Revisiting paper strength measurements for estimating combined board strength

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ABSTRACT: The ring crush (RC) test and the short-span compression (STFI) test can be used to evaluate the compression strength of corrugated board components, and can be correlated with combined board strength. Because each test evaluates paper strength at a different length scale, the correlations are not of equal quality. We find that the RC test correlates better with ECT strength of corrugated board, even when only a few RC specimens are used to evaluate the RC strength of the paper, and even when variations due to multiple combining sites are included in the analysis. We can relate the difference in correlation to the difference in failure mechanism within each paper test in relationship to the failure length scales in combined board.

Application: This paper will help readers understand differences between the ring crush and short-span compression test methods for evaluating paper strength, and identify why they do not equally relate to the edge crush performance of corrugated board.

Top-to-bottom compressive strength is one of the primary corrugated container end-use requirements, and is a performance metric often specified by corrugated board customers. The edgewise compressive strength of the combined board (as measured by the edgewise compressive test, ECT) may also be specified by customers, and plays the most important role in overall box compressive performance [1,2]. Historically, there have been many efforts to correlate the ECT of the combined board with strength properties of the containerboard components, the linerboard and medium, in an effort to predict this critical property more accurately. Our industry presently relies primarily on two methods for quantifying the strength of the components, the ring crush test (RC; TAPPI T 822) and the short-span compression test (SCT or STFI, TAPPI T 826), with occasional publications and ongoing side-bar discussions at technical conferences advocating the merits of each.

Both RC and STFI are material properties that depend on fiber mass. They can be used as independent measures of paper processes, and both depend on how we operate our papermaking equipment. While technical papers have been written correlating RC and STFI [3-5], they are not truly correlated above the level of noise beyond their mutual dependence on mass [6]. They can vary independently for a given grade of paper, either due to noise in the test procedures or due to clear differences in the paper machine processes by which these physical properties are achieved [3,7-10]. Because they are different and can vary independently, they cannot be similar measurements of the inherent strength of the material.

One might argue that the key indicator of the validity of a test method is whether it assesses an intrinsic property. Understanding fundamental material properties and their interactions can be very important when it comes to developing mechanistic models, particularly for combined board strength or box performance. Equally, if not more important, is our ability to accurately measure the parameters in, and apply the knowledge gained from, those models.

At present, about half the corrugating industry in North America prefers using one test method and the other half prefers the other method to characterize the strength of the materials that form corrugated board [10]. Ring crush testing has a strong historical footing [11] and until comparatively recently had been the default test for evaluating paper compressive strength for the industry (at least in North America). However, several authors have challenged the validity of the method's ability to identify the true compression strength of paper. They state that lower basis weight samples (actually, lower caliper samples [12]) tested using the RC method fail primarily by buckling [3,13-15] and observe that many of the lightweight papers now prominent in the industry fall out of the range for which the test is nominally specified. Additional challenges to the RC methodology that might impact comparison between results across different testing sites also have been raised [16].

Others argue that the TAPPI RC test is cumbersome and difficult to use in a mill environment, given the need to generate results rapidly. Operator error or poor equipment maintenance may also have a larger role in some mill environments when comparing RC testing to STFI testing. The analysis discussed in this paper assumes both tests are done correctly, according to their respective TAPPI Standards (T 822 ring crush using a load cell compression tester, and T 826). From our observations, this can be achieved in either a lab or a mill envi-

ronment, if testing is done carefully. This assessment also does not address the efficiency advantages gained by some of the automated testing units now on the market.

One might take 20-30 STFI measurements using automated or semi-automatic equipment in the time it would take to manually perform two or three RC measurements. Thus, while the RC test in its pure form may have merit historically, the confidence one has in estimates for combined board strength based on the STFI result is assumed to be much greater because of our ability to collect so many data points more quickly. A larger collection of measurements for the STFI test should by definition lead to a smaller confidence interval about the average value measured.

Compression failures occur in paper testing due to instabilities at different structural levels, and the two test methods probe different length scales. An excellent review of the scientific merits of various evaluations of the edgewise compressive strength of paper has been compiled by Fellers and Donner [17]. As they note, a substantial portion of the differences in results between test methods is due to difference in sample size and associated variations in nonhomogeneous material. The small area tested in the STFI test likely serves to overestimate the effective strength of paper on the larger length scales typically used in corrugated boxes, because of failure to measure and account for the "weakest link" in the paper structure. A large sample will fail at its weakest location (be it a RC specimen or a box panel), and will thus have lower strength than a small sample. The STFI test, stressing a 15 mm wide band that is 0.7 mm high, should by nature produce a larger strength measurement than a RC test stressing a strip 6 in. (152.4 mm) wide and 0.25 in. (63.5 mm) high, due simply to the much smaller area being tested. They also note that the RC test (as practiced in TAPPI T 822 and T 818) does not satisfy the criteria for a pure compression test of linerboard, and thus does not accurately quantify the intrinsic compression property of the material.

