ME 8883 Physical Properties of Paper Measurement

Lecture 16: Corrugated Board Flat Crush and the Torsion Pendulum
Flat crush test of corrugated board (rigid support method)

The flat crush test (/) is a measure of the resistance of the flutes in corrugated board to a crushing force applied perpendicular to the surface of the board under prescribed conditions. The test is satisfactory for single-faced or single wall (double-faced) corrugated board, but not for double-wall or triple-wall corrugated board, because of lateral motion of the central facing or facings. In this method the specimen rests on an essentially rigid support and is tested at a constant strain rate.

4.1 From each test unit of a sample obtained in accordance with TAPPI T 400 “Sampling and Accepting a Single Lot of Paper, Paperboard, Containerboard, or Related Product,” select a minimum of 10 specimens free of abnormalities not representative of the combined board. Each specimen should be cut, preferably in circular form, so that each is either 32.3 cm² (5.00 in.²) or 64.5 cm² (10.00 in.²) in area. All specimens should be cut at least 38 mm (1.5 in.) away from printed matter, scores, and diecuts.

4.1.1 If the specimens are not circular, exercise special care to maintain the desired area accurately.

4.2 Avoid crushing areas at the cut edges, and, where possible, avoid fractional flute counts.
Flat crush of corrugated board

• We use 3 x 3” samples having good clean edges
• Use the L&W compression tester, measure the peak load, report the peak as psi
• Using the Instron compression tester, the load compression curve can be interesting first noted by R.A. Stott 1968
Compression testers are set to detect the peak load based on the % “fallback of load, for flat crush this can be misleading…

5.1.1 Position each specimen centrally on the lower platen. Apply the crushing load to the specimen until the side walls of the corrugations collapse completely. Failure is defined as the maximum load sustained before complete collapse.

NOTE 1: Normally, a preliminary end point occurs when the tips of the corrugation flatten on one or both sides of the specimen. This should not be confused with the final end point when the corrugations collapse completely. If the collapse of the corrugations is so gradual that no such peak load is distinctly registered, note this fact. Maximum crush load is often near total collapse of the flutes. A strip chart recorder connected to the load cell output will aid in the determination of the correct endpoint of the test.
Notice that C flute is not as affected by crushing as A flute board.
Load-displacement flat crush

Note the large first peak

Crushed board shows a diminished first peak

Still a large max peak despite crushing

The value of the first peak is called "hardness"
A flute case is much clearer

First peak is prominent in an uncrushed board

First peak is drastically reduced in crushed board
Flat crush hardness and R55

Note the hardness correlates with the transverse shear rigidity measured by the torsion pendulum – more on this later in this lecture....
Flat crush test of corrugated board (flexible beam method)

Flat crush of corrugating medium (CMT test)

This is also known as the “Concora” medium crush test

Medium strips are sent through a Concora fluter

The corrugated medium strips are adhered to a supporting linerboard with double sided tape using a “rack” and “comb” arrangement to ensure good adhesion

Samples are tested for flat crush using a flexible beam type compression tester, load is read from a peak beam deflection holding micrometer

Samples are prepared and tested 5 to 8 seconds upon emerging from the fluter which is heated to 350 deg F
Concora flat medium crush

Fluter consists of mating corrugating wheels heated to 350 deg F, strips of medium 0.5 x 6” length along the MD, are passed through the fluter.
Strips of medium become corrugated exiting here.
Concora flat crush

Immediately exiting the fluter, the strips are paced in the rack and comb arrangement and the exposed flute tips are adhered to an adhesive tape strip using the rubber roller.
Flexible beam compression tester

Load is measured by a peak holding micrometer gauge, as platen moves downward the deflection increases then stops momentarily (first peak) then increases and finally starts to decrease stop the test after the second peak.
Torsion pendulum introduction

