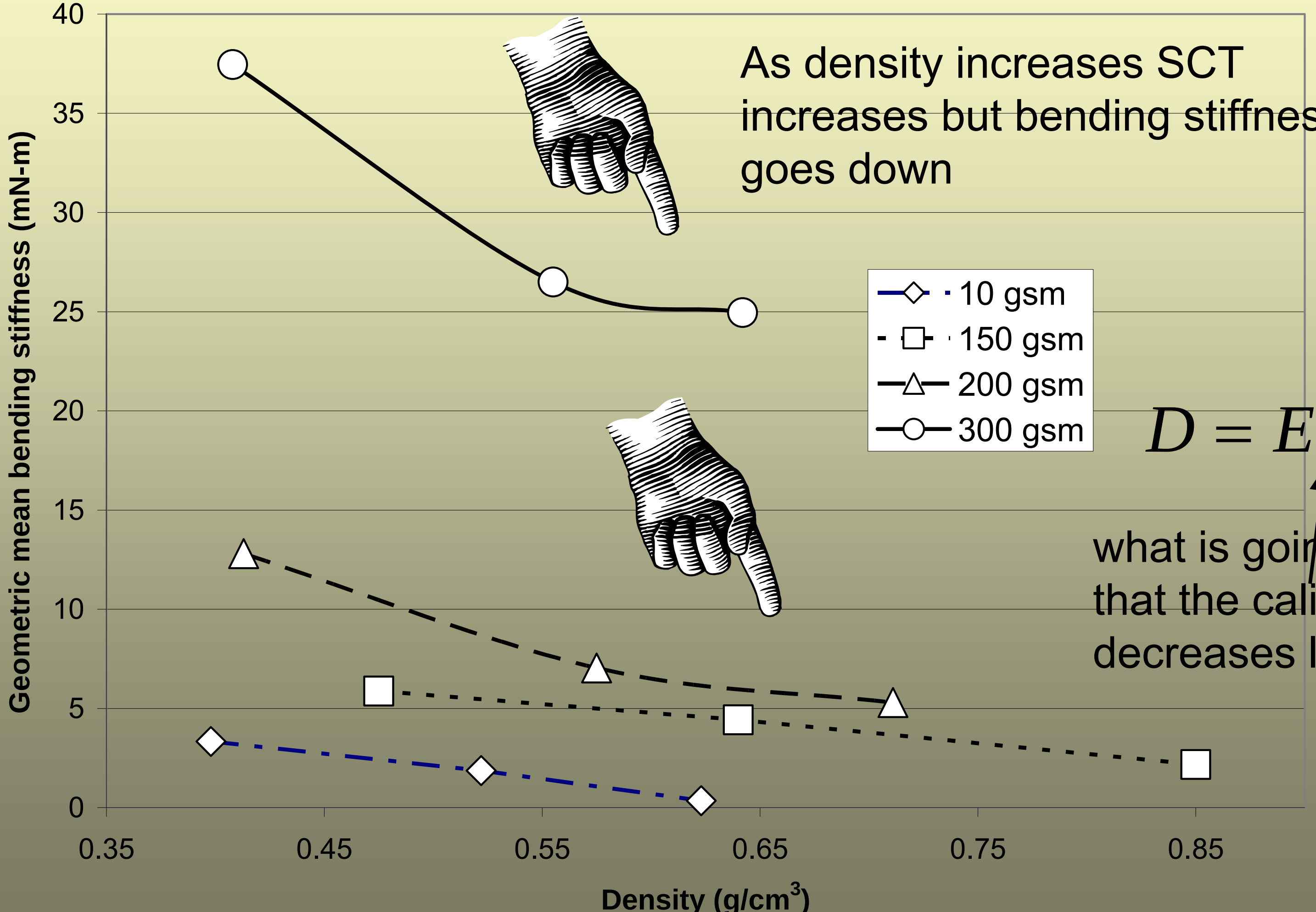
A series of boards were made from spliced handsheets of different basis weights pressed to various densities



SCT (linerboard strength) increases with sheet density – happens with extended nip pressing

Short span compression (SCT, aka “STFI”) strength results for handsheets wet pressed to various densities.