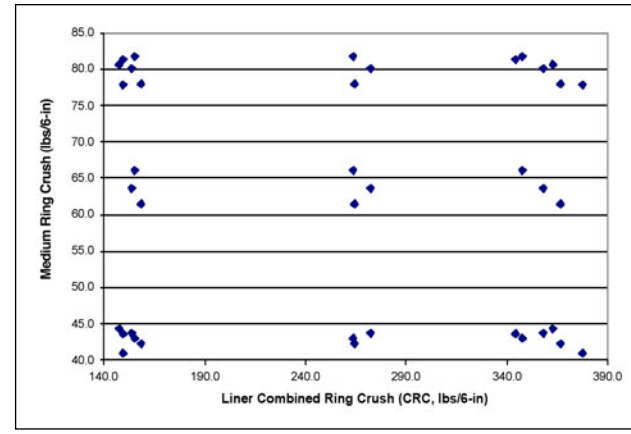
Rather than reanalyze all the test methods and their failure modes, in the discussion that follows we examine the application of the two most common methods of evaluating paper strength (or effective paper strength) in the estimation of the strength of combined board as determined by ECT (per TAPPI T 811.) ECT is used as the primary material property defining combined board strength. It has its own complexities and variations in failure modes [18,19], which make an assessment of the true material property of the combined board difficult. Nonetheless, estimating ECT as accurately and reliably as possible continues to be a goal for those endeavoring to connect paper properties to box performance [20,21]. An analysis of the correlation between paper test failure modes and combined board strength also sheds light on some of the mechanisms by which boxes fail.

In the next section we examine in detail model results based on test values from a designed experiment at a single box plant. These models allow us to evaluate the quality of predictions when using RC and STFI to estimate ECT. As well, we can divide the RC data to assess whether the STFI data collected by averaging 20 individual measurements does indeed provide better models or more accurate estimates of combined board strength (ECT) than smaller groups of RC measurements. We also expand this analysis to a larger but statistically unbalanced data set combining test results from several box plant trials. We then discuss these results in light of the hypotheses in the literature to identify which paper testing protocol provides the best mechanistic assessment of combined board strength and likely box performance.

RESULTS

The first data set contains 39 data points, distributed as a designed experiment with replication. This creates a very balanced, uncorrelated, and evenly distributed group of data with which to generate models of ECT performance. On a single corrugator with a typical C-flute roll, we combined linerboard with nominal basis weights of 170, 275, and 360 g/m^2 (35, 56, and 74 lbs/thousand square feet [msf]) with corrugating medium having nominal basis weights of 126, 161, and 197 g/m^2 (26, 33, and 40 lbs/msf). All combined board produced was "symmetric," with similar weights of linerboard used for both faces of the combined board. The distribution of the combined RC values of the linerboard (CRC) and the RC of the medium appears graphically in **Fig. 1**.

RC and STFI measurements on the papers, as well as ECT measurements of the combined board off the corrugator, are presented in full in Appendix A. From this data we can also generate "RC1" and "RC3" sets of paper test data by simply taking the first or the average of the first three individual RC



1. Distribution of data points for the single designed experiment. The RC of the medium is plotted against the sum of the RC values of the two linerboards. Distribution is similar for STFI and basis weight. Points are relatively evenly and symmetrically distributed, such that no single point has leverage in the model greater than 1.45 times the average.

Fitting parameter	RC	RC3	RC1	STFI
# specimens	10	3	1	20
R^2	0.994	0.994	0.985	0.978
MSResidual	1.38	1.27	3.35	4.86
Measured-model				
CI about zero	0.36	0.34	0.56	0.67
AAD	0.91	0.84	1.40	1.74

I. Statistical parameters describing the fits generated based on measurements of RC, STFI, and ECT for our limited (n=39) designed experiment performed on one date at a single box plant. Data for these fits appear in the appendix. The number of specimens indicates the number of individual test pieces used to calculate the reported (average) property. R^2 and MSResidual are parameters describing the statistical quality of the fit. The confidence interval (CI) about zero indicates the relative noise in the fit, with smaller values indicating a tighter model. Average absolute difference (AAD) indicates the average difference between zero and the absolute values of the differences between measurements and model estimates. For a perfect fit with no variability, CI and AAD would be zero. Values closer to zero indicate more robust models.

measurements (out of 10) made on each paper used. In this way we can generate models for ECT using STFI data, regular RC data, and RC data that one might generate given smaller numbers of specimens, in the same time frame that one could generate the STFI data. All testing was performed in a standard TAPPI environment (23°C, 50% RH) after preconditioning and conditioning according to TAPPI T-402.

