Edge crush testing methods and box compression modeling

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ABSTRACT: While multiple test procedures have been developed to assess the inherent compressive strength of corrugated materials (edge crush test, ECT), limited work has explored the appropriateness of each in the context of box compression modeling. This study incorporates a variety of real-world samples, highlighting the varying challenges different ECT methods face in measuring the intrinsic compressive resistance of combined corrugated board. We examine each of these methods as inputs for different types of models, as well as discuss the propagation of measurement variation through the modeling effort. By highlighting the cases in which a given ECT method no longer proves to be an optimal parameter in box compression strength modeling, we explore how we might better measure this material property.

Application: This work highlights the importance of identifying and developing more optimal test methodologies to measure the inherent compressive strength of corrugated materials (ECT).

Corrugated boxes contain and protect their contents throughout the distribution environment and are used to package the vast majority of goods sold and transported commercially. Container performance is impacted by how the distribution environment acts on the box, and in a stacking and storage situation (e.g., warehouse) box compressive strength (typically measured by a top-to-bottom compression strength test, BCT) is the key performance metric. Since the invention of the box, researchers have attempted to generate predictive equations for box compression strength to provide robust estimations without requiring the actual production and testing of each order or every box. Modeling approaches relying on fundamental properties, as well as first-principle mechanics, offer the promise of enabling package optimization and "right sizing" packaging to meet distribution needs, ideally providing the opportunity to perform cost-benefit analyses of packaging. The "McKee equation" is the most common closed form box compression model used in the industry [1], though many others have been developed using both closed form mechanics-based approaches [2] and numerical simulations [3-5]. For all these models, the inherent material strength of the board structure contributes most significantly to box strength [6-8]. We attempt to evaluate this property by measuring the edge crush strength of the combined corrugated board (edge crush test, ECT).

The industry has developed several different edge crush tests, and it may be confusing even for those experienced with corrugated packaging to identify which method is best for a given situation. The most common North American certification process for boxes, the conforming (circular) box manufacturer's certificate (BMC), specifies the use of TAPPI Standard Test Method T 811 "Edgewise compressive strength of corrugated fiberboard (short column test)" as the referee method for determining the ECT of boxes used for shipping (ISO 13821 "Corrugated fibreboard — Determination of edgewise crush resistance — Waxed edge method" is similar). Significant development work underlies this test in its attempt to measure intrinsic compression strength, particularly in the context of the BMC rules [9]. For this specific application the "best ECT method" is clear; it is the one required by the governing specification. However, that does not automatically imply that the same test is best for other applications. Many manufacturing operations measure ECT to control or optimize their processes and assure they meet customers' performance requirements, and the best method in this case might be one that is easiest to use and achieves "reasonably repeatable" results. In this context, North American box plants often use TAPPI Test Method T 839 "Edgewise compressive strength of corrugated fiberboard using the clamp method (short column test)," where carefully cut square pieces are tested with edges clamped to prevent the results from being influenced by the effect of loading on the edges. This approach simplifies the testing process by eliminating the waxing and reconditioning steps and by providing a single specimen height for all materials. In Europe, operations commonly use ISO 3037 "Corrugated fibreboard — Determination of edgewise crush resistance (unwaxed edge method)" (FEFCO 8 "Edgewise crush resistance of corrugated fiberboard" is similar), an even simpler testing approach that avoids the time-consuming sample edge waxing and reconditioning of the T 811 method as well as the hassles involved in a clamping approach. ISO 3037 tests a short unwaxed specimen by directly loading on the cut edges. Other methods (e.g., TAPPI T 838 "Edge crush test using neckdown," JIS Z 0403-2 "Corrugated fibreboard — Part 2: Determination of edgewise crush resistance") re-

quire test pieces where the width of the specimen has been substantially reduced at a point midway between the loading edges, again to induce failure away from those edges. Each of these different methods has distinct advantages and applicability in their specific applications, but it is not clear from their descriptions which best captures the inherent material strength of the board structure. From a model, mechanics, and estimation perspective, the "best ECT method" would provide the strongest correlation with what we actually care about when using boxes — box performance. Ideally, it would also have the smallest variation in the measurement (within a single laboratory operation and between laboratories in the industry). If a method had very narrow variation but did not relate to BCT particularly well, it would not be very helpful, as it would not facilitate "robust" package performance estimations.

These different methods each have sample preparation and measurement steps that can impact the results. Loading the sample directly, whether waxed or not, requires very tight specifications on the parallelism and cutting quality of the loading edges [10,11]. Clamping can cause damage to the specimen, reducing its load carrying capacity [12]. Loading on an unreinforced edge typically causes curling of the paper at the edge, which leads to failure at the edge rather than in the sample body and thus may not be representative of the inherent material strength of the bulk structure [10,13,14]. Because of these challenges and others, these various ECT measurement approaches often produce different test values for the same materials [11,15-23]. Historical discussions across the industry failed to achieve consensus [24-26] as to which may best assess strength, and the question has not been addressed by more recent finite element analysis of the ECT process [5] or full field strain measurement [27]. Each ECT approach can be used to create models predicting BCT, provided that the formula to predict BCT values from ECT results is based on data from the ECT method being used. But the accuracy of the different models, based on the failure mechanics of the different tests, has not been well studied in the literature. As noted by Urbanik in 1990 [26], "a more complete critique of superior tests would need to involve comparisons using identical materials."

In this paper, we leverage a data set of 118 single-wall boxes to explore the correlation of ECT measurement with box compression and to assess model quality. For each box, we measured ECT using multiple methods, which are described further in the following sections. Along with measurements for bending stiffness, caliper, and other parameters, this data set provides a unique opportunity to explore different measurement and modeling approaches, serving to highlight which method better captures the inherent material strength required by structurally relevant models. In parallel, we explore the impact of measurement variation to guide future research into improved ECT measurement techniques.

METHODS

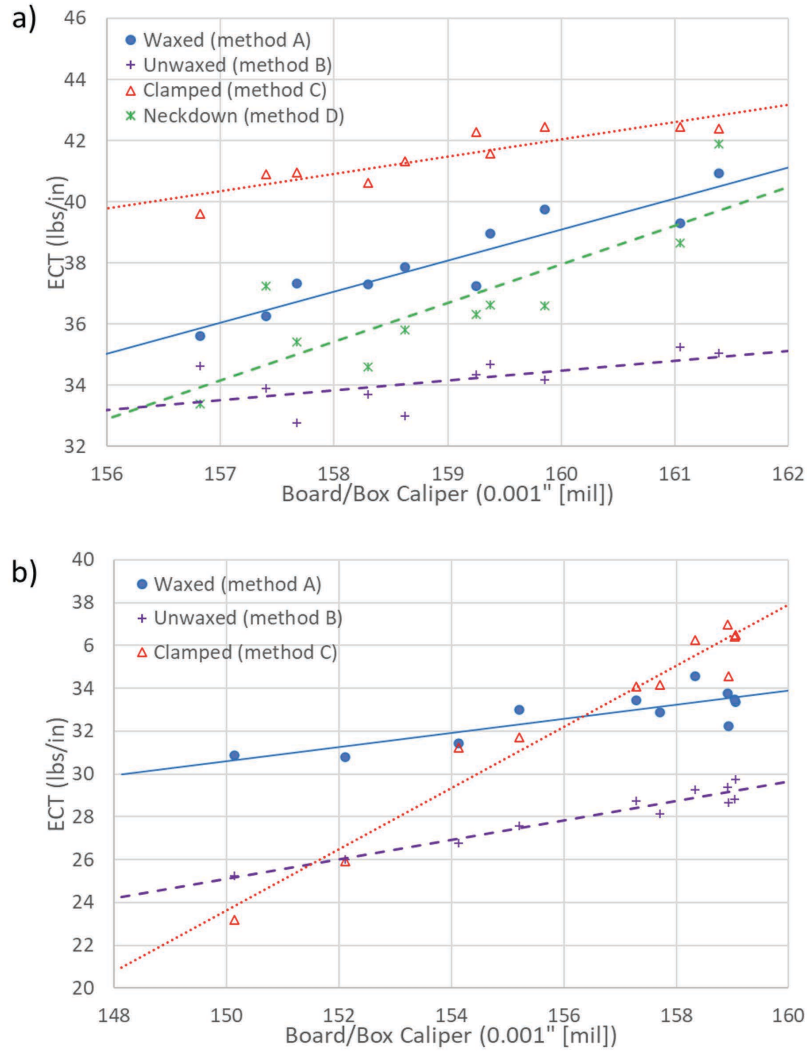
This research, and any comparative assessment of testing approaches, critically relies on the specifics of the testing process. All testing discussed in this paper was performed after preconditioning of the sample materials in a dry (~25% relative humidity [RH]) environment, followed by conditioning the materials at 23°C/50% RH, in line with the requirements of TAPPI T 402 "Standard conditioning and testing atmospheres for paper, board, pulp handsheets, and related products." Randomized sampling across each lot of commercially produced boxes assured that our different measurements were representative of the respective materials.