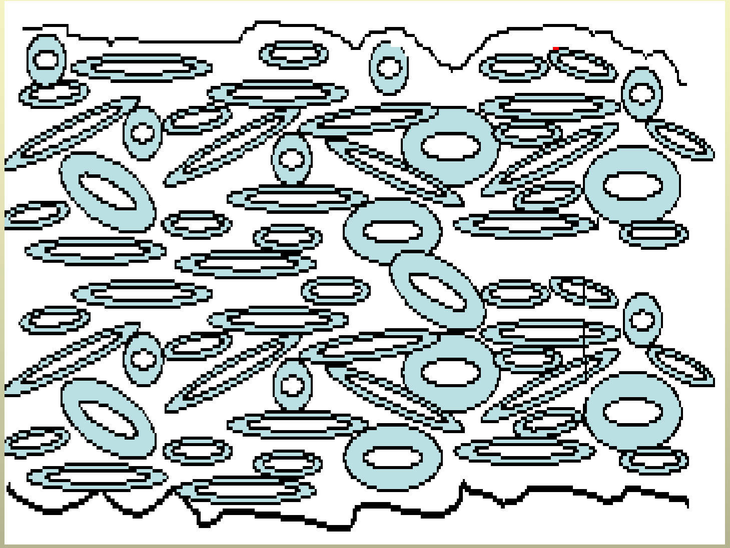
Wet pressing increases SCT but lowers bending stiffness