There are several ways to evaluate the quality of a model generated by fitting a limited data set. One approach is to examine the model fitting parameters (R^2, etc.) to see how well the model fits the data available. A model that fits present data better might reasonably be expected to predict future data more accurately. We can also evaluate how far off the model predictions are on an absolute scale from the data used in the model. Assuming we have done the modeling correctly, the average deviation from the actual values measured should be zero. We can examine the confidence interval on the average to see how precisely the model predicts the actual values. Similarly, we can examine the average of the absolute values of the deviations to identify how far off we might typically expect a given model prediction to be. The best models would not only have the best fitting parameters, but would also have the tightest confidence interval and the smallest average absolute value deviation.

Following the literature, we assume a linear relationship between paper properties and ECT, and fit our data to the model: ECT = A + B * (linerboard values) + C * (medium value) where A, B, and C are fitting parameters, linerboard values are the combined (summed) RC, RC3, RC1, or STFI values of the two linerboards, and medium value is the value of the medium measured in the same way as the linerboard values. In this work, we did not explore combining RC on one component with STFI on another, or combining any other measurement modes (CLT, CFC, Taber Stiffness, etc.) in our models.

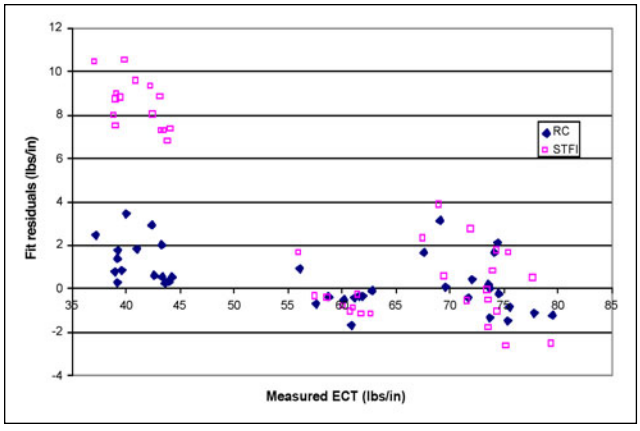
Statistical parameters describing the four models generated in this fashion (**Table I**) allow us to evaluate the fits. Both R^2 and mean-squared residual (MSR) values are comparative measures of the quality of the fit relative to the noise in the data set. Given that the data sets are all of the same size and target the same ECT values, these results are directly comparable between fits and can be used to assess relative fit accuracy. Of the four fits, we see (somewhat surprisingly) that the fits using RC and RC3 data have similar R^2 and mean-squared residual values, indicating that the fits are of similar quality. The R^2 value decreases, and the MSR increases, when we take only the first RC measurement into account for our model (RC1), and change even more when we use STFI data in our model. Thus, we see that whatever subset we use for RC measurements, our fit does better (higher R^2, lower MSR) than if we use STFI measurements as the independent parameter.

Similarly, we see that the accuracy for the prediction (measured values minus model values) is better for RC models than STFI models, with a smaller confidence interval about the zero average indicating less variability. The average absolute value of the difference between measured and predicted values on the RC and RC3 models is about half of that of the STFI model. In other words, our predicted values are closer to the actual values when we use RC rather than STFI. On the basis of these observations from this single trial data set, it would appear that RC is the better parameter to use in modeling.

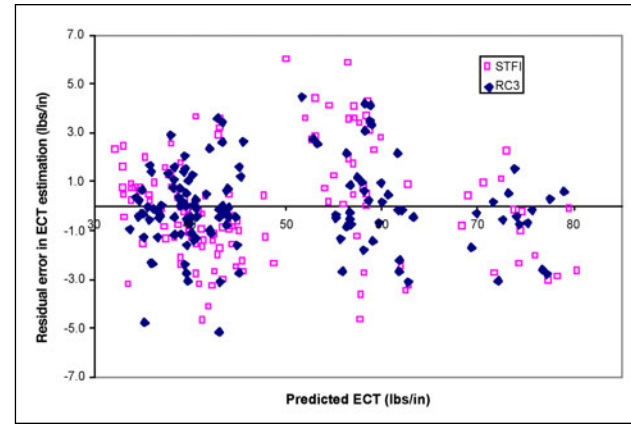
Given the literature discussion on the importance of buckling of RC samples at lower weights, we might expect significant deviation from a linear fit for the RC models when we use low basis weight linerboards, while for the STFI models we should find uniform fit quality across basis weights. However, our data set reveals the opposite. We can generate linear fits to the data for RC and STFI leaving out the lightest basis weight linerboard data (170 g/m^2 [35 lbs/msf]), and then examine the difference between those curves and the data at lighter weights.