We assessed BCT following TAPPI T 804 "Compression test of fiberboard shipping containers." As the rotation of the minor flaps into the box can impact the measured compression load, all boxes were sealed using hot melt glue to immobilize the minor flaps during loading and were tested on a fixed platen compression tester. We regularly checked and maintained equipment parallelism at 1:2000 or better, tighter than required by the standard, to minimize the impact on BCT due to differences in platen parallelism [2,28]. Each reported BCT value represents an average of 10 individual measurements.

We measured board caliper following TAPPI T 411 "Thickness (caliper) of paper, paperboard, and combined board" with a foot pressure of 7.3 psi in line with that standard. Other caliper measurement standards call out different pressures, and since combined board is compressible, these standards can produce different values when measuring the same combined board [29]. This can be particularly relevant when evaluating boxes that may have experienced damage from the fabrication process. Each reported caliper value represents an average of 20 individual measurements.

Bending stiffness measurements were performed following TAPPI T 836 "Bending stiffness, four point method" using the 4-point bending stiffness tester developed by L&W (and presently sold by ABB; Zurich). For many boxes in this study, we were able to evaluate the bending stiffness at the standard span for single-wall board, 200 mm. For boxes too small in one or both dimensions for testing at 200 mm, we tested at either 150 mm or 100 mm and scaled the results following the literature [30]. Each reported bending stiffness value, in either the machine or cross machine direction, averages 10 individual measurements, half with the sample bent to be concave to the double-back side and half concave to the single-face side. Root mean square (RMS) bending, used in some models, is the square root of the product of the bending stiffness in the two principal directions.

All ECT specimens were cut using a dual blade cutter with rigidly mounted single beveled blades, with the unbeveled side producing the loading edge of the sample specimens [11]. Using single beveled blades for all sample loading edges assures similar parallelism across the different test materials examined. We verified this parallelism with occasional measurements of random specimens for all test methods. As noted previously and described in the in-



1. Edge crush test (ECT) measurements using different methodologies on boxes crushed various amounts during the production process. The lines indicate best fit relationships between ECT and box caliper for each method. Each data point is an average of 10 individual measurements, with a typical standard deviation in ECT of 1–2 lb/in. For a) the combined board used a heavy medium while b) involved board using a lighter medium.

troductory information for both ISO 3037 and ISO 13821, the variety of methods currently in practice for the determination of edgewise crush resistance can be generally classified into four groups:

A. Methods in which the edges of the test specimens are waxed to prevent the test results from being influenced by edge effects, such as ISO 13821 and TAPPI T 811. In this study, all specimens were 2 in. long, with C-flute board specimens cut 1.5 in. high and B-flute board specimens cut 1.25 in. high, following the TAPPI protocol.

B. Methods in which carefully cut rectangular test pieces are tested without any special treatment to prevent failure at the loading edges, including ISO 3037 and FEFCO 8. In line with those methods, samples in this study were cut 4 in. long and 1 in. high and tested without any further modifications. We identified curling of the papers at the loading edges as the failure mode for most materials, supporting the observation that this approach likely does not measure the actual intrinsic compressive strength of the corrugated structure [13]. We include this testing approach in the present study given the prevalence of this test methodology in the worldwide industry.

C. Methods in which carefully cut rectangular pieces are tested with edges clamped to prevent the results from being influenced by edge effects, such as TAPPI T 839. Following TAPPI T 839, samples in this study were cut 2 in. long and 2 in. high and tested using the clamping fixture produced by Emerson Apparatus (Gorham, MA, USA).

D. Those methods in which the shape of the test piece is reduced, or "necked down," in the center of the specimen, including TAPPI T 838 (based on work at the USDA Forest Products Laboratory [31]) and JIS Z-0403-2 (where the necked down sample is tested in a clamping fixture). Reducing the width of the specimen in the center increases the stress on the specimen in that area, forcing failure to the necked down zone and away from the specimen edges.

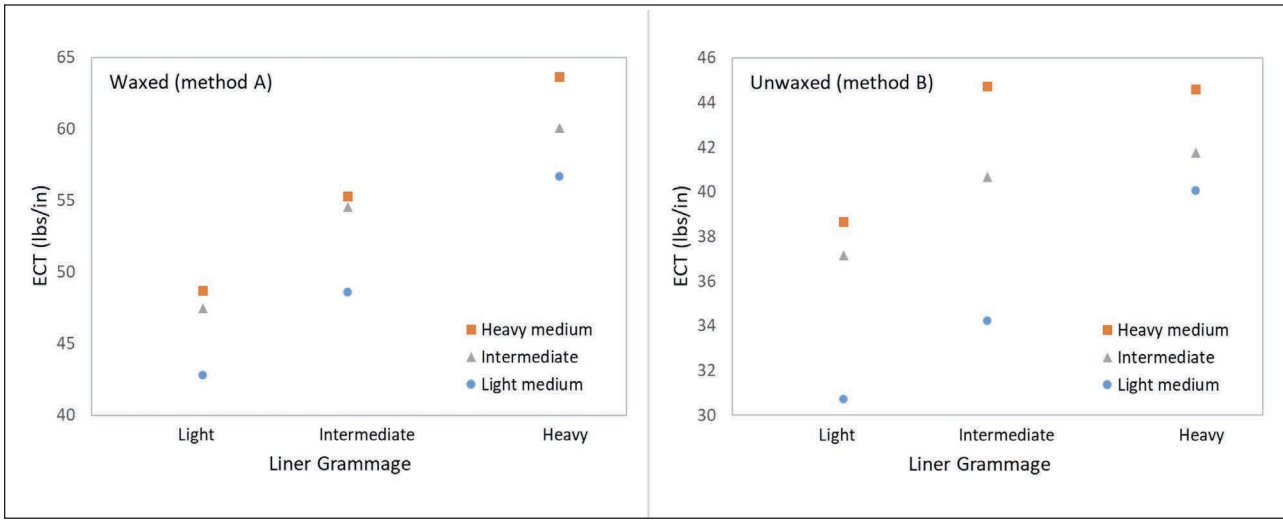
Examining test data using these four approaches on two lots of material crushed by different amounts during the fabrication process (**Fig. 1a** and **Fig. 1b**) highlights not only the significant difference in absolute values produced by these diverse testing approaches but also the different relationship these methods have to board damage (which occurs from crushing the board in its thickness direction, either in the box fabrication process or in erecting and use).

While this study incorporates data from ECT methods A, B, and C above, we were unable to reliably generate consistent, undamaged specimens in line with method D. However, we added an additional ECT approach to this study (method E), preparing 2 in. x 2 in. square samples in line with the clamping method (C) but then waxing those edges in line with the waxed method (A) before testing those specimens in the clamping fixture. The hardened wax should conceptually keep the samples from further crushing by the clamps (resulting in a significant shift in properties, Fig. 1) [12]. Method E is not useful as an expedited evaluation approach (since it incorporates both the waxing stage and the time required to execute clamping), but we will find below that it is helpful in separating/identifying contributions from different specimen failure mechanics.