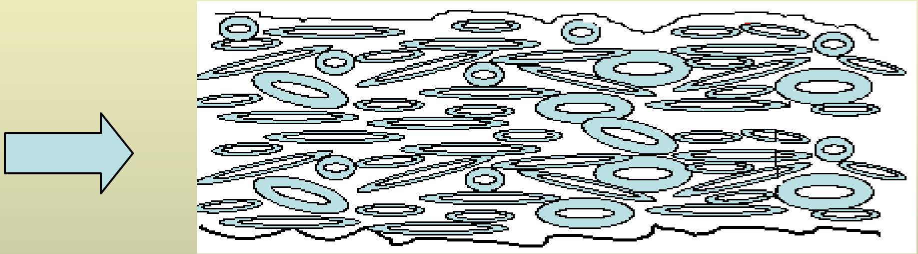
$$D = Et^3/12$$

what is going on is that the caliper decreases lowering D

What’s going on in wet pressing

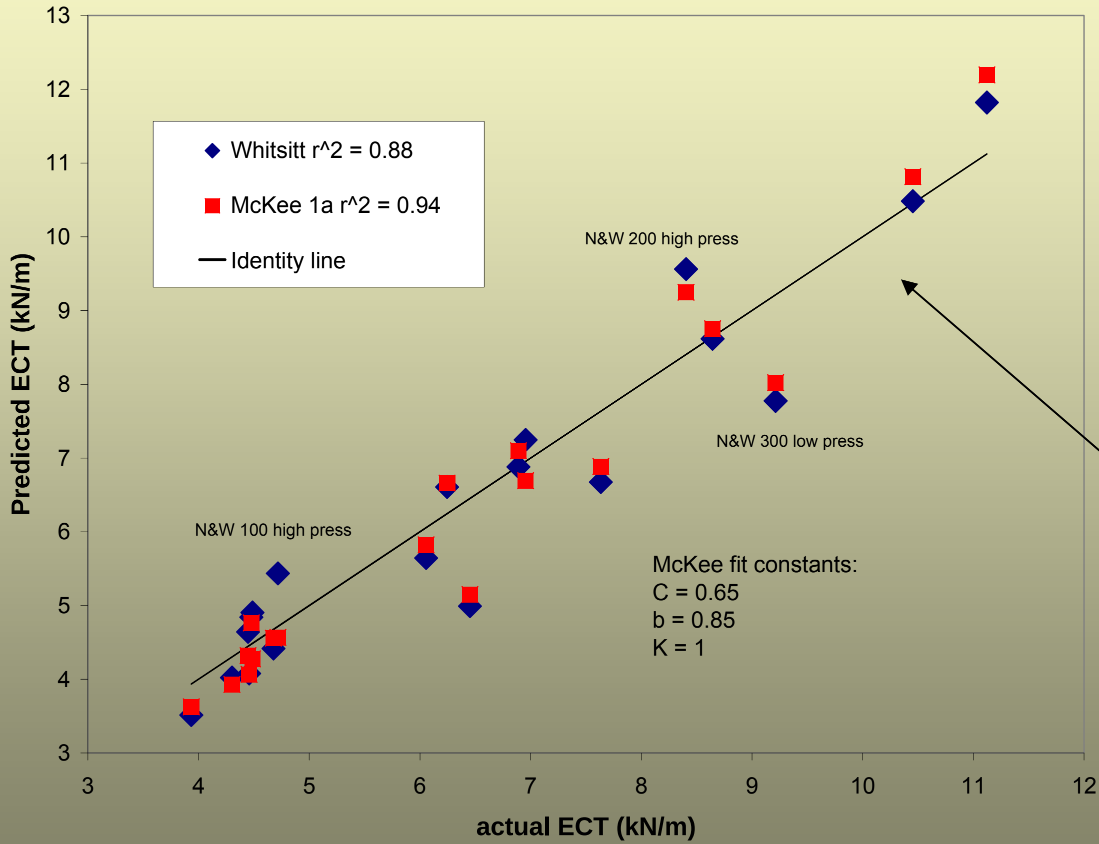


In wet pressing the sheet has been formed by draining the pulp stock but is not pressed and dried



More water is removed from the drained pulp stock mat by pressing, with higher pressure: Caliper decreases, bonding between fibers increases, bending stiffness decreases

So, applying the ECT buckling model to a series of boards made with spliced handsheets

