The BCT of Copy Paper Boxes – Applying McKee's Formula

Roman Popil, Ph.D.
Senior Research Scientist
Paper Analysis Lab Manager
Georgia Tech/Institute of Paper Science and Technology
Atlanta, Ga.

Problem definition

- Copy paper supplier/end-user (IPST testing services client) wishes to know who provides boxes of what strength for xerography copy papers – world-wide

- Supplier/end-user has limited/minimal testing capability but needs some (easy) means to predict BCT for stacking strength

- Office practice is to store copy paper pallets (5 x 5 x 5 boxes high) stack failure occasionally occurs, requiring restacking

Does BCT of copy paper boxes matter ?

Typical storage conditions at IPST

Pallets at Office Depot are 5 high

Close up of bottom edge shows edge-roll damage

What's different about Copy Paper Boxes:

- Stacking strength usually not a concern for design since the paper reams provide vertical support
- Design is "tray with cover" style, the board is used to "wrap" the product, side panels are often oriented with vertical load in the MD
- Footprint (box length and width) is constant (for this study), panel structure and flap designs vary

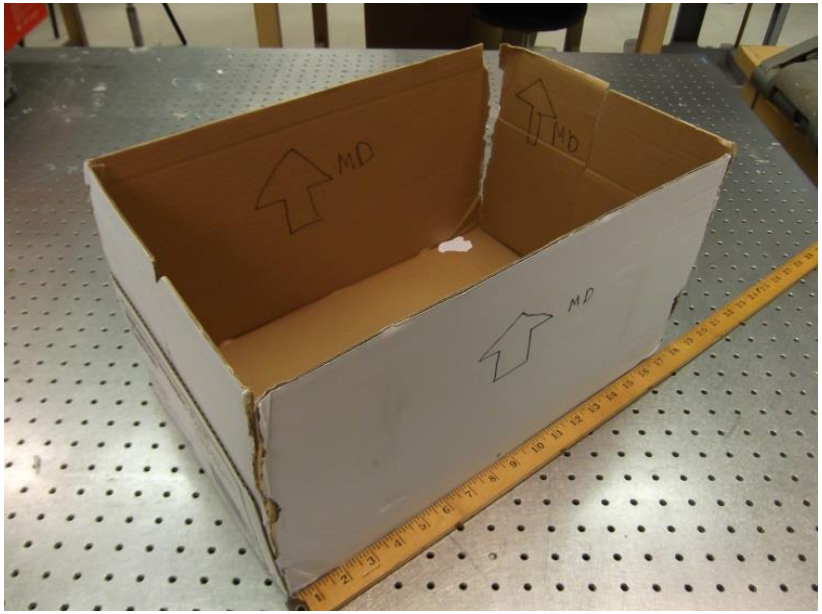
Copy paper boxes reassembled and ready for BCT

23 of the 42 boxes are constructed so the side panels have stack load in the board CD

Typical 5 pack copy paper box with the load along CD of the panels

A copy paper box loaded with 5 reams of paper weights 26 lbs.

Boxes with loads **along the MD**



42 different copy paper boxes – can the McKee formula be used to predict BCT ?

- Z (perimeter) is constant (41 inches)
- load supporting panels are oriented MD or CD
- Boxes have a tray lid
- Boxes for lab study were all supplied post-use

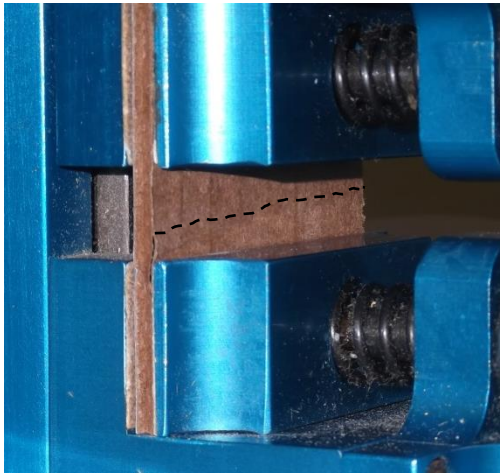
Approach

- Boxes collected by client were reassembled with hot melt at IPST
- Boxes were tested for BCT with their trays on
- Box bottom flaps were tested for caliper and ECT (T 839) in MD or CD
- Simplified McKee equation applied to fit the data

