Effect of Component Properties and Orientation on Corrugated Container Endurance

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Scientific objective: develop an understanding of effects of physical properties on box lifetime

- what factors govern the lifetime of stacked boxes
- how can we quantify the effects to predict performance?
• Boxes vertically stacked
• Experience creep, i.e. progressive vertical displacement
• Lifetime of boxes is shortened by 5X under cyclic humidity conditions…
• This is…
  “Accelerated creep”

This bottom box has the classic panel buckling structure appears ready to collapse in about 30 minutes from this time of snapshot.

This guy won’t be smiling too much longer.
Hygroexpansion of board components changes how the box handles load

Outside (double face) of the box absorbs moisture and expands largely in the vertical direction.

Inside of the box (single facing linerboard) remains the same dimensions until it equilibrates to the same moisture level.

Humid outside

Dry inside
Hygroexpansion increases the stress

High Humidity outside

Low humidity inside

Load from stacked boxes

Box wall side view

Double face linerboard experiences additional stress from its expansion from absorbed moisture
The situation reverses when the humidity outside decreases.

As outside humidity changes, the outside liner of the box experiences a different vertical stress than the inside of the box which is at a different moisture level – so the load is not evenly distributed through the cross section of the box wall.

Phenomenon discussed and modeled numerically by Coffin and Habeger JPPS 2001.
Paper fails when combined stresses exceed paper strength

A buckling pattern forms, the buckles eventually join to form a crease which leads the board to fold and the box to collapse.
Experimental design

• Hypothesis: if we make the corrugated board more uniform by having a heavier fluted medium, stresses are more equalized → get more lifetime !!

• So, at IPST we made a series of corrugated boards all using the same linerboard facings but with different weights of medium ranging from 14# to 42#
Experimental study to determine effects of board properties on BCT cyclic humidity lifetime

- Varied the fluted medium basis weight from 68 to 205 gsm
- Linerboard basis weight is constant at 205 gsm
- Boards and boxes made at IPST Pilot Plant
- Box dimensions: 36 x 20 x 20 cm

- Selected flute size “A”
- MD shear rigidity measured by IPST torsion pendulum ranged from 2.9 – 8.6 kN/m
- Static loads set for each type of box to be at 22.5% of BCT failure load
Preparation of various test boxes

Medium of various basis weight were combined with 42# linerboard using the IPST pilot corrugator

RSC boxes were manually prepared from the IPST made boards
Accelerated creep experiments

- Expose either corrugated board or boxes to humidity varying from 50 to 80% RH, keep temperature constant
- For board samples, vary humidity using a ten hour period
- For boxes, vary the humidity from 50 to 80% RH in a 24 hour period (mimics weather conditions od southeast US)
Basic experimental set-up

- Vertical load @ ~20% of failure load
- Displacement sensor
- Data acquisition using LabView™ records vertical displacement with time up to several months
- Test specimen
- Temperature maintained at 23 deg C, humidity varied from 50 to 80% RH
Creep measuring equipment at IPST

For Test Boxes, inside a programmable humidity walk-in chamber:

BCT creep: 8 stations, 50 – 80% RH
24 hr cycle - used to obtain multiple regression models for lifetime prediction.

For board samples:

ECT creep, 12 stations, 50 – 80% RH 5 hour cycle - applied to the A flute varying medium basis weight set to compare with BCT creep – also used for client contract work.
ECT creep stations

ECT specimens epoxied onto horizontal edge mounts, vertical load applied via transferring linear rail bearings and lead shot dead weight, Hall probes measure vertical displacement.

Suspended canisters filled with lead shot to 20% ECT failure load.

11/11/2005
Why a ten hour period for boards?

Corrugated board humidity equilibration time test.

Unloaded corrugated board samples conditioned at 50% RH, placed in ECT creep apparatus, RH changed from 50 to 30% then back to 50% RH 23 deg. C. each point 5 min.
BCT creep station detail

Combined lead bricks, steel plates lead shot at 22.5% of BCT load inside of acrylic box supported by vertical sliding rails

Static load transfer through ball bearing
BCT creep station detail (2)

Ultrasonic proximity transducer measures vertical displacement of load container

Static load container

Test box
Increasing Compression strain

Voltage signals converted to displacements through a calibration

Top of each cycle corresponds to low humidity

Bottom of each cycle corresponds to high humidity
Generalized creep strain curve

Compression strain

primary  secondary  tertiary

failure

$x_1, y_1$

$x_2, y_2$

$x_3, y_3$

$x_4, y_4$

time
Calculate slope from the creep curve:

\[
slope = \frac{\left(\frac{y_2 - y_1}{x_2 - x_1}\right) + \left(\frac{y_3 - y_4}{x_3 - x_4}\right)}{2}
\]

General relationship between lifetime and the creep slope:

\[
lifetime = \frac{A}{slope}
\]
ECT (Board) creep summary, 83 observations

Lifetime = $0.0241 \text{(strain/sec)}^{-0.98}$

$R^2 = 0.92$

Points are averaged by box types (medium basis weight)
Error bars are 95% confidence intervals
Grouping BCT creep data by medium basis weight

Much more scatter evident compared to ECT creep data – same board set!