Data set

In this study, we examine a diverse set of regular slotted cartons (RSCs) produced across a range of North American box plants for use in commerce. These include a mix of B-flute and C-flute boxes with lengths from 7.25–24 in., widths from 4.75–20.75 in., and depths from 5–26.5 in. We combine both B and C flute boxes when modeling in this study, as the literature [7] indicates that these single-wall boxes have the same general failure dynamics. Box perimeters were normally distributed with a mean of about 52 in. Average box depth was about 10 in. The ECT values (lb/in.) measured following method A ranged from ~25–75 lb/in. and BCT values ranged from 350–1160 lb. Given the variety in linerboard and corrugating medium grammages used for these different containers, this data set is assumed to be broadly representative of boxes in general. We did not conclusively determine the nominal grades of the component papers of all the different materials tested, nor the level of recycled or virgin content in each of the boxes. However, these factors are not input parameters in box estimation models; while perhaps desirable for future analyses, these are not relevant to the current study beyond indicating an expected change from one box to another where the grades or weights were known. Dimensional and physical property data on each box set examined in this study were collected from the boxes themselves, incorporating printed and unprinted areas in rough proportion to the level of print on the boxes, and are available in the Appendix.

Each method of ECT assessment has its own challenges, and we tried to incorporate boxes in our data set that would highlight those challenges. Though specimen heights for the waxed approach (A) are intended to achieve pure compression, that may not be the case for some unbalanced board combinations, as when sample caliper has



2. Corrugated boxes made by combining relatively light, intermediate, and heavy liners with light, intermediate, and heavy medium. For the waxed ECT method, strength increases linearly both as linerboard weight (and strength) increases and as corrugating medium weight (and strength) increases. For the unwaxed method, this is not the case. Data from samples 26–33 in the Appendix.

been dramatically reduced due to crush or when material bending stiffness is particularly low due to light liners [32]. Our data set thus includes crushed boxes and boxes with light liners (particularly for B-flute). For method B, the degree of edge curl may depend in part on the specific papers used, and in particular on the ratio of the strengths or weights of the linerboard and medium (**Fig. 2**). Our data set includes two groups of boxes (samples 26–33 in C-flute and 109–114 in B-flute) where the component weights (strengths) varied for the same box size. As we observed in Fig. 1, the impact of board damage (crush) in the converting process can also influence the different ECT tests in different ways. Because we sampled materials "from commerce," some boxes in this study likely experienced more converting damage than others. For one set of materials (samples 54–61), we systematically and significantly varied the amount of crush the board experienced in the box fabrication process, and we collected several additional groups of material where we evaluated the same box under more than one level of converting impact. All these different subsets of data were included to allow us to probe the appropriateness of each test method relative to the others across a wide range of boxes one might expect, given the natural variation of the box making process, and to highlight the responses of the different ECT methods.

Variation

Testing variation plays a critical role in our ability to develop robust models [33]. The less variation we have in measured properties, the better we know the values measured, and the more precise our models will be. Distinct from model accuracy, which would assess whether the model estimate is on target, variation impacts the amount of uncertainty around the estimated value. The best models would be on target and have a relatively low window of uncertainty around them. Since model uncertainty stems in part from measurement variation of the parameters that go into the model, if two ECT methods both assess the system in the same way and have similar correlations with the physical behavior leading to box failure, then the one with the lowest variation would result in the better model.

For our data set, we can calculate the average coefficient of variation (COV; percent variation, or standard deviation in the measurement divided by the average value) of the various properties measured, as well as their median values (**Table I**). If the uncertainty in measurement is randomly distributed about the average, we would expect the mean (average) and median values to be the same. Differences between them indicate the influence of skew in the sampled materials, typically arising from:

- Physical limitations on the boxes in the data set (e.g., there is a limit to how small a box dimension can be), leading to an uneven distribution of box sizes and strengths given that boxes in commerce are not evenly distributed (e.g., most boxes tend to be specific sizes to facilitate palletization).
- Variation of a physical property, part of which is of fixed size (e.g., due to test equipment) and part proportional to the magnitude of the measurement.
- Property changes through converting (e.g., crush increases COV for most properties), and the data set has an uneven distribution of damaged boxes.

	Perimeter	Caliper	RMS Bending	BCT
Mean	0.50%	1.09%	10.73%	4.51%
Median	0.48%	0.78%	8.35%	4.30%

RMS = root mean square; BCT = top-to-bottom compression strength test.

I. Average percentage variation (COV, the standard deviation of the measurement divided by the value) for physical properties used in box modeling across the 118 boxes in the data set.

	Waxed (A)	Unwaxed (B)	Clamped (C)	Wax in Clamp (E)
Mean	4.35%	4.97%	4.68%	4.23%
Median	4.07%	4.70%	4.13%	3.93%

II. Average percentage variation (COV) for the four edge crush test (ECT) methods studied across the 118 boxes in the data set.

We see this skew at some level in most physical properties, indicating that the measurement variations incorporated in this study are not uniformly distributed. In practice, for most parameters, we have a limited number of samples with particularly large COVs that shift the mean value somewhat from the median.

Despite all the challenges around sample preparation [11], the waxed ECT methods (A and E) have the lowest level of variation (COV, **Table II**) in our data. The mean values for methods A, C, and E are statistically similar, with overlapping confidence intervals. The values for methods B and C are also statistically similar to each other. We would expect ECT values with similar levels of variation to result in BCT estimations with similar levels of variation if the methods captured failure mechanics in the same way. We might also expect the lowest level of variation to produce the best fit. The difference between the mean and median values implies that something in each testing approach increases the measurement variation for a subset of the samples, skewing the distribution. As discussed previously, we intentionally selected samples to challenge each method and potentially enhance this skew. The larger the difference, the more significant it is across the population.

MODELS

The literature contains a wide range of closed form models for box compression strength [1,2,7,34-37]. For this study, we report on fits for just a few empirical models with their roots in first-principle mechanics, recognizing that even this simple modeling approach, based on a few measured parameters, remains challenged and challenging [38].

As a baseline, we start with the most common simplified form of the McKee equation [1]:

$$BCT = a * ECT * (c * p)^{\frac{1}{2}} \quad (1)$$

which relies on parameters relatively easily (and commonly) measured in a box plant: caliper (c) and box perimeter (p). Parameter a is a free fitting constant resulting from fitting the general model and is unique to each particular ECT test approach in combination with caliper and perimeter. McKee et al. arrived at this equation from their fundamental functional form (Eq. 3 below) by observing a relationship between ECT and caliper on the one hand and bending stiffness on the other, and by then rounding their exponent to simplify the calculations.

It is straightforward to approximate the expected variation in the calculated BCT based simply on the variation in each of the input parameters [33]. We can approach this in two ways: either by calculating the expected variation overall based on the mean value for the variation in each test (using the data from Tables I and II), or by using the same methodology to calculate the expected uncertainty for each box in the data set and then averaging those values. As we would expect from the differences in the means and medians in Tables I and II, the first approach should provide a slightly lower value for the COV estimate, because the high-end tail of the distribution for each property disappears when looking just at the averages. The advantage of using the average of the estimates for each box is that we can then also calculate a confidence interval on that estimate if we assume that the distributions are reasonably normal. We find, as expected, that the estimates based on the average value for each physical property included in the model are within the confidence interval calculated from the averages of each individual item in the data set (**Table III**). The confidence intervals in Table III also provide a sense of scale for when differences between two values, for example models generated using different ECT methods, become meaningful. As would be expected given the principles of error propagation, where we propagate the variances (squares of the COVs) of the inputs through the model to estimate the uncertainty of the output (BCT), the ECT methods with higher variation produce estimates of box compression strength that have higher COVs and wider confidence intervals around their estimates. Note that for the three established formal test methods (A, B, and C), the confidence interval is tightest and the average is lowest for method A, ECT on edge-waxed specimens.

The values in Table III are estimated average variance ranges between the actual BCT measured and what we would predict from the best fit of the data to Eq. 1. Differences arise entirely because of the measurement variations in the input parameters. We can compare these to the actual sum-squared error values for the best fit model to the functional form. (Other methods, including minimizing the absolute average error, the percent error, etc., provide qualitatively similar results with similar trends and are not discussed further here.) Each modeling approach and each method of measuring ECT generates a different value for parameter a, none of which match the value in the literature, which is unsurprising given prior literature summaries of data from multiple sources [7]. This highlights the importance of the specific data set in setting model parameters and the challenge of finding a universal equation to fit all data across the industry.