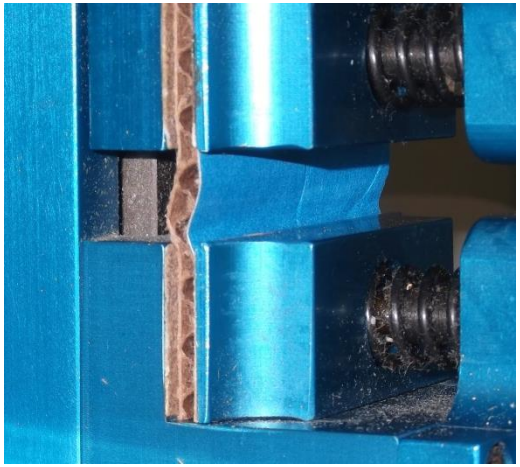
BCT of assembled boxes

Boxes were tested empty with the top lid trays on

ECT in the MD is a lot less



Medium fluting contributes to ECT when loaded in CD



When load is along the MD, the board fails by buckling

- B flute copy paper box board ECT along CD is 36lb/in, along the MD it is 16 lb/in

- One box with 5 reams of paper weighs 26 lbs, many bottom boxes in a pallet stack of 5 boxes are at their BCT failure load !!

Simplified form of the McKee model

$$BCT = 5.87 \times ECT \times \sqrt{t \times Z}$$

- Equation derivation assumes:
  - Square footprint box
  - No shear
  - Boxes are high enough for panel buckling
  - Panel buckling is proportional to “sandwich beam” bending stiffness which is proportional to tensile stiffness of the liners
  - Tensile stiffness of the liners is proportional to ECT
- But, ease of use makes this a preferred model, accuracy sufficient for many estimates