This box lasts 37 days on the average
Same BCT lifetime data plotted by point

Lifemote vs creep rate RSC BCT

Lifetime = 0.1451Creep^{-0.89}

R^2 = 0.71

68 observations
Where does the variability come from?

• Natural variation in paper properties:
  » Basis weight ~ 2%
  » Strength ~ 5 – 7%

• Preparation of test pieces, boxes
  » Cutting of edges
  » Mounting
  » Handling: folding of box flaps, gluing of joints
  » Application of load – sudden vs gradual
  » Imprecision of applied load
  \{ Parallelism, squareness \}

• Systematic error?
  » Electrical noise, sensor calibration drifts
  » Variations in humidity control
Regression Analyses of creep data

- Attempt to quantify creep, lifetime with measured properties – single variable:

<table>
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<th>BCT lifetime</th>
<th>ECT lifetime</th>
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<tr>
<td></td>
<td>R²</td>
<td>p</td>
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<tr>
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<tr>
<td>BWₘ</td>
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</tbody>
</table>

Note: a) BCT lifetime correlation with ECT lifetime
b) ECT lifetime correlation with shear rigidity R₅₅
Regression Analyses

- Multiple linear regression fits of the data:

\[
ECT \text{ lifetime } (s) = \{9.17 \text{ECT} + 9.51 \text{SCT}_m - 1.10 \text{BW}_m - 217.3 \pm 7.17\} \times 10^4
\]

MEAN ERROR \~ 1 DAY

\[
BCT \text{ lifetime } (s) = \{7.27 \text{SCT}_m - 0.729 \text{BW}_m - 6.31 \text{BCT} + 32.3 \pm 2.78\} \times 10^5
\]

MEAN ERROR \~ 3 DAYS

\( R^2 \sim -0.84 \), SCT of the medium appears to dominate lifetime in this data
Another idea: rotate the components

Paper is directionally oriented - not the best way for strength and hygroexpansivity

So what if we were to make boxes with one or more of the components rotated 90 degrees?
This is not so easy to do:

Lateral corrugator concept (ex Schaepe, 2004 Tappi summit)

So we have to turn the paper around 90 degrees, splice it back into a roll and run that through the corrugator
Manual preparation of rotated component test boxes

Full width rolls of linerboard and medium were obtained and CD strips were spliced together to produce transverse oriented 13” width rolls to run through the pilot corrugator – 205 gsm linerboard, 127 gsm medium

MD SCT is 1.7X CD SCT

MD hygroexpansivity is 0.4X CD
BCT increases with component rotation

- 36 x 20 x 20 cm test boxes, 205 gsm liners, 127 gsm medium
- BCT increases, 14% for “partial”, 26% for “lateral”, 33% for “linear”

Obvious differences here
Observation of creep behavior of rotated component boxes

- 7 boxes data plotted in each case
- lateral corrugated lifetime is somewhat longer, hygroexpansive strains are \textit{smaller} as expected
- scatter in BCT lifetime data is typical
Effect of rotated components on lifetime

Linear corrugated boxes last about 2 weeks in cyclic humidity at 22.5% of BCT load.
Pilot coating/corrugating trial - sequence

1. Rod coating of 42# linerboard at Spectra-kote
2. Linerboard rolls coated with polymer or clay/polymer coatings
3. Rolls sent through IPST pilot single facer combined with WAM
4. 14 x 8 x 8” test boxes manually made
5. Coated test boxes put through performance tests, e.g. lifetime in cyclic RH
6. Single facings manually combined with double facing
Relationship between hygro strain and creep

- Urbanik 1995 Wood Fibre Sci. hygroexpansion drives mechanosorptive creep in cyclic humidity
- reduce hygroexpansive strain either through component rotation of low WVTR coatings, creep rate goes down, lifetime increase
Summary

• Lifetime and creep observed for ECT and BCT, ECT creep dependencies are more clear.
• Effect of medium properties characterized: fluting SCT and basis weight for BCT lifetime.
• Effects of component rotation on lifetime observed, linearly corrugated lifetime is 2x higher.
• Low WVTR coated boxes last months compared to days.
• Generally → equalization of properties through the board cross section increases lifetime.