Where the actual model error (these sum-squared errors) is similar to what we would expect based on the propagated variation from average properties, we might assume that the model is capturing the physics to the best of its ability and all our model error is based primarily or entirely on measurement noise. In that case, the total uncertainty/error/noise in the model estimate can be attributed to variation in the input measurements. However, where the actual error of the best fit model is notably higher than what we would expect based on measurement noise, that implies there is an additional factor causing the deviation. The resulting model does not estimate as well as we would expect, because it is missing something in the physics or mechanics accounted for by the measurements.

	Waxed (A)	Unwaxed (B)	Clamped (C)	Wax in Clamp (E)
Estimate of the average COV (Eq. 1)	7.7%	8.4%	8.1%	7.5%
Average of the estimated COV (Eq. 1)	7.9%	8.7%	8.4%	7.8%
CI on estimated COV (Eq. 1)	0.4%	0.6%	0.6%	0.4%

III. Calculated variations in the estimates for BCT using two different approaches (see text) based on Eq. 1. Estimate of the average coefficient of variation (COV) is based on the mean variation in the input properties, while the average of the estimated COVs is the average of the calculations done for each individual box, with the confidence interval (CI) calculated for that average.

	Waxed (A)	Unwaxed (B)	Clamped (C)	Wax in Clamp (E)
Model sum-squared error	7.9%	10.8%	8.8%	7.7%
Model error-variation estimate	0.2%	2.4%	0.7 %	0.2%

IV. Best fit model variation based on Eq. 1, and comparison of the best fit model variation to the estimate of the average COV (Table III).

As anticipated from the level of variation in the tests themselves, when examining the existing test methods (A, B, C), the best fit model (with the lowest average difference between the estimated and actual BCT) in either approach occurs when we use method A, the waxed ECT test (**Table IV**). These models minimize the sum-squared deviation between the predictions based on the input parameters and the actual box strengths, calculated independently for each ECT method, and thus produce different values for the parameter a for each ECT method. The difference between the average of the best fit model and what we would expect from measurement variation is very close to zero for the fit generated using method A, and is within the confidence interval of the calculation of the expected variation based on the variation in the measurements themselves (Table III). By contrast, methods B and C have differences that are larger than the confidence intervals in the variations of the modeling fits and that are substantial relative to the values themselves. Put another way, while the clamp method (C) should provide an estimate of similar quality to that provided by the waxed method based on variation in the tests themselves, it does not. This implies that across the full set of 118 sampled materials, the ECT method does not capture the inherent material strength correctly for its need in the function form of the McKee equation (Eq. 1). While the unwaxed method (B) has more inherent variation, the deviation even from that higher variation is quite significant. Thus, the failure modes of specimens in these tests do not relate as well to box failure dynamics as the failure mode in the wax test (A).

In Tables II-IV, we have also included method E, where the specimen is waxed before clamping. The mean variation in that testing approach is similar to, but even lower, than that in the original wax test (method A). Subsequent calculations of the COV expected from the model (Table III) and actually found in the best fit model (Table IV) are slightly more accurate than method A. Since method E uses the same clamping fixture as method C, we might conclude that the problem with the clamp method is not the loading dynamics of the clamping mechanism itself. Rather, it likely arises because of the clamping pressure discussed previously and in the literature, which further damages any material that might be crushed from processing, artificially lowering the ECT value (Fig. 1). The crushed samples included among the 118 boxes in the data set highlight this problem. If we wanted to fix this approach, we could look to hardness [39-41] and identify the compressive forces a sample can support in its thickness direction at the hardness peak. We might then adjust our spring force so that the force applied even to a damaged specimen remains below the load the sample can support at the hardness deflection, even in the case of damaged samples. This might be fruitful for future exploration, if we can find a way to adjust the method to reduce the COV and better align behavior under crushing with the TAPPI T 811 results. By contrast, it is not clear how we could adjust method B to bring the failure mode in line. Those samples often fail by curling of the papers at the loaded edges, a load resistance mechanism clearly distinct from compression of papers or combined board. There are no opportunities for edge curl in the failure process of a box, and thus method B appears out of line with the failure mechanism captured in the structure of the model (Eq. 1).

While bending stiffness is not typically measured at a box plant, we included it in our testing in order to also examine the simplified model that incorporates bending:

$$BCT = a * ECT^{3/4}(RMSBending)^{1/4}p^{1/2} \quad (2)$$

as well as McKee's original model based on fundamental mechanics, with assumptions to enable closed form calculation:

$$BCT = a * ECT^{b} * (RMSBending)^{1-b} * p^{2b-1} \quad (3)$$

The RMS bending stiffness testing has a much higher variation than caliper measurements (Table I), and we might expect as a result that the variation in BCT calculation would thus be higher. However, Eqs. 2 and 3 have a correspondingly smaller impact from the variation in the ECT measurement, as well as lower contributions from bending variation than from caliper variation, and the overall estimate of COV is lower for Eq. 2 than for Eq. 1 (**Table V**). (For more detail on this calculation, see [33].) As with our fits to Eq. 1, in fitting Eq. 2 each ECT method was used in an independent calculation to find a best fit model and estimate of COV, resulting in different parameters for a and b for each method. We find that the best fit models using each of the ECT testing methods in Eq. 2 are more accurate, with lower variations, when we use

	Waxed (A)	Unwaxed (B)	Clamped (C)	Wax in Clamp (E)
Estimate of the average COV (Eq. 2)	7.5%	7.9%	7.7%	7.4%
Model sum-squared error (Eq. 2)	7.6%	9.7%	8.3%	7.4%
Model sum-squared error (Eq. 3)	7.6%	9.2%	8.2%	7.3%

V. Calculated variations in the estimates for BCT (based on mean values of testing variation), measured variation of BCT for Eq. 2, and measured variation in BCT for Eq. 3.

bending stiffness data instead of board caliper. Bending stiffness clearly does a better job at capturing the physics of failure than board caliper. While caliper "captures" the mass distribution of the liners in the board as a first order assessment of the moment of inertia of the material, measured bending stiffness more thoroughly captures the multiple contributions to material rigidity. Though we cannot get a clean, closed-form estimate of the propagated variation from the testing process for the full McKee equation (Eq. 3), we find further improvement in model quality. However, even with Eq. 3, the difference between the actual model error and the error estimate based on propagation of the error of the respective tests is larger than the confidence interval around the calculation for ECT method B.

We also examined the much more complex model developed by Urbanik and Frank [7] that, by removing the assumptions of McKee et al., better captures the mechanics at failure, especially for boxes that are particularly deep, shallow, or of significant aspect ratio. However, few of the boxes in this data set had aspect ratios substantially above two, few were particularly deep compared to the size of their panels, and fewer than 5% were expected to fail in a completely inelastic mode. Thus, the added physics captured by the more fundamental approach did not meaningfully impact the overall results, and in particular, did not provide additional insight on the contribution of the failure mechanism of the ECT test itself to the assessment of box performance.

Different methods of attempting to measure a given physical property do not necessarily provide the same level of model robustness, particularly (as we see here) when it comes to assessing inherent material strength (ECT). Much of the effort over the years has focused on adjusting the functional form (for a closed form model) or modeling approach (e.g., finite element analysis [FEA]) to create an assessment method that better represents the data, whether gathered from a single testing facility, as in the present study, or across multiple sources. These various approaches are all empirical, typically from first-principle mechanics, but with missing components that might explicitly account for unbalanced structures, torsional stiffness [42,43], or other factors. Model inaccuracy is usually attributed to the lack of completeness of the approach. Here, we see confirmation [33] that the impact of variation in our measurements themselves can be, and often is, the limiting factor on model quality. No amount of computer-aided mechanical modeling or adding more parameters to a closed form model can overcome the variation in the parameters we are using. As we strive to do a better job estimating package performance, we need to improve all the physical assessments we all rely on, particularly for the intrinsic compressive strength, reducing their inherent variability to the limit of what is possible given the nature of our materials.