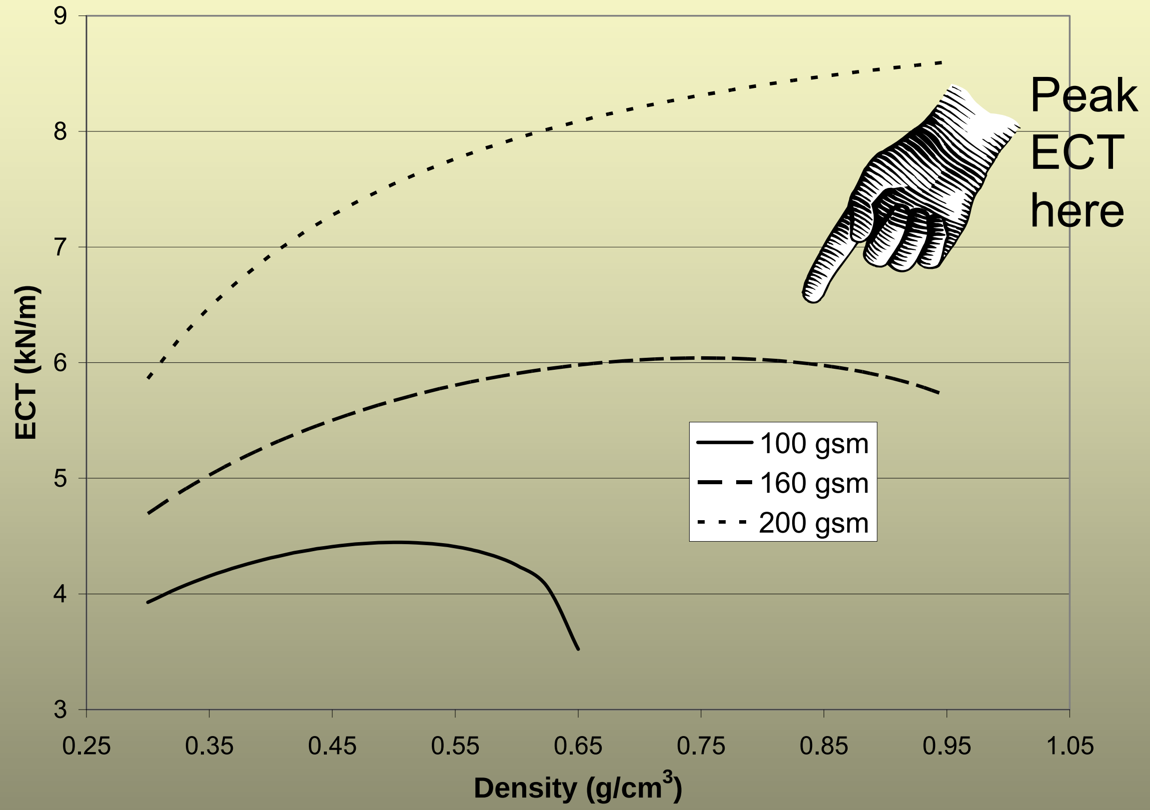


Comparison between predicted and actual R^2 goes from 0.88 to 0.94 when buckling is considered

Identity line

Predicted versus actual ECT for boards prepared with handsheet linerboards pressed to various densities.

The ECT buckling model is used to predict the optimum liner density for ECT



The ECT buckling model predicts the optimal density for 160 gsm liner single wall C flute to be .75 g/cm^3

Here, the data for SCT and bending stiffness as they have found to vary with density are plugged into the ECT model.

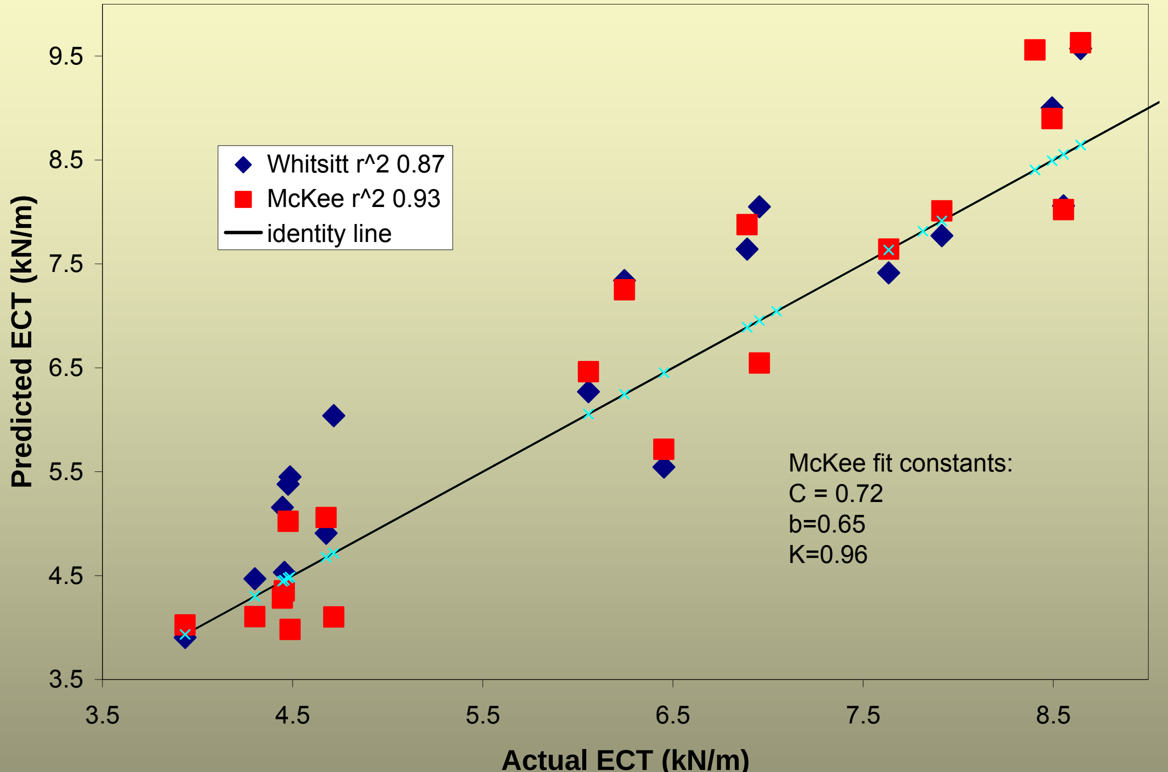
What the model and data tell us

- ECT is a combination of compression and bending failure

- linerboard can be made stronger with increased density achieved by higher pressure wet pressing but…