We are interested in the torsional stiffness of corrugated board, which we will represent as an orthotropic plate. For the plate, we are interested in three curvatures and two transverse shear deformations. The constitutive equation for the plate is written as

\[
\begin{bmatrix}
M_{xx} \\
M_{yy} \\
M_{xy} \\
Q_{yz} \\
Q_{xz}
\end{bmatrix} = \begin{bmatrix}
D_{11} & D_{12} & 0 & 0 & 0 \\
D_{12} & D_{22} & 0 & 0 & 0 \\
0 & 0 & D_{66} & 0 & 0 \\
0 & 0 & 0 & R_{44} & 0 \\
0 & 0 & 0 & 0 & R_{55}
\end{bmatrix} \begin{bmatrix}
\kappa_{xx} \\
\kappa_{yy} \\
\kappa_{xy} \\
\gamma_{yz} \\
\gamma_{xz}
\end{bmatrix}
\]

(1)

where the distributed moments and shear forces, \( \kappa_{ij} \) are the curvatures, \( \gamma_{ij} \) are the transverse shear strains, \( D_{ij} \)'s are the bending stiffnesses, and \( R_{ii} \) are the shear rigidities. Equation 1 is the starting basis for calculating the potential effects of transverse shear on box properties.

The properties of interest for the immediate current discussion are the three shear terms, \( D_{66}, R_{44}, \) and \( R_{55}. \) For a sandwich structure similar to corrugated board the twisting bending stiffness is approximately

\[
D_{66} = \frac{1}{2} G_{xy} t h^2
\]

(2)

where \( G_{xy} \) is the in-plane shear stiffness of the liners, \( t \) is the thickness of the liners, and \( h \) is the thickness of the sheet.
Corrugated board directions

There is less resistance to shear in the MD direction of corrugated board.

So MD transverse shear rigidity is affected by flute crushing.

The twisting motion of corrugated board can be used to determine transverse shear rigidity R55.

\[ k = \frac{T}{\theta} \]
Torque/angle of rotation = torsion stiffness
There have been several analytical models in the literature for the prediction of torsional stiffness of corrugated board, we have selected the one proposed by E. Reissner “On Torsion and Transverse Flexure of Orthotropic Elastic Plates”, Journal of Applied Mechanics, 47, pp 855-860, (1980). The plate solution for the torsional problem can be expressed as

\[
\frac{T}{\theta_{Reissner}} = \frac{4D_{66}b}{L \left(1 + 12 \frac{D_{66}}{R_{55}b^2}\right)} = k_{MD}
\]

where the length of the plate \(L\) is assumed to be large compared to the width \(b\) and thickness. In our procedure, \(L\) is 24 cm and \(b\) is 7.6 cm or less.
Calculation of the twisting stiffness $D_{66}$

$$D_{11} \approx \frac{E_x th^2}{2}, \quad D_{22} \approx \frac{E_y th^2}{2}, \quad D_{66} \approx \frac{G_{xy} th^2}{2}$$

where $E_x, E_y$ are the in-plane moduli of the liners and $G_{xy}$ is the in-plane shear modulus of the liners, $D_{11}, D_{22}$ in-plane bending stiffness of the combined board and $D_{66}$ is the combined board twisting stiffness as before. Moreover, Baum et al., ( "Orthotropic elastic constants of paper" Tappi Journal 64, 97-101 (1981)) showed a relationship between the liner in-plane shear modulus and the in-plane moduli to be:

$$G_{xy} \approx 0.387 \sqrt{E_x E_y} \quad \text{So:} \quad D_{66} \approx 0.387 \sqrt{D_{11} D_{22}}$$

These can be measured from the four point bending stiffness.
Use L&W 4 point bending stiffness for $D_{11}$ and $D_{22}$ for corrugated board

$$D_{66} \approx 0.387 \sqrt{D_{11}D_{22}}$$

Get a $k(\text{MD})$ from the torsion pendulum

For $k(\text{MD})$ the boards of length $L$ width $b$, between clamps are cut along the MD, clamped portions have metal dowels to prevent crushing

$$R_{55} = \frac{12D_{66}kL}{4D_{66}b^3 - kLb^2}$$

$R_{55}$ is the transverse shear rigidity for corrugated board
Torsion pendulum details

Running program

- From the Desktop on PC 336-locate then double click the Torsion Pendulum icon
- A User login dialog box will appear with username: ZD Core Test 2...hit the OK button
- The Torsion Pendulum Main Menu. vi panel will appear, Figure 2.