CONCLUSIONS

Testing variation plays a critical role in our ability to develop robust models. The less variation we have, the better we know the values measured and the more precise our models will be. The best models would be on target and have a relatively low window of uncertainty around them. The BCT estimations based on the traditional waxed ECT test (TAPPI T 811) have lower variation than the other standard test methods examined. This test allows us to produce the most precise models, where the limits on modeling accuracy are almost entirely accounted for by variation in the underlying physical tests. By contrast, the average BCT estimation error when using other common ECT methods is larger than what we would calculate based on the testing variation alone, indicating a systematic problem with the relationship between the underlying test methods and the model's functional form. Using a waxed sample in the clamping fixture identifies the clamping pressure itself as the source of additional uncertainty/inaccuracy in the resulting models using the clamp test, and highlights edge curl as the likely source of added inaccuracy from unwaxed methods. These insights point to additional approaches we might take in the development of even better assessments of the inherent material strength of corrugated board. **TJ**

APPENDIX

The dimensional and physical property data on each box set were examined in this study, collected from the boxes themselves and incorporating printed and unprinted areas in rough proportion to the level of print on the boxes. See pages 428-433 for this data.

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About this journal

ABOUT THE AUTHORS

Across the industry, we still wrestle with the different ECT methods in use. It can be hard to explain to customers what their differences are and why. This study was our effort to better understand and resolve the challenge, and it builds on our previous work around box compression modeling and test method assessment. In many ways, it pulls those efforts together.

Generating a robust data set was challenging and time consuming. Many of the prior research articles on this topic came out of efforts to understand the input data parameters and generation process.

Through this study, we discovered many things, including how important it is to define up front what we intend to achieve when developing a test method. It can be very hard to clarify or "clean up" discrepancies once the test methods are in active use. Our most interesting finding was that the original ECT method seems to be the most robust of those in common practice.

Box plants and their customers can benefit by understanding the methods we use in the industry, and by basing discussions regarding specifications on a solid foundation. Our next step is to figure out how to further reduce variation in our systems so that we can continue to improve models and predictive approaches.

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Frank



Cash

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CORRUGATED BOXES

	Inside Dimensions			Caliper (n=10)		ECT Method (lb/in.)							
						TAPPI T 811 (n=10)		TAPPI T 839 (n=10)		TAPPI T 839 Waxed (n=10)		FEFCO (n=10)	
Sample #	L	W	D	Avg	STD	Avg	STD	Avg	STD	Avg	STD	Avg	STD
1	12 5/8	9 1/4	7 7/8	159.46	1.60	39.10	1.51	43.89	2.13	44.82	2.38	27.64	2.15
2	12 3/4	8 5/8	12	161.77	4.50	49.80	1.55	43.49	2.27	48.85	2.27	32.94	0.82
3	18 1/4	12 1/8	6 1/4	163.54	1.73	51.91	3.92	54.04	0.65	54.59	2.16	37.49	2.46
4	16 5/8	7	12	155.67	2.92	46.40	1.64	54.02	2.34	54.19	1.74	34.69	1.55
5	17	14 1/4	11 3/8	148.69	4.29	33.83	1.48	34.68	3.03	35.71	2.29	26.65	1.25
6	13 1/2	11 7/8	9 7/8	160.41	7.59	63.49	2.60	65.53	3.66	62.41	3.71	50.86	2.87
7	12 1/4	9 1/2	5 1/4	158.21	0.55	37.97	1.47	40.15	2.69	39.71	2.16	28.19	1.87
8	18 1/4	9 1/8	8 1/4	112.19	3.43	35.84	3.65	37.64	1.81	40.04	1.98	31.48	2.30
9	19 3/8	12 3/4	9 3/4	120.25	0.31	42.08	1.66	45.20	1.87	43.92	1.98	33.34	0.82
10	12 1/8	12	6 1/4	161.06	0.43	50.23	1.79	51.77	2.16	52.41	1.99	36.80	2.01
11	15 5/8	12 3/4	9 1/2	171.37	0.55	67.07	2.61	66.99	2.11	69.96	2.16	47.98	2.22
12	15 3/4	7 3/8	8 1/2	160.61	1.13	40.37	1.52	42.86	0.90	41.83	2.11	28.41	1.36
13	15 1/2	9 3/4	12 1/2	150.78	0.82	27.40	1.50	28.12	1.13	29.13	1.38	22.48	1.66
14	13	11 7/8	14	150.45	2.33	34.96	1.85	39.05	1.24	40.55	1.85	27.34	1.23
15	16 1/2	12 3/4	12 7/8	155.01	1.40	38.71	1.82	40.04	1.63	41.61	2.10	27.63	1.45
16	12 1/8	12	8 1/4	157.42	1.08	40.40	1.19	41.90	1.51	41.76	1.04	29.59	1.85
17	7 1/4	7	7 7/8	116.01	3.31	40.99	2.74	45.26	2.08	44.75	4.07	32.23	1.66
18	10 3/8	6 1/2	10	152.45	4.83	39.30	1.68	38.08	1.89	39.76	1.92	27.48	2.27
19	9	7 3/8	9 1/4	154.49	4.48	33.99	1.65	31.26	4.00	35.75	2.28	24.80	1.71
20	13 1/8	11 1/8	6 3/8	156.30	2.91	45.36	2.73	50.31	2.14	52.48	2.72	34.36	3.67
21	12 1/2	10 1/2	7 1/4	159.25	2.40	42.07	1.89	48.16	2.21	49.82	1.67	32.15	1.02
22	13 7/8	10 7/8	6 5/8	174.04	0.96	65.95	2.14	67.15	2.72	71.20	2.42	45.86	1.90
23	18	7 1/4	11 3/4	150.73	0.86	38.60	1.68	40.70	1.37	39.41	3.12	30.77	1.33
24	17 1/2	9 3/4	9 1/8	151.40	1.44	40.66	1.69	39.86	1.85	42.92	1.30	28.79	0.68
25	16 1/8	12 1/8	10 3/8	160.58	0.32	54.55	1.14	54.30	3.03	57.55	1.93	40.67	0.83
26	16 1/8	12 1/4	10 3/8	155.75	2.15	48.63	1.05	50.97	1.51	49.60	2.00	34.23	1.44
27	16 1/8	12 1/8	10 3/8	161.35	0.95	56.68	2.78	57.08	3.28	60.43	2.83	40.08	2.38
28	16 1/8	12 1/8	10 3/8	162.14	2.22	55.30	1.50	57.27	1.99	56.36	2.62	44.74	1.43
29	16 1/4	12 1/4	10 3/8	151.71	1.62	42.79	1.69	43.28	1.75	43.66	1.70	30.74	2.45
30	16 1/8	12 1/8	10 3/8	156.90	0.71	47.44	1.53	47.39	2.57	47.34	2.70	37.15	1.52
31	16 1/8	12 1/8	10 3/8	164.72	0.90	60.08	2.40	62.12	1.09	57.05	3.55	41.77	3.72
32	16 1/8	12 1/8	10 3/8	160.01	0.62	48.69	1.84	52.99	1.65	52.86	1.70	38.65	2.26
33	16 1/4	12 1/8	10 3/8	167.42	0.33	63.66	1.29	64.98	2.33	64.84	2.81	44.59	2.96
34	15 1/2	7 1/2	7 1/2	153.50	1.38	36.52	1.50	36.95	1.56	37.21	1.41	27.13	1.27
35	15 5/8	11 3/4	10 1/8	154.99	1.75	37.56	1.72	36.45	2.13	38.69	1.22	28.03	1.33
36	15 1/2	7 1/2	7 1/2	154.60	1.60	39.20	1.55	37.37	2.16	38.22	1.45	30.18	1.51
37	15 5/8	11 3/4	10 1/8	157.01	2.22	39.11	1.41	38.17	2.05	39.15	1.02	27.49	1.54
38	14 1/8	10 1/8	10 3/8	157.90	1.40	39.90	1.80	40.80	2.80	43.05	2.17	28.40	2.10
39	14 1/8	10 1/8	10 3/8	156.50	3.10	41.80	1.80	41.90	2.20	43.88	2.72	31.70	2.30
40	12	9 1/8	9 1/4	155.18	1.19	40.84	1.52	41.64	1.85	38.51	1.80	32.11	1.92

