# Importance of specimen preparation for edgewise compressive strength (ECT) testing

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**ABSTRACT:** While more than 50 years of published studies recognize the importance of rectangular, parallel edgewise compressive strength (ECT) specimens, none of the existing test methods address the degree to which a sample specimen is defined as sufficiently parallel. We present a detailed exploration of ECT results for specimens whose edges deviate from parallel with varying severity. We work to identify causes of variation in dimensional measurements and the corresponding ECT values across several industry standard cutters. These variations present a significant challenge to the industry in satisfying customer expectations for performance-based packaging, as well as to the development of improved predictive models for packaging performance.

***Application:*** This work serves as an early step for identifying or developing more optimal test methodologies to measure the inherent compressive strength of corrugated materials.

Although box compression strength (box compression test [BCT]) of corrugated containers is the primary end-use performance criteria for many boxes, the edgewise compressive strength (ECT) of the material remains the most common parameter specified by customers. ECT measures the force required to cause a vertically-oriented specimen of corrugated fiberboard to crush, with measured values providing an assessment of a fundamental material property. The ECT value can be related to the ultimate stacking performance of the container, and has been used in predictive modeling for over 50 years [1-3]. As well, many box plants measure ECT to control or optimize their processes and assure they are meeting customers' performance requirements. ECT is also codified in the most common certification process for boxes, the conforming (circular) box manufacturer's certificate (BMC). The BMC is a guarantee by the box maker that the box meets certain standards set in the National Motor Freight Classification (NMFC), so that the carrier in a less-than-truck-load shipping environment will agree to accept the shipment for carriage. The rules outlined in National Motor Freight Traffic Association Item 222 [4] specify 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.

ECT testing strives to capture the strength of the bulk composite structure formed by the linerboard and fluted medium, an intrinsic material property. Various factors can affect the measurement of ECT. These include failure at the specimen's loading edges, specimen buckling, and structural damage sustained during the production and handling of specimens, all of which can reduce the measured value from a true reflection of the material strength. Several different specimen preparation approaches, including waxing edges (TAPPI T 811), necking down (TAPPI T 838 "Edge crush test using neckdown"), clamping (TAPPI T 839 "Edgewise compressive strength of corrugated fiberboard using the clamp method [short column test]"), and testing geometrically short columns (ISO 3037 "Corrugated fiberboard — determination of edgewise crush resistance [unwaxed edge method]"), attempt to mitigate the effect of these factors. As the literature consistently demonstrates [5-13], these differing approaches do not produce similar results. For samples loaded directly on their edges (TAPPI T 811, TAPPI T 838, and ISO 3037), Eriksson's exploration of test factors [14] highlights specimen parallelism in particular as an important consideration, as do McClain and Boltnott [15] and Ernst and Graf [16].

The TAPPI standards have generally incorporated the learnings from these and similar studies in their equipment specifications. The tolerance on the compression equipment, used consistently throughout all tests on containerboard materials (see, for example, TAPPI T 822 "Ring crush of paperboard [rigid support method]" and TAPPI T 809 "Flat crush of corrugating medium [CMT test]"), is designed to prevent artificially low values due to one part of the material under load failing before the entire specimen is loaded. For example, the specification for parallelism of the compression tester in TAPPI T 811 (section 3.1.1) states, "Within the specimen contact area, each platen shall be flat within 0.0025 mm (0.0001 in.) of the mean platen surface, and the platens shall remain parallel to each other within 1 part in 2000 throughout the test." What seems an arbitrarily tight tolerance (0.05%) becomes less capricious when one considers that paper materials fail at strains on the order of 0.5%–1%.

The initial development of the ECT test required the use of a table saw to prepare specimens [17]. In that work, the authors observe that a slightly tilted saw blade, which would produce trapezoidal specimens (from an end-on perspective), "can cause a very severe reduction in compression results because of the bevel incurred in the loading edges of the specimens. Every effort should be made to ensure that the blade is as perpendicular as possible." (Note: Throughout this paper, we use the word "trapezoidal" to describe ways in which the samples are not pure rectangular parallelepipeds. Trapezoids are planar figures; the description of samples as trapezoidal actually refers to a given face of a sample, not to the entire piece. For example, if one examines the ECT specimen from the side of the doubleback liner, the piece is rectangular if the opposite edges are the same size and parallel with the corners forming right angles, and it is trapezoidal if the top edge of the liner is parallel to but not the same length as the bottom edge.)