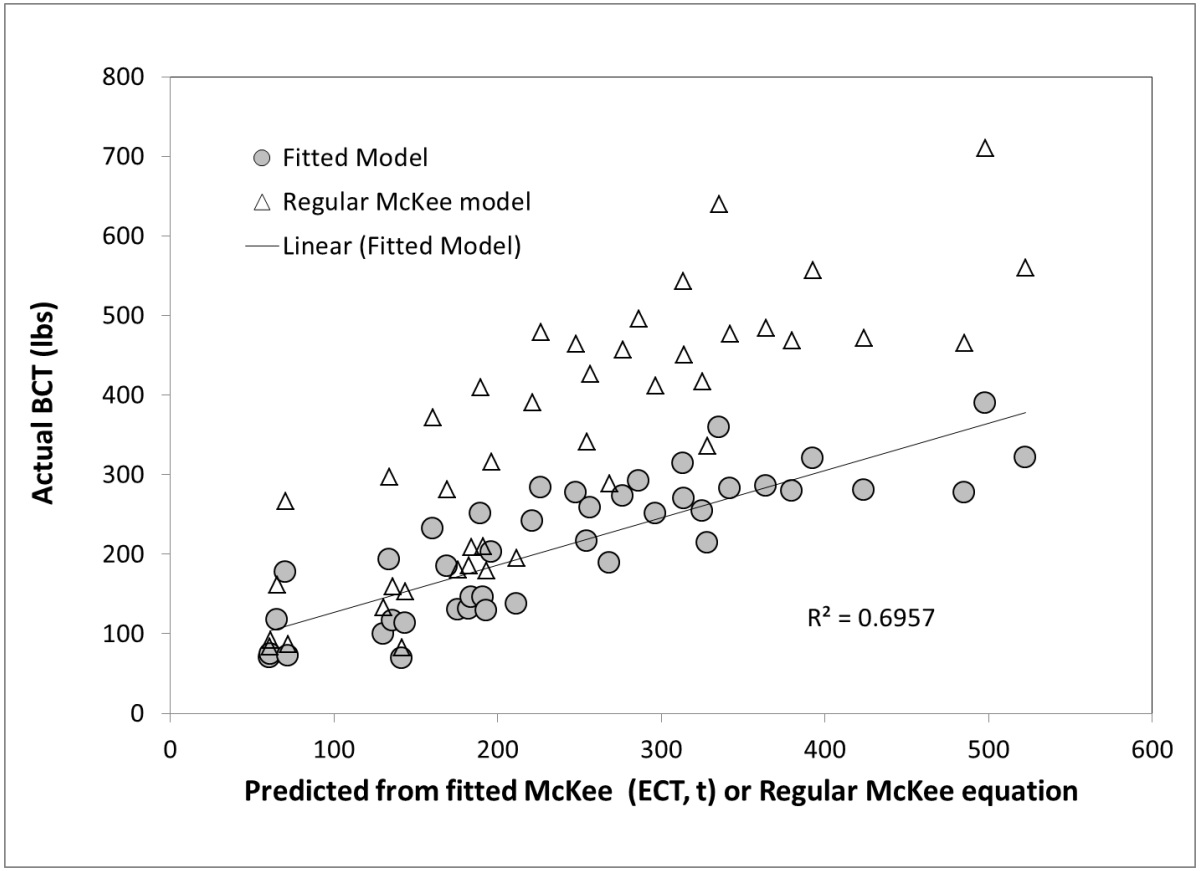
Fitting a "McKee" BCT to the data

$$BCT_{(lbs)} = C \times ECT_{(lb/in)}{}^{a} \times t_{(in)}{}^{b} \times \sqrt{41}$$

- Assume basic form of the simplified McKee equation can describe the BCT of copy paper boxes
- Fit data using ***ECT*** and ***t*** measured from the bottom panels
- Excel® Solver function is used to minimize the difference between the fitted McKee and actual BCT by iteratively changing ***C, a,*** and ***b***

Fitted form of McKee for Copy paper boxes

$$BCT = 6.03\ ECT^{0.803} t^{0.844} \sqrt{\{41t\}} = 38.6\ ECT^{0.803} t^{0.422}$$



Units: BCT lbs, ECT lb/in, t inches.

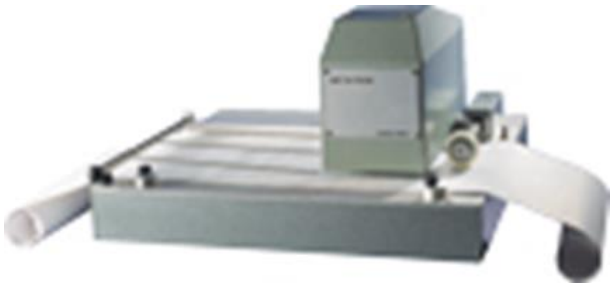
Actual BCT vs Model Predicted values

- Original McKee equation: $BCT = 37.6\ ECT\ \sqrt{t}$ generally predicts values that are too high, average error 52%

- Fitted McKee model: $BCT = 38.6\ ECT^{0.804}\ t^{0.422}$ predicts values closer to actual, average error 25%

- Client can now predict BCT from measurements of ECT (in CD or MD) and caliper of the board

Can the TSO replace ECT testing ??



Elastic modulus ***E***, density ***ρ*** and speed of sound ***V***:

$$E \cong \rho V^2$$

V² is called ***TSI_CD*** or ***TSI_MD***

$$E \times t = \rho t \times V^2 = \text{basis weight} \times V^2$$

So, if we measure the **basis weight *BW*** and the **speed of sound squared *V²*** - we get the tensile stiffness ***Et***

McKee (1963) assumed and showed the proportionality of tensile stiffness ***Et*** to ***ECT*** of the board - so why not measure ***V²*** of corrugated board <u>instead</u> of ECT ? ***No cutting, no waxing, no clamping…***

Using the TSO to predict ECT of corrugated boards – an idea:

$$ECT \approx 0.7\,(2 \times SCT_{liner} + 1.42 \times SCT_{medium})$$

1. TSI_CD = $\boldsymbol{E_{CD} \times t}$ = ***basis weight x*** $\boldsymbol{V_{CD}^2}$

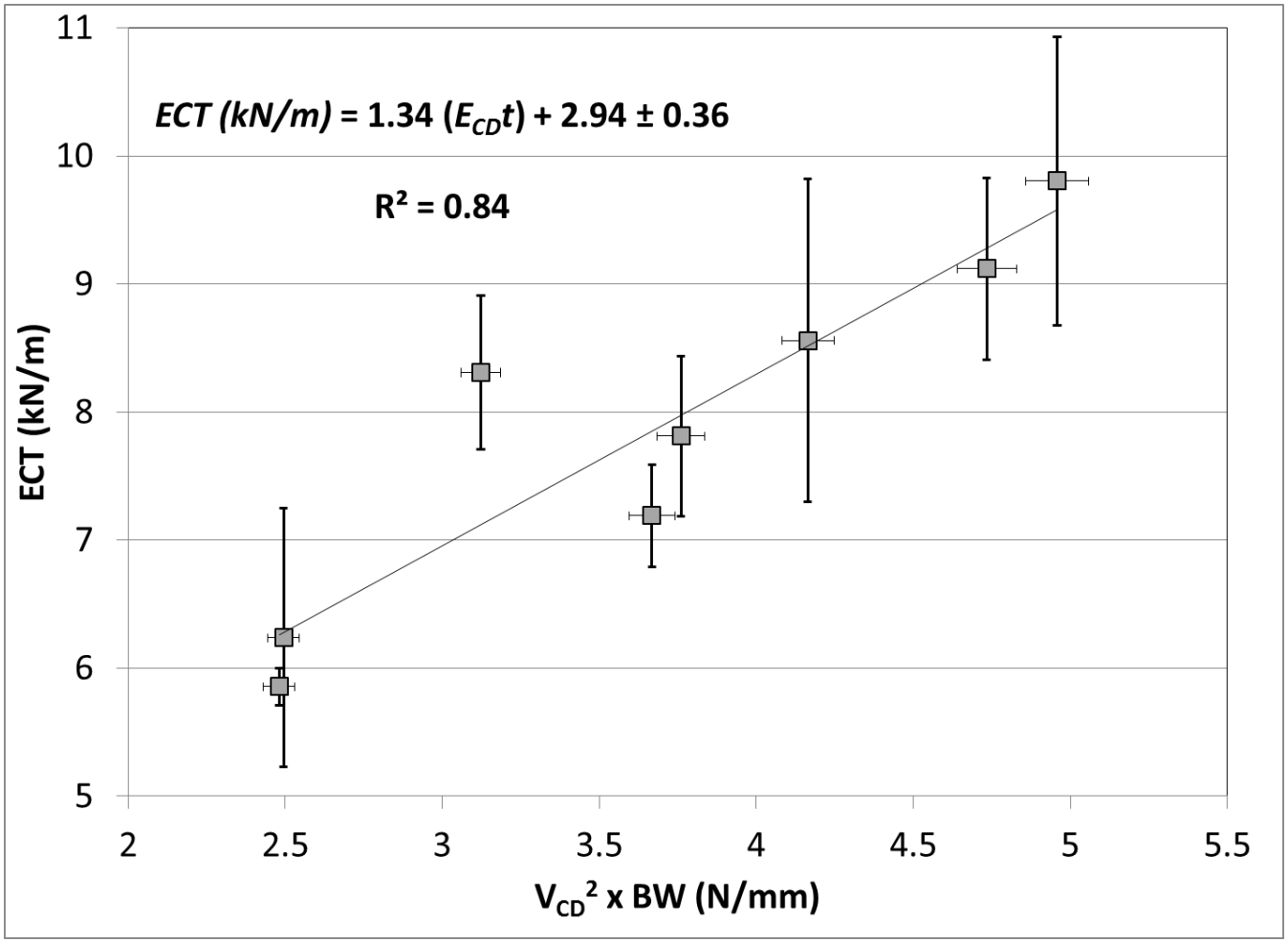
2. Wavelength $\boldsymbol{\lambda}$ of ultrasonic sound waves of 100 kHz exceeds thickness **t** of boards:

3. $\boldsymbol{\lambda}$ = 2.7 km/s/100 KHz ≈ 2.7 cm

4. Sound waves propagate along the board through the whole board

5. Therefore ECT ≈ (***board basis weight x TSI_CD***)

ECT of lab-made A flute boards with different weights of medium, all have the same liner weight