	Bending Stiffness 200mm (actual or scaled)						BCT (lb) (n=10)		Deformation (in.) (n=10)	
	CD Bend (Nm) (n=10)		MD Bend (Nm) (n=10)		RMS Bending (lb-in.) (n=10)					
Sample #	Avg	STD	Avg	STD	Avg	STD	Avg	STD	Avg	STD
1	6.25	0.38	10.50	0.59	71.67	5.93	571	29	0.393	0.016
2	8.43	0.52	11.84	1.76	88.44	14.20	706	16	0.404	0.019
3	9.15	1.74	16.31	3.77	102.28	24.24	1050	49	0.437	0.012
4	7.65	0.25	13.71	0.92	90.64	6.80	687	36	0.436	0.034
5	5.17	0.21	9.62	0.45	62.42	3.90	497	26	0.302	0.022
6	6.84	0.20	15.93	1.18	92.36	7.36	901	61	0.423	0.008
7	6.16	1.17	7.51	1.48	54.63	8.36	681	24	0.352	0.012
8	3.07	0.09	4.64	0.22	33.40	1.86	480	11	0.279	0.010
9	4.92	0.12	5.74	0.39	47.00	3.37	600	35	0.296	0.008
10	6.48	1.38	12.38	2.10	73.37	12.82	770	14	0.446	0.015
11	11.14	0.29	17.81	0.56	124.66	5.08	1100	40	0.543	0.011
12	6.86	0.36	14.74	1.19	88.97	8.54	620	21	0.365	0.010
13	3.47	0.16	6.71	0.85	42.69	5.74	407	25	0.378	0.011
14	5.66	0.22	9.10	0.45	63.50	3.98	585	28	0.371	0.014
15	5.77	0.16	12.80	0.89	76.04	5.69	586	27	0.409	0.010
16	6.62	0.33	10.19	0.96	72.72	7.79	522	30	0.374	0.015
17	3.36	0.92	7.02	1.61	36.94	6.63	395	22	0.281	0.019
18	5.52	0.14	11.53	1.22	70.58	7.71	487	31	0.355	0.066
19	4.66	0.16	9.85	1.07	59.92	6.87	387	17	0.344	0.037
20	6.64	0.30	12.07	1.00	79.24	7.49	593	29	0.404	0.006
21	6.95	1.05	10.75	1.79	70.77	9.20	619	23	0.417	0.010
22	11.64	0.66	25.15	1.14	151.41	10.98	1110	45	0.497	0.010
23	5.96	0.19	9.45	0.32	66.40	3.08	614	33	0.361	0.014
24	5.74	0.15	8.89	0.28	63.25	2.59	512	27	0.407	0.013
25	8.56	0.24	12.31	0.69	90.85	5.71	878	48	0.512	0.012
26	7.95	0.31	11.88	1.44	86.04	10.98	802	51	0.479	0.011
27	9.82	0.33	15.09	0.72	107.69	6.28	934	93	0.522	0.021
28	8.66	0.20	12.71	0.81	92.84	6.25	941	50	0.508	0.016
29	7.24	0.22	8.61	0.47	69.86	4.37	765	52	0.454	0.012
30	8.03	0.39	9.98	0.45	79.23	5.26	823	26	0.493	0.010
31	10.26	0.43	14.87	0.25	109.30	4.95	864	69	0.501	0.008
32	8.28	0.24	9.78	0.57	79.65	5.15	869	21	0.493	0.008
33	10.59	0.30	16.06	0.78	115.39	6.51	1163	75	0.538	0.008
34	5.32	1.28	9.90	1.45	58.36	9.27	463	9	0.338	0.012
35	5.95	0.57	10.13	0.64	68.71	7.84	526	13	0.312	0.009
36	5.03	1.19	13.92	3.04	67.62	14.71	477	15	0.354	0.012
37	5.49	0.31	13.79	0.46	76.98	5.07	523	11	0.335	0.014
38	5.60	0.20	10.76	0.75	68.71	5.38	548	8	0.380	0.020
39	5.57	0.23	11.02	0.75	69.37	5.56	580	18	0.380	0.010
40	5.95	0.09	10.70	0.76	70.59	5.13	540	22	0.376	0.009

CORRUGATED BOXES

	Inside Dimensions			Caliper (n=10)		ECT Method (lb/in.)							
						TAPPI T 811 (n=10)		TAPPI T 839 (n=10)		TAPPI T 839 Waxed (n=10)		FEFCO (n=10)	
Sample #	L	W	D	Avg	STD	Avg	STD	Avg	STD	Avg	STD	Avg	STD
41	12 1/8	8 1/4	9 7/8	155.88	2.64	38.93	1.39	40.50	2.00	38.43	2.56	30.29	1.80
42	14 1/8	10	8 7/8	152.97	2.07	34.23	2.39	36.38	2.32	36.56	2.00	27.14	1.89
43	13 1/4	9 1/2	6 1/2	160.69	2.60	51.21	3.61	52.55	3.15	54.71	5.23	35.67	1.43
44	17 1/2	9 7/8	6 1/2	157.43	1.13	40.50	1.92	41.70	1.67	43.18	1.53	34.43	1.12
45	12	9 5/8	7 1/8	152.04	2.02	36.65	1.40	42.45	2.30	40.36	2.40	28.80	1.56
46	11 1/2	7 1/8	5 5/8	148.51	2.97	39.98	1.67	33.14	4.76	39.72	3.24	27.43	3.88
47	13 3/8	10	9	149.84	0.77	50.42	1.54	57.47	1.65	56.10	2.79	41.11	2.12
48	7 7/8	7	10	148.66	4.31	50.86	2.25	51.59	2.95	56.05	2.44	38.22	1.60
49	18 1/8	16 1/4	10 3/8	157.13	1.79	42.05	1.54	34.37	1.62	39.09	1.02	32.36	1.54
50	18 1/8	16 1/4	10 3/8	157.45	1.26	43.03	1.33	34.97	2.32	40.77	2.10	31.65	1.32
51	24	18 7/8	20 1/8	134.55	2.40	36.05	1.62	30.90	2.44	36.41	1.05	27.14	2.11
52	10 3/4	7 1/4	7 3/4	155.78	1.45	39.13	1.71	38.88	2.05	38.93	1.87	28.05	2.07
53	11 7/8	4 3/4	7	143.54	3.52	40.65	2.65	40.09	2.34	40.99	2.90	25.28	2.76
54	15 1/2	11 5/8	10 1/8	155.69	1.19	38.01	1.43	36.87	0.94	36.87	1.96	24.88	2.93
55	15 1/2	11 3/4	10 1/8	154.29	0.97	35.36	0.86	34.18	1.95	34.91	1.28	24.98	2.56
56	15 1/2	11 3/4	10 1/4	148.09	0.91	33.99	1.74	31.10	1.20	34.41	1.31	24.08	1.74
57	15 1/2	11 5/8	10 1/4	151.98	1.17	35.07	1.66	32.61	0.99	34.63	1.24	23.17	1.95
58	15 1/2	11 3/4	10 1/4	155.99	0.83	37.86	1.67	36.21	1.47	38.90	1.61	26.64	1.55
59	15 1/2	11 5/8	10 1/4	156.66	1.54	36.53	1.20	38.47	1.96	38.35	0.70	25.78	1.71
60	15 1/2	11 3/4	10 1/4	156.64	0.86	37.50	1.52	38.28	1.59	40.82	1.67	25.57	2.04
61	15 1/2	11 3/4	10 1/4	155.83	1.08	35.58	1.95	34.72	0.84	37.81	0.55	25.00	1.37
62	15 7/8	11 7/8	10 3/8	162.07	1.26	57.84	2.08	58.55	2.07	57.77	1.91	40.55	4.80
63	15 7/8	11 3/4	10 3/8	162.10	1.27	56.61	1.91	55.90	1.72	59.00	2.23	39.52	1.56
64	15 7/8	11 7/8	10 1/4	157.86	1.02	58.02	1.97	58.19	1.73	58.49	2.00	39.36	3.15
65	17 7/8	7 5/8	6 3/4	114.42	1.67	37.33	2.36	40.61	2.06	42.21	1.52	30.33	1.21
66	11 5/8	8 5/8	21 1/4	114.25	0.67	38.69	2.01	41.99	1.53	40.40	0.92	32.27	1.66
67	13	9 1/2	10 7/8	119.70	1.41	56.17	2.14	58.94	2.14	62.34	1.52	41.40	1.49
68	17 1/4	10 1/8	14	152.99	2.19	34.94	1.52	34.64	1.48	34.76	1.24	24.72	0.94
69	18 7/8	7 5/8	18 3/8	145.36	1.88	34.16	1.22	34.19	2.97	35.51	1.91	36.00	1.75
70	23 1/4	15 5/8	8 3/4	123.73	0.71	55.81	1.85	59.67	1.76	64.65	2.66	41.30	2.88
71	10 3/4	10 1/2	7	122.92	0.67	56.15	2.53	58.13	2.08	60.90	1.36	43.13	1.74
72	19 3/4	11 3/4	6 1/2	116.09	3.10	48.86	3.08	52.35	1.83	52.96	2.53	33.32	0.88
73	22 1/4	17 5/8	22 1/4	151.30	1.09	37.42	1.81	39.29	3.74	42.35	2.84	28.46	1.46
74	15 5/8	13 1/8	21 3/4	158.90	0.91	44.67	2.27	45.74	1.98	43.37	2.31	31.11	1.85
75	15 3/4	9 3/8	9 1/8	160.46	1.38	51.48	1.22	54.55	6.11	53.17	2.66	43.54	1.93
76	15 1/4	11	13 1/8	129.30	0.90	69.09	2.97	70.35	1.98	70.47	2.20	54.12	2.30
77	15 1/8	11	13 1/8	118.98	0.56	47.52	1.24	48.44	1.46	47.26	2.20	36.78	0.87
78	17	15 3/4	14 1/8	121.42	0.16	51.14	1.69	54.05	1.24	51.21	1.78	42.09	1.23
79	19 1/2	12 7/8	12 7/8	120.59	0.31	50.43	1.41	53.04	1.18	50.44	1.91	41.87	0.32
80	13 3/4	11 3/4	13 3/8	159.17	1.48	49.83	2.44	52.06	2.58	56.08	2.43	36.20	1.89

