Corrugated board bonding defect visualization and characterization

Dr. Roman Popil and Dr. Shane Johnson

Renewable Bioproducts Institute
Georgia Institute of Technology
Atlanta, Georgia, U.S.A.

University of Michigan and Shanghai
Jiao Tong University Joint Institute
Shanghai, China
Corrugated board bonding defect visualization and characterization – background

- Work performed using samples prepared at IPST Atlanta by Mike Schaepe for the 2003 Corbotec Corrugated Board Defect Workshop: Croker, Schaepe, McDaniel

- Samples were investigated using TSA-IR set-up at GT Civil Engineering for grad theses, supervised by Dr. R. Haj-Ali (now Tel Aviv U.), partial funding by IPST Engineered Packaging Industry Consortium program 2003-2008

- Data since re-analyzed and written up 2015 in Int. J. Adhesion and Adhesives:
Formation of the “Single Face” in Corrugating

Corrugated board

Iodine stained cross-section:

Photo from R. Skuratowicz, Corrugating International
Starch adhesive and bonding mechanisms

- 1930’s Stein-Hall Bauer starch system: combined 30% solid slurry of uncooked and cooked starch, caustic, borax:

- requisites for good bonding are:
  a) apply “just enough” to the flute tips and,
  b) have roll temperatures/speeds allowing fast gelatinization to secure the fluting to the liner, and also have the right drying rate to form the “green bond”

Close tolerances of component alignments must be observed

Checking the finger clearance with a feeler gauge
Measuring bond performance, conventional methods

- Pin Adhesion (PA) Testing (Tappi method T 821)
  - Series of alternating pins, separate selected facing. Peak load indicates PA strength.

- Iodine Staining (Tappi method T 610)
  - Produces dark line patterns on linerboard indicating presence of residual starch

- Edge compression strength (ECT) (Tappi methods T 811, 839, 838)
  - Vertically loaded corrugated board peak load is affected by bonding strength
Supplemental and Innovative Methods for Bonding Visualization

Thermoelastic Stress Analysis

Pin Adhesion Testing using a UTM

Backlighted NIR imaging “x-ray”
Thermoelastic Stress Analysis Principle → Lord Kelvin 1878 (!)

Adiabatic conditions:

\[ \Delta T = \frac{-\alpha T}{\rho C_p} (\Delta \sigma_x + \Delta \sigma_y) \]

Computer synchronized with cyclic load signal to detect \( \Delta T \propto \Delta IR \) signal.

3 Hz oscillating displacement = +/- 0.18mm
Thermoelastic Stress Analysis of Boxes – Preliminary Studies

- Some preliminary examples, boxes with damage:
- localized stress/strain concentrations → color contrast

IR-TSA image of pre-collapsed open top tray box (plastic tray placed on top) measured under cyclic loading showing the stress concentration at the corners and the unstressed creased and damaged region. IR-TSA image of a box with induced two vertical crease lines. Flutes were crushed along 2 lines prior to cyclic loading. This demonstrates the feasibility of detecting hidden damage in corrugated containers using the IR-TSA technique.
Thermal Stress Analysis of Boards - any damage “lights up” as a contrasting $\Delta T_{IR}$ signal

Blue/red/yellow $\rightarrow$ low to high strain

CD sample with crease damage

Flip side toward camera

MD sample subjected to cut damage
Specimen preparation and experimental set-up

- Standard commercial production operating conditions were deliberately altered for simulation of common manufacturing bonding errors

- Single face samples with defects:
  - Fabricated on 1956 vintage Langston model EX pilot corrugator
  - 205 g/m² (42 lbs/msf) unbleached kraft linerboard
  - 112 g/m² (23 lbs/msf) medium