As the industry moved to safer and cleaner cutting methods, including the single knife and double knife systems described in the next section, we continued to observe that test specimens should "be cut with the loading edges exactly perpendicular to the flutes" [8] and that "lack of parallelism in the loading edges across the board width or along the thickness… will result in lower ECT values." Nowhere, however, does the literature provide actionable guidance on how much lower, for a given amount of deviation from perfect parallelism, nor any scale of the effect of trapezoidal specimens.

As Eriksson noted, the parallelism requirement for the equipment is more than an order of magnitude greater than the typical accuracy in cutting a test specimen. TAPPI T 811 provides only that "opposite edges shall be parallel to each other and perpendicular to adjacent edges," with no quantification. The interior alignment of the clamping text fixture in TAPPI T 839 uses similar language of "held exactly perpendicular to the base," with no quantification of how parallel or perpendicular, nor any obvious means of measuring or checking such alignment. Given the dimensions of a typical C-flute ECT specimen for TAPPI T 811 (2 in. [50.8 mm] wide specimen, ~0.160 in. [~4.1 mm] thick), a 0.5% difference across the length would be 0.01 in. (0.254 mm). Higher levels of deviation from "true parallel" were observed in Eriksson's work. More critically, in the thickness direction, one part in 2000 from the TAPPI T 811 parallelism requirement is ~0.00008 in. (~0.0020 mm). This provides a sense of the scale over which parallelism may matter.

This paper does not solve the challenge of cutting a specimen parallel. By presenting a detailed exploration of the issue, we hope to spur the industry to develop better cutting methods and perhaps better test methods to help reduce the level of variation present in our current test results. This variation presents challenges to the industry as we attempt to satisfy customer expectations for performance-based packaging and develop better models to predict package performance. The deviations inherent in specimen preparation limit our ability to quantify the inherent material strength, and to optimize our materials.

Because of its effective codification in U.S. Carrier Rules and its primary use by customers as a specification for combined board strength, in this paper we focus on the effect of parallelism on specimens prepared for TAPPI T 811, where the specimen is loaded directly on the cut edge after the edge has been supported by waxing. After a discussion of several styles of specimen preparation equipment, we explore parallelism measurement. We will then be equipped to discuss deviation from "parallel" observed on typical specimens and to measure the impact those shifts have on ECT values.

## CUTTING DEVICES

Several cutters are used across the industry, all with distinguishing features that add to the diversity of the data. While some conform to the TAPPI T 811 requirement to use single beveled blades, others do not. We examined five in detail in this study, and divide them into two general categories: dual blade and single blade.

- Single blade cutters always require two cuts to produce the loading edges, potentially allowing for the sample material to twist or shift between cuts. This could affect the parallelism of the specimen loading edges. Given that cutting blades are typically beveled on at least one side, these types of cutters tend not to allow full conformance with the requirements of the TAPPI T 811 test method, as at least one edge (depending on cutter configuration) typically ends up being cut against the beveled side of the blade.
- Dual blade cutters attempt to assure parallelism in the two specimen loading edges by cutting the specimens to size in one stroke using a pair of parallel blades. Specimens cut with a single pass have parallelism defined by the accuracy of the blades and cutting instrument. Specimens that might need to be cut to a smaller size than the blade spacing (for example, a 1.5 in. [38.1 mm] C-flute specimen prepared on a dual blade cutter with a 2 in. [50.8 mm] spacing) require a second cut of one edge. This two-step process potentially allows for some twisting or lifting of the specimen during cutting that might cause deviation from perfectly parallel, similar to a single blade cutter.

For all cutters, samples are held against a backstop nominally perpendicular to the travel of the blades so that the resulting specimen's loading edges are cut orthogonal to the vertical edges. Out of deference to the various cutter suppliers, we will refer by number to the five cutters we examined. Challenges with parallelism can apply to all the cutting approaches explored.