- The linerboard becomes flimsier so get more localized buckling, limiting the ECT

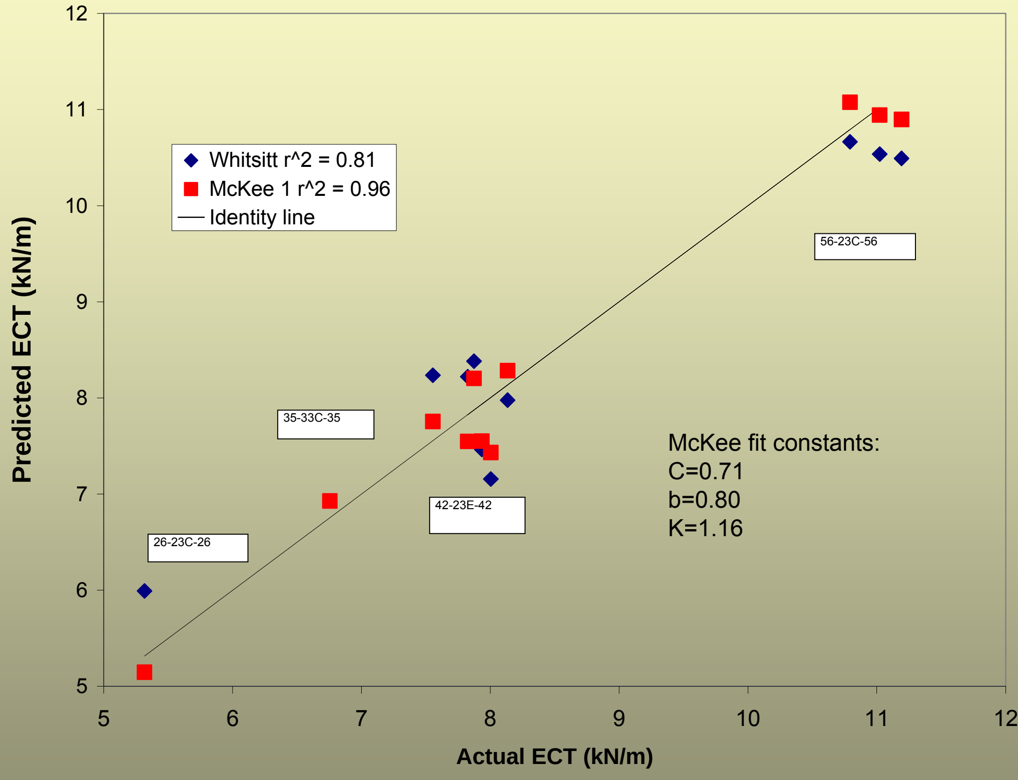
Applying the ECT buckling model to a series of IPST lab-made boards



The r^2 of predicted values with actual goes from 0.87 to 0.93 when buckling is considered.

Comparison plot of predicted versus actual ECT values of the IPST lab made board data set of corrugated boards

Applying the buckling ECT model to a commercial board sample set



Yeah, man…an ECT model with buckling is way ***cool*** !!

Henric Kent of IP Tuxedo Park attending the 1987 International Paper Physics Conference

R^2 of predicted values goes from 0.81 to .96 when buckling is considered

Comparison plot of the predicted versus actual ECT values for a range of commercially made corrugated boards.

Summary of the check of the buckling ECT model

Data Set	ECT Model	C or C’	b	K	R^2
1) All board	Whitsitt	0.717	1		0.857
	McKee	0.743	0.665	1.02	0.915
2) Commercial board	Whitsitt	0.766	1		0.813
	McKee	0.795	0.710	1.16	0.960
3) N&W and Formette	Whitsitt	0.695	1		0.881
	McKee	0.646	0.849	1	0.936
4) all IPST lab made board	Whitsitt	0.703	1		0.871
	McKee	0.717	0.651	0.956	0.931

- improved accuracy in predicting ECT
- optimize ECT for lightweight linerboards