We find (**Fig. 2**) that the ECT at lighter weights is much closer to the estimate generated by using a RC model for the heavier weight liner combinations than by using a STFI model based on the heavier weight liner combinations. While in both cases the light weight samples deviate from the fit generated for the heavier liner combinations, the actual ECT misses the RC model by 1.4 lbs on average while the actual ECT misses the STFI model by 8.5 lbs on average. This implies greater consistency across the basis weight range for our RC model than for our STFI model, at least in this single corrugator experiment.

While this experimental design was statistically robust, the data set was small and it may be that unique or unex-



2. The difference between measured ECT values and fits generated without the lighter weight segment of the single designed experiment. RC residuals at the lighter weights are much closer to zero than the STFI residuals, indicating much less deviation for RC at lighter weights from expectations based only on the heavier (nominal 275 g/m² [56 lbs/msf] and above) data. The legend corresponds to the data sets described in the text.



3. Residual plots for two of the four fits of RC or STFI measurements to ECT values generated for the larger data set (n=131). Residuals are evenly distributed about zero. The legend corresponds to the data sets described in the text.

pected features or biases associated with the particular corrugator or box plant might somehow skew the model results. Therefore, we repeated the analysis on a larger data set of 131 samples collected from six box plant trials. This larger set includes the first set of 39 data points. Given that flute profile can be expected to affect ECT results, we ensured that each corrugator in our larger set had corrugating rolls with similar chordal height and pitch. Nominal linerboard weights across these six trials varied from 150-360 g/m² (31-74 lbs/msf) and medium weights varied from 110-197 g/m² (23-40 lbs/msf). Since this larger data set incorporates data from half a dozen trials, it might be considered more representative of the real world and less subject to vagaries that may affect the analysis from one data set.

While each individual trial was statistically balanced in its distribution of data points, the combined set is skewed toward the lower basis weight range. This data set includes a significant fraction of points where the RC values fall in a range typically considered suspect for valid measurement of RC as a material property [8,12,15]. (Note that results of any measurement that follows the RC procedure is a valid RC measurement. In question here is whether that measurement is a meaningful indication of the intrinsic compression strength of the paper.) Of the data points, 73 involve linerboard with a nominal weight of 170 g/m² (35 lbs/msf) or less, and 89 of the data points involve medium with a nominal weight of 126 g/m² (26 lbs/msf) or less. Despite the inclusion of both light weight and heavier material, the linear fits to all models (RC and STFI) had evenly (and similarly) distributed residuals (**Fig. 3**.) These model results (**Table II**) lead to conclusions similar to those from the smaller data set.

Once again, more significant curvature in the RC models might have been expected compared with the STFI models, given the literature hypotheses on problems with the RC test at low weight. Following the same procedure as for the smaller data set, we also generated fits using only the upper segment of the linerboard basis weight range (58 points from the larger set of 131). While again the light weight ECT values deviate from all fits generated for the heavier liner combinations, the actual ECT misses the RC model by 1.0 lb on average while the actual ECT misses the STFI model by 2.4 lbs on average. Thus, we reach the same conclusion when we focus only on the lighter weight samples in this larger set as in the earlier, smaller data set, indicating clearly that regardless of what the RC test is actually measuring, the property quantified correlates well even when we include the data for which RC may not be measuring an intrinsic material property. We have repeated this analysis on completely independent sets of data for corrugators with other profiles, observing similar relationships.

DISCUSSION

Given the data mentioned, we find that nearly all models based on RC, even when we only take a single RC specimen as representative of the paper used (RC1), provide more accurate estimates of the ECT value on average than models based on STFI values averaging 20 individual measurements. Comparing the analyses of the two data sets sheds further light on the factors governing model accuracy. For the RC models, we see that the average absolute differences (between estimated and actual ECT values) increase when we go from a data set encompassing one corrugator trial to a set with six trials. Variations between trial sites contribute numerous additional parameters to the noise component of the overall models. The growth in the absolute difference indicates

Fitting parameter # specimens	RC 10	RC3 3	RC1 1	STFI 20
R^2 MSResidual	0.982 2.90	0.981 3.06	0.975 4.06	0.969 5.03
Measured-model CI about zero AAD	 0.29 1.25	 0.30 1.28	 0.34 1.52	 0.38 1.77

II. Statistical parameters describing the fits generated based on measurements of RC, STFI, and ECT for our more expanded (n=131) data set. We see lower R^2 values and higher MSResidual values than in Table I because of the added variability that comes from agglomerating data from multiple production sites. Since the CI is dependent on the number of measurements, values are smaller than in Table I.