Cutter 1 has two single-bevel blades that run along the inner wall of parallel channels, with the unbeveled blade side facing the inside of the channel. Setting the blades so that they rest along the inner wall limits the movement of the blades during cutting. This configuration reduces potential deviation from a parallel specimen by preventing inward movement of the


***1. Images of the measurement of a sample specimen. Note that the jaws of the caliper, resting on a level surface, are elevated above the surface and so measure just the area of the upper facing at one edge.***

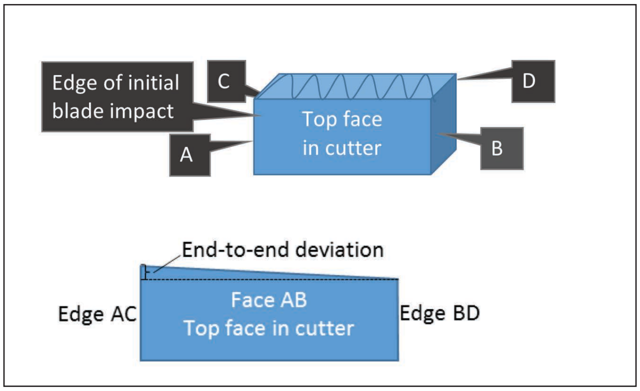
blades and providing some support to restrict blade bowing. Specimens cut with both blades have a nominal height and parallelism defined by the channel width, 2 in. (50.8 mm) for our version of the equipment. A mountable guide bar running parallel to the blade channel can be installed to prevent the right-most blade from affecting the material being cut, allowing a second cut on the specimen to trim it to a smaller height.

Cutter 2 is similar, a dual blade device with blades that are at a 2 in. (50.8 mm) fixed separation. These blades are installed with some pressure against the inside edge of their guiding channels, potentially causing the guide to wear over time, thus leading to deviations from parallel in the shape of the specimen in the initial cut. The right-most blade can be removed, allowing a metal guide block to be mounted to set a new specimen height with a second cut.

For cutter 3, also a dual blade cutter with single bevel blades, the blades rest in the center of their guiding channel, preventing wear on the channel itself. However, this allows some movement of the blades during cutting, potentially causing the specimens to exhibit a variation in edge measurements from blade flexing. For this cutter, the blade carriage itself is adjustable, allowing the distance between the two blades to be shifted to cut ECT specimens of any height with a single pass. This avoids any effects from the specimen twisting in a second cut and maintains the parallelism levels achievable by the spacing and rigidity of the instrument and blades.

Cutter 4 is a single blade cutter, using a blade beveled on both sides that runs in the center of its guide channel. An adjustable guide bar parallel to the blade channel enables specimen preparation to any desired size. Because the blade is beveled, there is no need, nor option, for non-beveled edges on the specimen to be maintained. In many operations, this common cutter may be used for the machine direction cuts of the board before cross directional cuts performed on other cutters to create the loading edges, but some may also use it for cutting the loading edges despite its inability to support conformance with TAPPI T 811.

Cutter 5 is also a single blade cutter, with the blade running along the center of a channel and the sample resting against a guide stop to determine specimen size. Uniquely, this cutter's blade is circular, with a much less significant bevel on both sides. However, the existing bevel still means this cutter does not strictly follow TAPPI T 811 standards for specimen preparation.




***2. Definition of the four vertical sample edges used to define sample geometry. End-to-end variation is the difference in the averages of A with C (defining sample edge AC) and B with D. Face-to-face variation is the difference in the averages of A with B (defining face AB) and C with D.***

Cut specimens were examined as produced, with the cutting blades changed at the first sign of wear, when specimen edges diverged from clean and crisp. This varied by cutter, blade system, and sample material, but was typically at least daily.