		Bending Stiffness 200mm (actual or scaled)						BCT (lb) (n=10)		Deformation (in.) (n=10)	
		CD Bend (Nm) (n=10)		MD Bend (Nm) (n=10)		RMS Bending (lb-in.) (n=10)					
	Sample #	Avg	STD	Avg	STD	Avg	STD	Avg	STD	Avg	STD
	41	6.18	0.16	11.02	0.93	73.05	6.42	516	36	0.375	0.011
	42	5.29	0.12	9.32	0.52	62.13	3.75	455	14	0.326	0.014
	43	9.36	2.00	14.38	2.53	96.95	20.03	763	23	0.369	0.014
	44	7.15	1.30	9.17	1.08	66.08	7.41	685	12	0.405	0.008
	45	6.19	1.20	10.82	2.21	72.43	20.41	569	20	0.301	0.014
	46	5.19	0.97	8.94	1.64	60.30	15.74	478	26	0.239	0.019
	47	7.67	0.41	13.12	0.88	88.80	7.66	721	32	0.436	0.012
	48	6.96	1.39	13.11	2.32	84.52	22.54	605	39	0.367	0.019
	49	5.52	0.45	12.34	0.79	73.03	7.52	615	61	0.365	0.032
	50	5.99	0.43	15.42	0.83	85.09	7.62	713	26	0.414	0.015
	51	4.89	0.13	8.40	0.70	56.71	4.94	681	54	0.360	0.030
	52	5.89	1.22	9.91	1.75	67.61	18.35	515	20	0.295	0.025
	53	6.11	1.19	9.49	1.67	67.42	17.75	462	9	0.246	0.010
	54	5.62	0.21	8.52	0.61	61.23	4.90	597	19	0.386	0.016
	55	5.67	0.16	8.05	0.76	59.79	5.88	594	39	0.383	0.013
	56	5.25	0.14	7.60	0.58	55.91	4.49	554	35	0.367	0.013
	57	5.91	0.20	7.69	1.22	59.70	9.64	579	25	0.377	0.014
	58	5.71	0.10	9.17	0.45	64.04	3.29	601	30	0.389	0.012
	59	5.92	0.17	8.31	1.06	62.10	8.09	598	33	0.394	0.014
	60	5.92	0.19	8.38	0.64	62.35	5.13	625	10	0.396	0.006
	61	5.76	0.27	8.55	0.63	62.12	5.40	598	27	0.389	0.010
	62	8.32	0.35	18.35	0.36	109.39	5.13	850	26	0.377	0.013
	63	8.49	0.24	14.49	0.58	98.13	4.83	1087	17	0.463	0.009
	64	7.50	0.31	16.98	0.40	99.89	4.76	1007	82	0.406	0.018
	65	4.59	1.15	5.62	1.01	44.95	13.87	409	20	0.258	0.054
	66	2.88	0.31	6.37	0.37	37.92	4.62	456	25	0.286	0.011
	67	4.91	0.54	8.11	0.74	55.85	7.95	675	17	0.370	0.009
	68	5.51	0.17	9.80	0.78	65.03	5.56	611	21	0.386	0.010
	69	5.35	0.29	9.33	0.24	62.56	3.78	490	34	0.307	0.022
	70	4.63	0.55	9.88	0.74	59.86	8.37	941	35	0.505	0.040
	71	5.52	1.35	10.83	1.34	68.47	18.76	709	36	0.307	0.015
	72	4.18	1.15	6.93	1.32	47.65	15.95	700	15	0.252	0.007
	73	6.16	0.15	8.62	0.73	64.47	5.66	721	45	0.434	0.024
	74	6.82	0.28	13.77	0.67	85.76	5.45	698	48	0.429	0.018
	75	7.49	0.23	12.72	0.50	86.38	4.33	758	39	0.466	0.010
	76	6.12	0.35	12.56	1.06	77.58	7.90	875	29	0.383	0.010
	77	3.14	0.27	8.05	0.39	44.51	4.43	618	25	0.336	0.012
	78	3.52	0.14	8.30	0.47	47.86	3.28	631	27	0.330	0.012
	79	3.36	0.12	8.42	0.53	47.08	3.39	671	24	0.349	0.012
	80	8.43	0.23	14.60	0.43	98.18	3.93	774	20	0.400	0.018