Structure	Flutes/m	Flutes/ft	in/fl*	mm/fl*
A-flute	108	33	0.36	9.24
C	128	39	0.31	7.82
B	157	48	0.25	6.35
E	262	80	0.15	3.81
F	394	120	0.1	2.54
N	590	180	0.07	1.69

III. The approximate or typical flute pitch of different corrugated structures. Note that F- and N- flute have interflute spacings that are closer to the length scale of the STFI test (0.7 mm, 0.028 in.) than the length scale of the RC test (6.4 mm, 0.25 in.) Fl = flute.

that those sources of variation are on the same order as variation in the test method itself and contribute to increasing uncertainty in the model. By contrast, the difference between the models for STFI from the two sets of data is small, implying that the additional variation arising from multiple sites is not significant compared with the inherent variation/uncertainty in the correlation between the STFI test and the ECT values on the specimens collected. The natural variation in the STFI measurement itself apparently swamps the influence of other fabrication-related factors.

The STFI test is a pure loading test at the fiber length scale (0.7 mm), specifically designed to avoid buckling. Thus, it well quantifies the absolute load carrying capacity of the paper at small length scales. STFI results tend to be higher than those produced by many other compression-test methods (on a load-per-length basis), implying a value closer to intrinsic compression (or perhaps fiber strength) and less influenced by other factors. However, failure of a STFI sample is restricted to occur in this narrow region. Since larger scale paper samples typically fail when voids created by delamination join together [17, 22, 23], the STFI test likely does not allow the paper to fail in the same mode as in an ECT sample, or a box. As noted by Fellers and Donner, one must correct the strength values produced by the STFI test to account for weak links in the larger structure and relate the values to failure in larger scale paper structures. By contrast, the RC test specimen is large enough for voids to join.

The noise/variability in the STFI test due to the nonuniformities in the substrate dominates the measurement. The resulting uncertainty in the correlation on the single data set is sufficiently large at the outset to be affected only slightly by additional sources of uncertainty (e.g. run-to-run variations). RC values have better signal to noise (lower STD in measurement) than STFI [6], likely in part because of physical averaging over the larger test specimen. A single RC sample provides ~1.5 in.^{2} of area for failure over which it is averaging. A single STFI sample provides 15 mm x 0.7 mm, or 0.016 in.^{2} of area for failure. Thus, to average over the same amount of area as one RC sample, and explore the same area for "weakest links," one would need to test ~100 STFI samples. An interesting experiment exploring this hypothesis would involve comparing the RC subsets described above to average STFI incorporating 100, 300, or 1000 measurements corresponding to one, three, or 10 RC tests. That would provide for similar areas under testing and would identify whether the difference in fit quality comes only as a result of averaging affects relative to material tested. However, it is likely that so many tests would strain the ability of even automated equipment in a typical operation.

STFI may correctly assess the material property of paper compression at its fundamental scale, the intrinsic compression strength, but may not properly describe the macroscopic property at play in box compression failure. Just as one would not expect the zero span tensile strength to be the sole factor governing the tensile strength of a sheet at the length scale of a typical tensile test, the compressive strength at the very-short-column length scale does not appear to describe adequately the compressive behavior at the typical length scales of a box panel or ECT specimen. Regardless of which mechanism explains the difference in the fits, the difference implies that the failure mode in the ECT test is inherently more correlated with the failure mode in a RC sample than in a STFI sample.

A common statement in the literature is that for RC tests of thin or low basis weight samples, (typically below 205 g/m^2 (42 lbs/msf)), buckling contributes to the failure mode [14]. Buckling is often put forward (correctly or not) to account at least in part for the difference between RC values and STFI values, and to challenge the usefulness of the RC test in assessing combined board compressive performance. Somewhat recent measurements of the full load-deflection curve for the ring crush test question whether this buckling corresponds to the peak value measured or occurs only after peak load [24]. Specimen buckling before or at the peak load value would clearly invalidate RC as a measure of pure (intrinsic) compression strength. However, regardless of when any buckling might

occur in a RC specimen under test, the statistical analysis would appear to indicate that intrinsic compression strength of paper (perhaps as measured by STFI) is not necessarily the correct parameter to use to assess combined board and box performance.