- Test board Specimens double-faced manually using a heated press plate

M. Schaepe and R. Hall, at the IPST corrugator, July 2007.
Single face bonding defects deliberately produced on the pilot corrugator, 6 cases:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Defect Name</th>
<th>Cause</th>
<th>Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>white glue lines</td>
<td>corrugating roll temperatures too low</td>
<td>no gelatinization, adhesive appears white, low bond strength</td>
</tr>
<tr>
<td>B</td>
<td>applicator gap</td>
<td>misalignment of applicator roll to medium flute tips</td>
<td>sporadic uneven glue coverage, missing gluelines</td>
</tr>
<tr>
<td>C</td>
<td>brittle bond</td>
<td>corrugating roll temperatures too high</td>
<td>no glue penetration into substrates, liner peels off easily without fiber tear</td>
</tr>
<tr>
<td>D</td>
<td>fingers too far out</td>
<td>retaining fingers are too recessed from medium</td>
<td>heavy deposits of glue at finger glueline gaps</td>
</tr>
<tr>
<td>E</td>
<td>excessive glue</td>
<td>adhesive layer thickness on applicator roll too large</td>
<td>ungelatinized white thick gluelines, possible board washboard profile</td>
</tr>
<tr>
<td>F</td>
<td>applicator roll</td>
<td>applicator roll surface speed largers than corrugator roll</td>
<td>glue accumulates on the MD side of each glue-line</td>
</tr>
</tbody>
</table>
Defect Samples TSA IR Results: TSA IR gray-scale Images are superimposed with Highlighted (false color) Iodine Stains

Pin adhesion = 1.86 N/mm
Pin adhesion = 8.95 N/mm

Corbotec, 2016
Data Images (1/2): Processed TSA, Iodine Stain, NIR transmission

Corbotec, 2016
Data Images (2/2): Processed TSA, Iodine Stain, NIR transmission

- **Pin A.**
  - **TSA-OPT**
  - **Iodine Staining**
  - **NIR**

<table>
<thead>
<tr>
<th>Image</th>
<th>TSA-OPT</th>
<th>Iodine Staining</th>
<th>NIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>d. Brittle Bonds</td>
<td>7.90 N/mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e. Appl. Roll Too</td>
<td>8.95 N/mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f. Exce. Glue</td>
<td>9.07 N/mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A closer look at Pin Adhesion: test load-displacement data analysis

a) Slope $\Delta L/\Delta z \propto$ Stiffness = $E \times t = (modulus \times caliper)$

b) Area under the curve = $\int L(z) \, dz =$ Work (Toughness)
**Results**: Pin Adhesion Work, Stiffness and TSA IR glue-line signal vs Pin Adhesion Strength

Pin adhesion work and stiffness *increase* with pin adhesion strength

Normalized $\Delta TSA-IR$ signal at the glue-line *decreases* with increasing pin strength
3D FEA of Corrugated Board: allows exploring potential affects of adhesive, structure, materials - explains results


Current Study: strain at glue-lines under MD tension

BCT video: FEA simulation, HSC box
3D FEA of Corrugated Board & Adhesive in this Study

Two case scenarios:

a) Varying Adhesive Modulus:

b) Varying Liner Modulus at Glue-line:

TSA shows lower signal at glue line with higher pin adhesion – so liner modulus increases at glue linear higher pins
Conclusions

- TSA images displayed
  - Show an instructive localization of stresses that coincide with increasing bond strength.

- ↑ Pin Adhesion Strength, ↑ Stiffness, ↓ strain, ↓ TSA IR signal, all mean…

Higher pin adhesion strength occurs with higher linerboard stiffness at gluelines arising from starch penetration and bonding
Future Work: Development of a 3D FEA Model for BCT prediction based on component properties, box structure

**Input:** Constituent Properties

- MD
- σ_{11}
- ε_{11}
- CD
- σ_{22}
- ε_{22}
- Shear
- τ_{12}
- γ_{12}

**FEA Box Compression Strength Prediction**

- Force (lbs)
- Displacement (in)

**Neural Networks Training and Prediction**

- Input: Geometry
- Humidity
- Basis Weights: 42-40-56
- Output: BCT

**BCT and Performance Predictions Considering Variations in Humidity, Geometry**

Corbotec, 2016
Thank you! Comments, questions?

Contact:

- Roman Popil, Georgia Tech/RBI, Atlanta
  Roman@gatech.edu, 404 894 9722

- Shane Johnson, Shanghai Jiao Tong University
  shane.johnson@sjtu.edu, 18601647502