

The Role of Liner Buckling on the Edgewise Compressive Strength of Corrugated Board

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The edge compression strength (ECT) of corrugated board is used as a fundamental quality control parameter since it correlates to box stacking strength (BCT) as predicted by the McKee equation. An empirical model is proposed and verified in this work that relates ECT to properties of the components of the corrugated board. Such a model allows quantitative tailoring of papermaking strategies such as the balance between basis weight and density to optimize ECT.

Specifically, the proposed model is based on an empirical premise for plate failure⁴ combining compressive with buckling failure which takes the general form of

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

where P_z is the plate failure load per unit plate width, P_m is the compression strength which for the case of corrugated board liners, we take to be the short span compression strength STFI. Plate buckling is incorporated in P_{cr} , the critical plate buckling load, which for the case of an anisotropic plate, neglecting out-of-plane transverse shear, to a good approximation can be described as:

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

In the above equation, $(D_{11}D_{22})^{1/2}$ represents the geometric mean (MD-CD) flexural rigidity of the plate and is approximated as the bending stiffness. In ECT of corrugated board, we consider buckling occurring in the liners between the glue lines prior to board failure, hence b_f is the inter-flute spacing and K is a fitting parameter that we have found to be close to unity in all cases studied. That K is about unity, indicates that the buckling liner plate elements are simply held at the flute tip glue lines allowing bending of liners at the glue lines.

This approach to describe the failure load in ECT is analogous to the McKee equation for predicting box strength (BCT) by applying the combination of the intrinsic compressive strength of the material and the loss of that strength from buckling. This differs from previous predictive models for ECT where either the liner intrinsic compressive strength or buckling load, but not both simultaneously in combination, are taken as the failure load of the combined board.

Indeed, the presence of patterned liner buckling prior to peak load has been repeatedly observed as a dimpled surface morphology by detailed video recording of several

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⁴ McKee, R.C., Gander, J.W., Wachuta, J.R., Paperboard Packaging, August 149 (1963).

hundred ECT tests of a variety of combined board test samples synchronized with stress-strain data used to characterize the nature of the buckling phenomenon.

About 50 different corrugated board combinations were prepared either using IPST corrugating and sheet making facilities or obtained from commercial corrugating plants. Variables investigated in designed experiments were liner grammage and density, flute spacing, asymmetry of facing liner grammage, single wall and double wall structures with different flute sizes. Patterned buckling of the liners as plate elements held between glue lines was observed to occur through the video records prior to samples sustaining peak loads in those cases where the flute spacing is comparatively large and/or the liner grammage is medium or low. In multi-wall or asymmetric corrugated board structures, the facing that has the lower P_{cr} is observed to buckle first independently of other facings. The curvature of the fluted medium prevents its buckling as has also been confirmed by observation. The criterion for buckling to occur is that the critical buckling load P_{cr} must be less than the compressive strength STFI as is the case in many common lightweight grades of combined corrugated board.

Therefore, based on our empirical observations and analysis of previous data,⁵ the generalized model for ECT is proposed to be a linear summation of “McKee-like” plate buckling elements F_i for the individual liners⁶ and length weighted compressive strength terms for the medium flutings:

$$ECT = C(F_{liner1} + F_{liner2} + F_{liner3} + (\alpha_1 STFI_{medium1} + \alpha_2 STFI_{medium2}))$$

$$F_{lineri} = \begin{cases} (STFI_{lineri})^b (P_{cr})^{1-b} & \text{if } P_{cr} < STFI_{lineri} \\ STFI_{lineri} & \text{if } P_{cr} > STFI_{lineri} \end{cases}$$

The above equation is generalized for a double wall board consisting of 2 flutings and 3 liners. Analysis of our extensive sample set showed that the empirical fit of constants b and C with actual data is best if buckling is allowed as an option according to the criterion described above. This contrasts with other treatments⁷ which model the ECT as a linear summation of only compressive strengths. We also note that the proposed model which uses STFI strength together with bending stiffness provides a significantly better predictor of ECT than use of the Ring Crush test value, which combines compressive and buckling failure in the liner.

Therefore, we demonstrate that because bending stiffness affects the buckling load of corrugated board liners, it must be considered when optimizing papermaking to achieve compressive strength. An IPST handsheet study varied the density of various basis weight kraft liners by varying wet pressing pressures and then using these handsheets to produce combined corrugated board for ECT tests. As expected, the liner STFI increases

⁵ Whitsitt, W.J., Tappi Journal, 58(12):163 (1988).

⁶ Koning, J.W., Tappi Journal, 58(12): 105 (1975)

⁷ Sprague, C.H., Whitsitt, W.J., Tappi Journal, 65(10):98 (1982)
Seth, R.S., Tappi Journal, 68(3):98 (1985).

monotonically with density whereas the bending stiffness being proportional to the caliper cubed decreases over the same density range. The ECT empirical best fit for this single wall data set resulted in the constants of $C = 0.646$, $b = 0.85$, $K = 1$ so that the ECT model becomes:

$$ECT = 0.646 \left\{ 2 \times (STFI_{liner})^{0.845} (P_{cr})^{0.155} + \alpha (STFI_{medium}) \right\} \text{ if } STFI_{liner} \geq P_{cr}, \text{ liner buckling occurs}$$

$$= 0.695 \left\{ 2 \times (STFI_{liner} + \alpha (STFI_{medium})) \right\} \text{ if } P_{cr} \geq STFI_{liner}, \text{ Whitsitt formula holds}$$

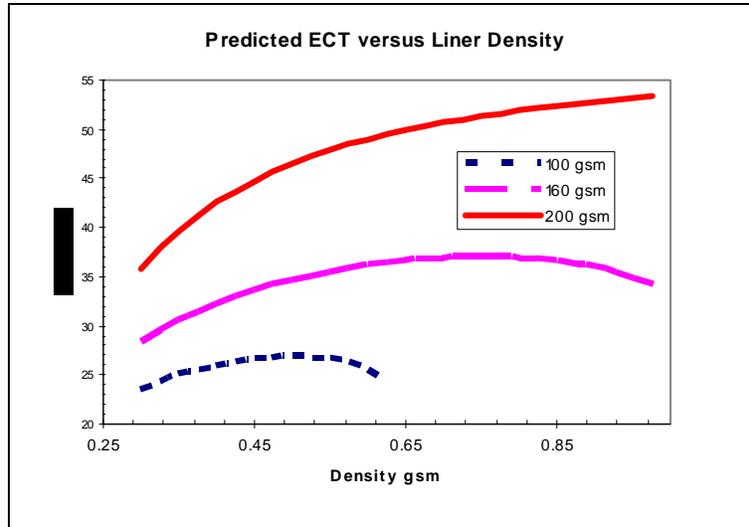


Figure 1. Predicted ECT of single walled corrugated board based on handsheet relationships of density to STFI and Bending Stiffness.

The relationships of STFI and Bending Stiffness with apparent sheet density for the handsheets were substituted into the best empirical ECT fit model to obtain the curves shown in Figure 1 that illustrate the deleterious effect of increasing density in lightweight liners on ECT. The prediction shows for example, that no further increase in ECT can be expected for 160 gm² board beyond a density of 0.7 g/cm³.

Densification through wet pressing as is commonly done in production practice will of course, increase liner compressive strength through increased fiber bonding as intended. However, the gain in compressive strength through wet pressing comes at the cost of lower bending stiffness from the accompanying sheet caliper reduction and this phenomenon compromises expected ECT values. Our model provides a means to quantify these effects.

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