The RC test is a loading test at a ~6.4 mm (0.25 in.) length scale, nearly an order of magnitude larger than the STFI length scale and similar to the failure length scale of the linerboard between the flutes in a C-flute corrugated box [25]. Linerboard buckling is observed between the flutes when ECT is evaluated for combined board samples using light-weight (lower caliper) linerboards, at a similar weight/caliper transition point as the onset of bucking is hypothesized for the RC test [26, 27]. Buckling of the linerboard in combined board appears similar to the diamond pattern one might expect in the buckling of cylinder walls when the cylinder is not short, as is the case for RC tests on sufficiently thin samples. Whether this bucking occurs as part of the failure mode of the paper, as assumed by most researchers, or only after the peak load has actually been reached, as noted by others [24] the behavior in the RC test specimen parallels the behavior observed in combined board samples when tested for ECT and in actual boxes.

Given the similarities in failure modes and cross-over points, it seems logical to use the RC test to predict combined board properties under load (ECT). The test probes the correct length scale, inherently incorporating the combination of compression and flexural failure modes that likely occur in practice. To be as reliable, predictions based on intrinsic compressive strength would also need to incorporate buckling or stiffness measurements explicitly to capture the full physics of combined board failure [27,28]. Simply using the STFI test method, which does not incorporate buckling, does not meet this requirement. The relative accuracy of broader types of analyses combining STFI with other methods, and a discussion of the complexity of making all the required measurements in the field, remains to be investigated.

It is interesting to apply the logic above to current explorations of lighter-weight papers and thinner corrugated structures with more closely spaced flutes. These types of boxes are beginning to replace folding cartons in a

APPENDIX A

	Linerboard				Medium				ECT (T811)	
Data Set	CRC	CRC3	CRC1	CSTFI	RC	RC3	RC1	STFI	Avg	STD
1	157.9	157.0	157.7	41.0	42.4	40.9	40.4	12.3	39.2	1.6
2	153.2	151.5	151.6	40.6	43.8	44.2	41.0	13.1	39.5	1.2
3	154.8	153.3	157.9	40.3	43.1	43.7	46.5	12.6	39.1	1.9
4	157.9	157.0	157.7	41.0	61.5	63.7	62.4	17.1	42.6	2.6
5	153.2	151.5	151.6	40.6	63.7	62.9	61.3	16.9	41.0	2.3
6	154.8	153.3	157.9	40.3	66.2	67.9	67.6	16.7	39.9	2.6
7	263.8	265.3	262.8	58.9	42.4	40.9	40.4	12.3	56.0	1.8
8	272.0	270.8	258.2	59.7	43.8	44.2	41.0	13.1	58.7	2.3
9	263.1	262.3	261.1	58.4	43.1	43.7	46.5	12.6	57.5	2.3
10	366.2	366.7	364.6	86.4	42.4	40.9	40.4	12.3	72.0	3.8
11	357.4	357.0	360.6	80.7	43.8	44.2	41.0	13.1	71.6	2.8
12	347.1	346.7	338.3	79.2	43.1	43.7	46.5	12.6	69.5	3.2
13	366.2	366.7	364.6	86.4	61.5	63.7	62.4	17.1	75.5	3.7
14	357.4	357.0	360.6	80.7	63.7	62.9	61.3	16.9	73.6	3.2
15	347.1	346.7	338.3	79.2	66.2	67.9	67.6	16.7	73.7	2.9
16	263.8	265.3	262.8	58.9	61.5	63.7	62.4	17.1	60.8	2.6
17	272.0	270.8	258.2	59.7	63.7	62.9	61.3	16.9	61.1	2.2
18	263.1	262.3	261.1	58.4	66.2	67.9	67.6	16.7	60.1	3.5
19	263.8	265.3	262.8	58.9	78.0	76.7	73.3	19.5	61.5	2.7
20	272.0	270.8	258.2	59.7	80.3	81.8	79.1	19.5	62.8	2.9
21	263.1	262.3	261.1	58.4	81.9	82.7	82.9	19.3	61.9	2.5
22	366.2	366.7	364.6	86.4	78.0	76.7	73.3	19.5	77.7	5.0
23	357.4	357.0	360.6	80.7	80.3	81.8	79.1	19.5	74.0	4.2
24	347.1	346.7	338.3	79.2	81.9	82.7	82.9	19.3	74.5	2.5
25	157.9	157.0	157.7	41.0	78.0	76.7	73.3	19.5	43.2	2.9
26	153.2	151.5	151.6	40.6	80.3	81.8	79.1	19.5	44.2	2.7
27	154.8	153.3	157.9	40.3	81.9	82.7	82.9	19.3	42.3	1.8
28	149.2	150.3	147.4	39.0	41.1	40.9	41.5	12.3	39.1	1.5
29	147.1	144.0	149.1	39.2	44.4	43.9	46.9	12.6	37.1	1.5
30	148.8	147.1	145.2	39.1	43.8	45.0	42.9	12.4	38.9	2.0
31	149.2	150.3	147.4	39.0	77.9	78.2	77.1	20.1	43.6	1.6
32	147.1	144.0	149.1	39.2	80.8	80.5	79.0	19.4	43.3	1.6
33	148.8	147.1	145.2	39.1	81.5	81.5	79.9	19.8	43.9	2.4
34	377.0	374.6	389.4	84.7	41.1	40.9	41.5	12.3	75.3	3.2
35	362.3	361.2	362.5	82.6	44.4	43.9	46.9	12.6	69.0	4.0
36	343.8	342.0	360.4	78.5	43.8	45.0	42.9	12.4	67.6	3.1
37	377.0	374.6	389.4	84.7	77.9	78.2	77.1	20.1	79.5	4.6
38	362.3	361.2	362.5	82.6	80.8	80.5	79.0	19.4	74.4	2.5
39	343.8	342.0	360.4	78.5	81.5	81.5	79.9	19.8	73.5	2.3