CORRUGATED BOXES

	Inside Dimensions			Caliper (n=10)		ECT Method (lb/in.)							
						TAPPI T 811 (n=10)		TAPPI T 839 (n=10)		TAPPI T 839 Waxed (n=10)		FEFCO (n=10)	
Sample #	L	W	D	Avg	STD	Avg	STD	Avg	STD	Avg	STD	Avg	STD
81	13 3/4	11 3/4	13 3/8	164.18	1.10	52.92	2.60	59.15	1.19	60.66	1.86	45.83	0.81
82	13 3/4	11 3/4	13 3/8	161.42	0.83	46.35	1.93	50.53	1.93	53.85	2.09	35.90	0.90
83	14 7/8	10 1/8	26 1/2	139.25	1.33	28.85	1.74	26.38	2.75	27.99	1.10	20.08	1.03
84	19 3/8	10 1/8	6 1/4	161.99	2.36	51.34	3.36	45.06	5.88	54.94	3.42	34.92	2.14
85	18 1/8	9	24 1/4	151.98	1.29	36.29	3.00	37.49	1.39	37.76	2.18	25.60	1.61
86	16 1/8	11 1/4	8 1/4	162.41	0.94	48.69	2.04	52.94	1.67	55.29	2.23	34.50	1.70
87	8 5/8	7 7/8	9 1/4	155.56	3.45	42.06	1.71	40.75	1.75	43.80	2.91	31.45	1.25
88	8 1/2	7 5/8	7 1/8	148.98	0.81	37.33	1.33	38.97	1.38	39.70	1.82	24.38	1.24
89	9 1/4	8	7 3/4	166.15	4.25	65.52	3.67	61.08	1.89	67.42	4.41	47.07	1.74
90	14 5/8	11 1/2	9 1/8	170.25	0.92	72.09	1.82	70.31	2.94	74.27	1.14	55.29	1.22
91	14 5/8	11 1/2	9 1/8	169.56	1.24	71.28	1.79	70.13	2.46	72.41	1.40	52.42	1.07
92	14 5/8	11 1/2	9 1/8	169.08	1.04	74.27	2.67	72.57	2.43	72.41	2.87	54.34	1.01
93	14 5/8	11 1/2	9 1/8	168.92	1.49	73.05	3.10	73.43	3.02	76.50	1.95	56.65	1.25
94	14 5/8	11 1/2	9 1/8	170.32	1.36	68.52	1.92	69.09	2.85	68.70	1.85	49.93	1.17
95	14 5/8	11 1/2	9 1/8	169.14	1.42	69.86	2.63	68.78	3.01	71.14	2.11	49.12	1.50
96	14 5/8	11 1/2	9 1/8	171.91	0.89	70.57	2.93	70.63	2.92	72.25	1.59	54.76	1.38
97	14 5/8	11 1/2	9 1/8	170.41	1.25	70.94	2.45	72.81	2.37	70.53	2.64	54.20	0.65
98	14 5/8	11 1/2	9 1/8	167.02	1.31	63.79	1.77	62.94	1.79	61.27	2.65	47.11	0.76
99	14 5/8	11 1/2	9 1/8	166.51	1.54	64.03	1.87	62.15	2.51	63.66	1.99	46.38	1.96
100	23	17 1/4	14 7/8	148.52	1.20	29.91	1.15	31.43	1.53	34.93	1.37	22.63	0.92
101	12 1/8	9	6	148.70	1.47	31.59	1.66	32.71	1.15	34.43	1.67	22.41	0.85
102	18	9 1/4	15 7/8	144.02	0.95	29.81	1.67	31.17	1.29	33.63	1.28	19.94	0.94
103	13 1/2	11	5	110.44	0.19	31.20	1.72	34.33	1.78	32.06	0.90	27.16	0.66
104	12 1/8	13 1/4	10 1/2	160.18	0.66	38.73	1.35	40.11	0.94	41.07	1.43	28.43	0.59
105	12 1/8	13 1/4	10 1/2	159.37	0.39	37.60	1.36	39.76	1.40	39.60	0.51	28.16	0.66
106	12 1/8	13 1/4	10 1/2	159.60	0.89	39.70	1.29	41.54	0.97	41.68	1.13	29.37	0.40
107	12 1/8	13 1/4	10 1/2	141.94	0.92	33.10	3.41	31.50	4.93	31.25	2.23	23.35	0.76
108	12 1/8	13 1/4	10 1/2	141.81	8.01	32.40	2.03	27.08	3.76	33.13	3.20	22.17	1.19
109	16 1/2	8	11	117.37	0.35	42.99	1.34	45.36	1.36	45.68	1.11	33.07	1.24
110	16 1/2	8	11	115.64	0.37	39.78	1.44	43.06	0.93	41.44	0.97	31.62	1.18
111	16 1/2	8	11	113.02	0.41	33.14	1.45	36.29	0.84	34.79	1.13	27.00	0.67
112	16 1/2	8	11	115.02	0.22	36.14	1.07	38.45	0.99	37.43	0.64	29.20	1.18
113	16 1/2	8	11	110.63	0.19	29.91	1.00	31.96	0.71	31.60	0.83	23.91	0.52
114	16 1/2	8	11	108.65	0.18	27.64	0.96	29.48	0.62	29.53	0.40	21.76	0.62
115	20 1/8	12 1/4	8 3/8	161.00	3.60	54.90	3.20	55.30	2.20	59.56	1.53	44.25	1.47
116	20 1/8	12 1/4	8 3/8	155.10	3.50	58.20	2.20	57.20	2.50	62.06	1.70	46.34	1.38
117	14	14	14	149.02	0.67	33.50	2.35	35.68	1.49	39.31	1.19	32.14	2.04
118	22	20 3/4	20	156.26	2.28	36.15	2.84	38.99	1.08	39.50	1.55	31.31	1.47

	Bending Stiffness 200mm (actual or scaled)						BCT (lb) (n=10)		Deformation (in.) (n=10)	
	CD Bend (Nm) (n=10)		MD Bend (Nm) (n=10)		RMS Bending (lb-in.) (n=10)					
Sample #	Avg	STD	Avg	STD	Avg	STD	Avg	STD	Avg	STD
81	8.91	0.27	15.37	0.60	103.57	5.12	897	42	0.432	0.012
82	7.80	0.40	13.75	0.56	91.65	5.99	708	25	0.359	0.016
83	3.54	0.10	7.32	0.22	45.09	1.87	393	26	0.340	0.020
84	4.69	1.05	13.01	1.70	69.13	17.96	976	30	0.401	0.019
85	6.00	0.22	10.05	0.25	68.73	3.07	590	38	0.340	0.010
86	8.46	0.32	13.58	0.70	94.86	6.04	994	28	0.472	0.015
87	6.11	0.99	9.66	1.73	67.97	16.42	479	16	0.414	0.053
88	5.40	1.01	9.50	1.50	63.37	15.56	460	18	0.304	0.026
89	10.61	1.30	17.10	2.36	119.23	21.98	829	24	0.386	0.007
90	10.70	0.74	24.50	1.38	143.31	12.83	1087	48	0.435	0.010
91	10.13	0.56	24.25	1.04	138.72	9.67	961	43	0.448	0.016
92	10.51	0.63	25.27	1.61	144.23	12.60	1038	60	0.440	0.014
93	10.53	0.65	23.71	1.38	139.86	11.87	996	59	0.428	0.010
94	10.47	0.83	23.30	1.91	138.20	15.79	970	34	0.444	0.011
95	10.91	0.80	21.46	2.00	135.38	16.08	922	44	0.434	0.009
96	10.59	0.54	25.23	1.13	144.68	9.78	1067	56	0.467	0.011
97	10.36	0.69	25.09	1.08	142.68	11.32	1016	41	0.464	0.010
98	9.67	0.43	23.46	1.14	133.27	8.79	972	58	0.423	0.012
99	9.90	0.46	22.86	1.35	133.13	10.01	947	48	0.422	0.011
100	4.45	0.12	9.17	0.51	56.50	3.45	665	30	0.373	0.008
101	5.61	1.34	10.92	0.67	69.29	17.14	506	11	0.310	0.020
102	4.56	0.16	8.33	0.68	54.55	4.84	484	21	0.318	0.013
103	7.44	1.64	2.75	0.22	40.05	9.36	418	18	0.236	0.022
104	6.73	0.44	12.57	0.44	81.39	6.00	688	26	0.396	0.012
105	6.25	0.23	11.77	0.49	75.90	4.22	716	18	0.415	0.016
106	6.39	0.18	12.33	0.26	78.55	2.78	769	19	0.415	0.013
107	4.80	0.62	9.93	1.26	61.08	11.00	512	15	0.328	0.008
108	4.96	0.11	9.77	0.98	61.60	6.35	496	24	0.349	0.019
109	3.28	0.03	5.37	0.15	37.12	1.08	546	16	0.234	0.008
110	3.17	0.12	5.05	0.14	35.40	1.66	510	22	0.211	0.009
111	2.47	0.04	4.56	0.14	29.69	1.03	409	20	0.210	0.012
112	2.57	0.04	4.67	0.09	30.65	0.79	431	10	0.195	0.009
113	2.22	0.05	4.24	0.09	27.16	0.85	362	15	0.183	0.013
114	2.16	0.17	4.28	0.15	26.93	2.27	347	18	0.183	0.019
115	14.82	0.54	9.74	0.30	106.34	5.06	1038	37	0.383	0.005
116	12.03	0.74	9.93	0.68	96.69	8.91	1008	24	0.364	0.007
117	9.32	0.42	4.92	0.17	59.90	3.42	599	46	0.355	0.022
118	12.04	0.75	7.03	0.46	81.43	7.31	598	71	0.372	0.021