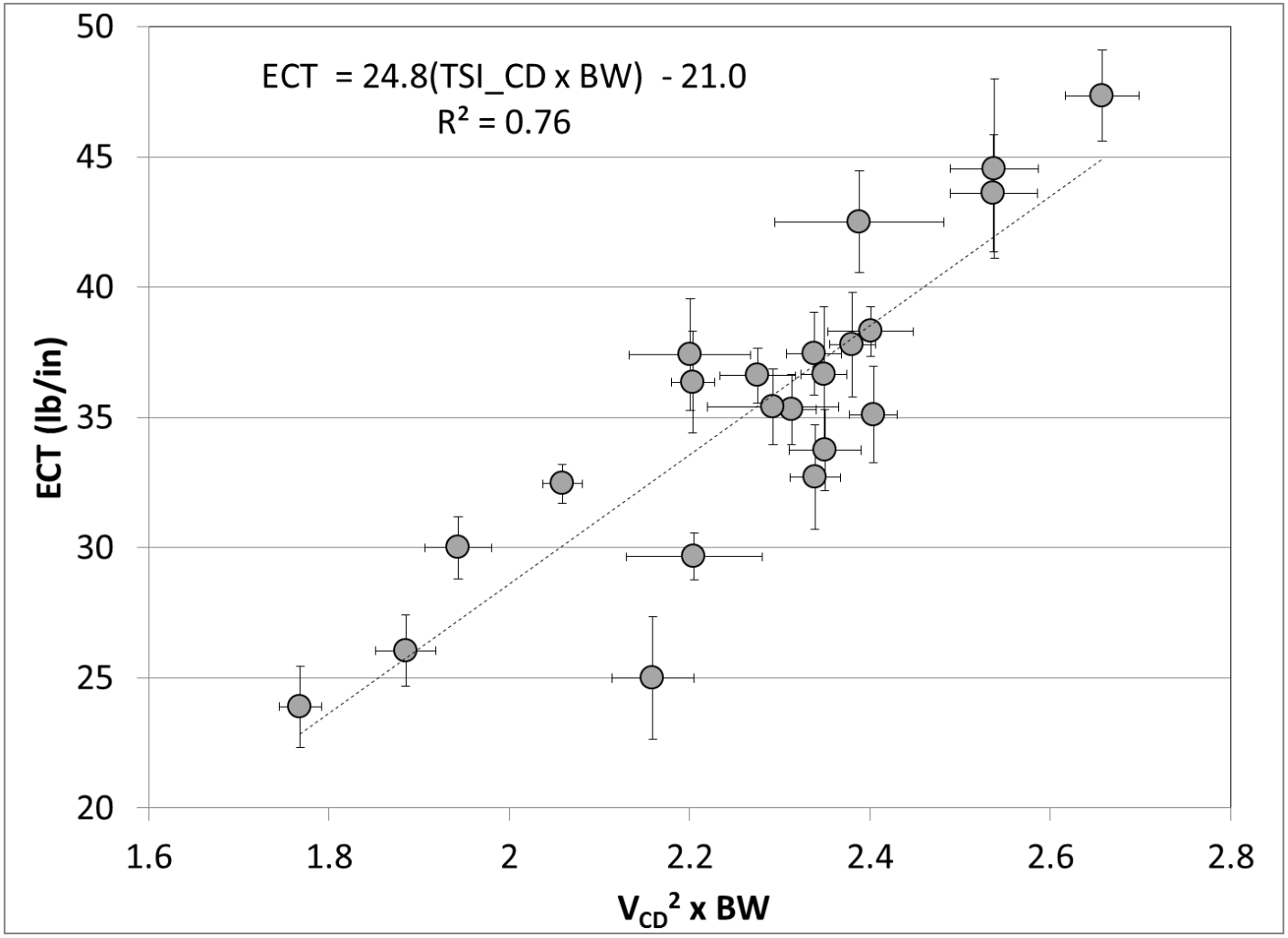
– here the TSO detects changes in medium strength

Now back to the Copy Paper Box set from Southeast Asia:

Can Ultrasonic Testing Replace ECT ? (*maybe !*)

- Shipped boxes submitted by client were reassembled, tested for BCT, bottom flaps for ECT
- Side panels were ultrasonically tested <u>*after*</u> (!) BCT
- Used $\boldsymbol{V_{CD}^2 \times BW}$ for those boards where vertical loading of the side panels is ***in the CD***
- $\boldsymbol{V_{CD}^2 \times BW}$ correlated well with ECT

Correlation of Copy Paper box ECT with ultrasonics



Average variation in ECT ~ 8%, variation in TSI x BW ~ 2 %

Summary

Contemplating a world without damaged boxes ...

1. A modified simplified McKee equation can be used to predict the BCT of copy paper boxes using board caliper and board ECT

2. Copy paper boxes with vertical load in the CD of the board have higher BCT, (of course !)

1. Ultrasonic *TSI_CD* with board basis weight predicts *ECT* of boards loaded in the CD *with* ***less variation*** – can be a new convenient quality control check i.e., no cutting, no sample prep, …

Thank you! Send questions, comments, testing samples to: Roman@gatech.edu

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