Measured values used in modeling the single-site designed experiment, described in the text. Linerboard values are the sum of measurements on the two linerboards that formed the combined board. STFI values (TAPPI T 826) are averages of 20 measurements, reported in lbs/in. ECT values (TAPPI T 811) are averages of 24 measurements, reported in lbs/in. RC values (TAPPI T 822, with modifications in # of samples) are reported in lbs/6-in., and are averages of 10 (CRC and RC) or 3 (CRC3 and RC3) measurements, or represent single measurements (CRC1, RC1), as indicated in the text.

number of applications. In structures with more flutes (**Table III**), the spacing between flute tips decreases to a point much closer to the length scale probed by the STFI test than the length scale probed by the RC test. Thus, for small-flute corrugated, it may be that STFI better describes the failure mode of the structure, and thus of boxes in compression. At the same time, small-flute cartons are predominantly made using progressively lighter and thinner papers. This shift in component weight may serve to maintain the importance of facing buckling in the failure mode. The increasing use of small-flute cartons thus points to a potentially fruitful area for additional research probing the relationship between test method length scale and box failure mode dynamics.

CONCLUSIONS

The ring crush test and the STFI test both can be used to evaluate the compression strength of corrugated board components, and both can be correlated with combined board strength. While the STFI test probes paper strength at a length scale likely conducive to identifying the intrinsic compressive strength of the material, the RC test probes load-bearing capacity at the typical length scale of the inter-flute spacing of a corrugated box. The STFI test is also strongly influenced by unevenness in the material at the structural level, which is effectively averaged out in the RC test. As a direct result of these two differences, the RC test correlates better with ECT strength of corrugated board. This improved correlation holds even when only a few RC specimens are used to evaluate the strength of the paper, and even when variability from multiple combining operations at different box plants is included in the analysis.

ACKNOWLEDGMENTS

All physical property test data discussed in this article came from testing at the Materials Testing Lab of Packaging Corporation of America in Mundelein, Illinois. The author is indebted to the many technicians who have worked in the lab over the past several years, including Benjamin Tan, Vitaliya Dubilirer, Matt Landskroener, John Koch, and Michael Gilgenbach, for performing the physical measurements that underlie this discussion and analysis. As well, the author would like to thank the paper's reviewers for their thoughtful comments and suggestions that helped strengthen the presentation. **TJ**

Received: October 11, 2006
Accepted: February 2, 2007

LITERATURE CITED

1. McKee, R.C., Gander, J.W., and Wachuta, J.R., *Paperboard Packaging* 48(8): 149(1963).
2. Urbanik, T.J. and Frank, B., *Wood Fiber Sci.* 38(3): 399(2006).
3. Markstrom, H., *Testing Methods and Instruments for Corrugated Boards*, Lorentzen & Wettre, Kista, Sweden, 1999, p. 41.
4. Rennie, G.S., *Tappi J.* 78(7):183(1995).
5. Whitsitt, W.J., Institute of Paper Chemistry (IPC) Report, "Relationships Between Elastic Properties and End-Use Performance," Project 2695-23, January 30, 1985; available at http://hdl.handle.net/1853/701.
6. Frank, B., *TAPPI J.* 2(11): 13(2003).
7. Dexter, R.J., Letscher, M.K., Barton, D.W., et.al., *Paper Age*, 115(10): 19(1999) and 115(11): 24(1999).
8. Replogle, J.W., *Corrugating Intl.* 3(3): 15(2001).
9. Institute of Paper Chemistry (IPC) Report, "Optimization of Machine Properties for Compressive Strength: Survey of Factors Affecting Compressive Strength," Project 2695-22, March 15th, 1982.
10. Batelka, J.J., *Corrugating Intl.* 2(4): 163(2000).
11. Institute of Paper Chemistry (IPC) Report, "Effect of Specimen