Place the cursor in the No Operation box to view the following

- No operator
- Angular calibration
- Spring constant determination
- IR determinator
- Torsion Pendulum

**Torsion Pendulum multiply test**
Select the Torsion Pendulum multiply test option from the pull down main menu and the Institute of Paper Science and Technology Torsion Pendulum test screen will appear Figure 3.

Figure 1. Torsion Pendulum Multi-test screen.

Enter sample length and width for subsequent calculations.
The following data is entered for record keeping:

- Operator Name:
- Project Name:
- Sample Name:
- Sample length (cm)
- Width (inches)
- Sample Direction … then click on the “Test” button on the panel

![Test panel for acquiring data for each single specimen.](image)

**Figure 1. Test panel for acquiring data for each single specimen.**

Select the **Acquire** button on the test panel Figure 4 which will then be followed by a yellow working button will appear underneath

Align the pin on the 20° mark located at the bottom of platform and release
When the test comes to a stop a wave form will appear on the screen as shown in Figure 5.

Figure 1. Typical waveform appearing after a sample has stopped twisting after release.
Hitting the **Exit** option will return you to the Torsion Pendulum data screen Figure 6 where the current ks, rs, tan, average and standard deviation of each quantity are shown.

![Torsion Pendulum Multi Tester](image)

**Figure 1. Torsion Pendulum data screen showing the output of a specimen test.**

The sample specimen is then removed and a new specimen is placed into the clamps and firmly tightened with the ratchet hex wrench. Be sure to have steel pins installed into the specimens to prevent crushing of the flutes in the clamps. **Test** option is once again selected from the panel shown in Figure 6 and the procedures above are repeated for a total of 5 test pieces, finally producing a data screen resembling Figure 7.
The sample specimen is then removed and a new specimen is placed into the clamps and firmly tightened with the ratchet hex wrench. Be sure to have steel pins installed into the specimens to prevent crushing of the flutes in the clamps. Test option is once again selected from the panel shown in Figure 6 and the procedures above are repeated for a total of 5 test pieces, finally producing a data screen resembling Figure 7.

Figure 1. The multi-test screen with data from 5 consecutive tests
Calibration procedure

The procedure is performed in sequential order by selecting the operations from the main window: Angular calibration, Spring Constant Determination, Ir determination. Detailed instructions on the steps to be followed are contained in the Help file accessed by clicking on the Help button associated with calibration vi panel. The calibration procedures should be performed whenever there is some change in hardware, e.g., the Hall magnets are replaced. Required accessories for the calibration include a steel bar, pulley with string and hook and various weights.

An example of the angle calibration is shown below. This procedure ensures that the electrical signal from the Hall probe will be converted to a true angular displacement of the pendulum.

Figure 1. Output screen form a typical angular calibration

A steel beam is placed in the sample clamps and the angle of deflection manually set to acquire voltages vs angles for the Hall probe proximity detector
\( k_p \) the “spring constant”. There is a hole at the front of the static pendulum base. While performing the direct \( k_p \) determination procedure, a stand with a pulley mounted on top is inserted into this hole and fixed with a set-screw. See Figure 10, below.

Here, using the steel calibrating beam in place, use the pulley and fixed lead shot weights (0.419, 0.769, 1.065 kg) to pull the pendulum to various angles, entering the weight information at each prompt, do this to swing the pendulum both positive and negative degrees.
Torsion pendulum calibration

The spring constant is taken as the first order fit coefficient and expressed in Nm/rad. in the lower left hand corner.

Figure 11

Metal plate spring constant determination

Check that the spring constant is close to this value.