INSIGHTS FROM THE AUTHORS

I chose this topic to research because the issue of which paper test method best relates to combined board and box performance is one that arises regularly at CORBOTEC and other technical forums, but there is a dearth of information on the subject.

The results we find in our lab differ from those in some of the literature from prior decades, in our finding that ring crush is a more reliable predictor of ECT. It was of interest to explore further the reasons for the differences.

The idea of correlating ring crush and STFI results with ECT, assuming different numbers of measurements, arose directly from a comment made at a CORBOTEC meeting that STFI must be more accurate since so many more individual readings can be collected in a short period of time. The assumption behind the comment was that more readings lead to a higher confidence level, not just in the accuracy of the value, but in its relationship to other properties.

While this did not seem to me to be universally true at the time of the discussion, I was surprised at how few ring crush samples could be collected to meet the modeling/predictive accuracy of the STFI test using 20 specimens. This somewhat counter-intuitive result highlights the importance of defining the right mechanism in choosing parameters for modeling complex phenomena.

How might mills benefit from or use this information? The results of this study imply that we may be better off measuring ring crush at our mills, rather than STFI, if issues pertaining to conditioning, equipment maintenance, etc., can be addressed. In any event, for mills that can perform the test accurately, this paper supports those mills who continue to test RC as their primary paper strength assessment.



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Dimensions on Edgewise Compression Tests of Linerboard and Corrugating Medium", Project 1108-4, Reports 82 and 83, March 23rd, 1966.

12. Dahl, C.B., *Tappi J.* 68(10): 108(1985).
13. Whitsitt, W.J., IPC technical paper series, no. 163 (1985); available at http://hdl.handle.net/1853/2651.
14. Shallhorn, P., Ju, S., and Gurnagul, N., *J. Pulp Paper Sci.* 31(3): 143(2005).
15. Seth, R.S., *Tappi J.* 67(2): 114(1984).
16. Van Eperen, R.H. and Crouse, B.W., Institute of Paper Chemistry (IPC) Report, "Ring Crush/STFI Test Methodology," Project 2694-12, April 26, 1991; available at http://hdl.handle.net/1853/698.
17. Fellers, C. and Donner, B.C. in *Handbook of Physical Testing of Paper* (R.E. Mark, C.C. Habeger Jr., J. Borch, et. al., Eds.) 2nd edn., Marcel Dekker Inc., New York, 2002, p. 481-525.
18. Schrampfer, K.E., Whitsitt, W.J., and Baum, G.A., *IPST Project 2695-24 Progress Report 1*, February 27, 1987; available at http://hdl.handle.net/1853/686. Accessed Aug. 21, 2007.
19. Frank, B. *Corrugating Intl.* 5(2): 3(2003).
20. Institute of Paper Chemistry (IPC) Report, "ECT/Component Relationships," Project 3511, February 18, 1983; available at http://hdl.handle.net/1853/633.
21. Johnson, M.J. Jr., Urbanik, T.J., and Denniston, W.E., *Paperboard Packaging*, 65(4): 98(1980).
22. Habeger, C.C. and Whitsitt, W.J., IPC technical paper series, no. 130 (1982); available at http://hdl.handle.net/1853/2733.
23. Hoke, U. and Gottsching, L., *Papier* 37(10A): 67(1983).
24. Jackson, T. and Parker, I., *Appita J.* 51(5): 349(1998).
25. Allan, R., *Appita J.* 56(2): 88(2003).
26. Popil, R., "ECT Literature Review," 2005 Corrugated Packaging Conference, available at http://www.tappi.org/s_tappi/doc_bookstore.asp?CID=5019&DID=527044. Accessed Aug. 20, 2007.
27. Schaepe, M., and Popil, R., Corrugating Intl., 8(2):3(2006).
28. Popil, R., Coffin, D.W., and Kaewmanee, P., "The Role of Linerboard Buckling on the Edgewise Compressive Strength of Corrugated Board," Progress in Paper Physics Seminar 2004, Trondheim, Norway.

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