## MEASURING PARALLELISM

Quantifying the parallelism of an ECT specimen presented some unique challenges. We needed a method that was relatively robust, repeatable, and easily executed. For this work, we used a standard digital caliper with a resolution of 0.0005 in. (0.0127 mm) and an accuracy of ±0.001 in. (0.0254 mm) to measure each vertical edge of the test specimens (**Fig. 1**). By measuring each facing at each end of the specimen, we get four measurements. This allowed us to calculate an average change across the specimen, both along the length of the specimen (end-to-end) and front to back (face-to-face) (**Fig. 2**). Note that the accuracy of our measurement is the same as the specified tolerance for the parallelism of the crush

| Cutter No. | Blade Thickness, in. | Impact Angle, ° | Impact Depth, in. | Bevel Depth, in. |
|---|---|---|---|---|
| 1 | 0.0257 | 40 | 0.315 | 0.130 |
| 2 | 0.0177 | 35 | 0.301 | 0.073 |
| 3 | 0.0241 | 26 | 0.284 | 0.109 |
| 4 | 0.0237 | 40 | 0.237 | 0.083 (double) |
| 5 | 0.0118 | ~40 (circular) | 0.282 | 0.038 (double) |

***I. Blade dimensions for the blades used in each cutter. The impact angle and depth are fixed by the geometry of the structure holding the blade in place for most cutters. Note that for cutters 4 and 5, the beveled area rises up along each side of the blade. For cutter 5, the angle of impact is estimated at the top of a typical C-flute specimen, and changes based on the thickness of the specimen to be cut, given the curvature of the blade itself.***

tester platens themselves, as stated in the TAPPI T 811 ECT method.

Each ECT specimen has a specific orientation in the cutting process. For all the cutters, a sample strip is placed flat on a support surface and the cutting blade travels across the sample. Given the blade angle, the blade first impacts the top surface of one edge of the specimen (edge A). We call the edge immediately below that, on the same end of the specimen, edge C. The average of our caliper measurements on edge A and edge C define for us the height of the specimen on that end. On the other end, edge B is on the top face in the cutter and edge D is on the bottom face, with the average of measurements B and D defining the height of the specimen on the other end. The difference in the averages on each end defines the edge-to-edge or end-to-end deviation from parallel along the length of the specimen. This mimics the measurements made by Eriksson [14]. Similarly, the difference between the average of A and B (defining the size of face AB, facing up in the cutter) and the average of C and D (defining the face CD, facing down) provides an assessment of the average face-to-face deviation from one side of the specimen to the other. This quantifies the deformation to one liner/facing, which would occur before the other liner picks up any load.

Given these definitions, all cutters showed some challenges maintaining parallelism. This might have resulted from strips moving vertically or twisting during the cutting process. It also might have resulted from individual specimens shifting in the cutter for cases where a second cut is necessary. The blade(s) might also be flexing as they pass through the sample. Each cutter uses a different blade, impacting the specimens at different angles, with bevels of different sizes (**Table I**). The one common factor for all cutters is that the top liner receives the initial impact before the rest of the specimen. This can cause a slight roll at the edge (**Fig. 3**), which we observed for many specimens.

***3. Three specimens from the same material cut with cutter 5. The left side of each specimen was face up in the cutter, and the blade impinged first on the leftmost surface. Note that both liners are curled in the same direction because of the force of the blade pressing down during cutting. The left specimen is unwaxed and appears as cut. The middle specimen is after edge waxing. The rightmost specimen has been tested, with a clear edge bias following the initial edge curl. Specimens were identically sized and are offset one from another in the image for visual clarity. Few samples have this dramatic an edge curl, but many samples cut with the various cutters have some observable edge impact.***

## TYPICAL SPECIMEN PARALLELISM

From the literature, we would expect specimen parallelism, both end-to-end and face-to-face, to affect measured ECT values. To understand how much variation might exist, we can look at a subset of randomly sampled materials cut on a range of cutters at laboratories across the industry. We find that a set of specimens can have an average deviation from parallel of several mils (0.001 in.; 0.0254 mm), both along their length and, more critically, through their thickness (**Table II**). The majority of these values are statistically different from zero, indicating a meaningful deviation from parallel across each set of specimens. The most parallel "face-to-face" specimens came from fixed distance dual blade cutters using single bevel blades, despite the requirements of a second cut when the specimen size requirement was smaller than the blade separation distance. The most parallel "end to end" specimens came from single blade cutters. Effectively, independent of labora-

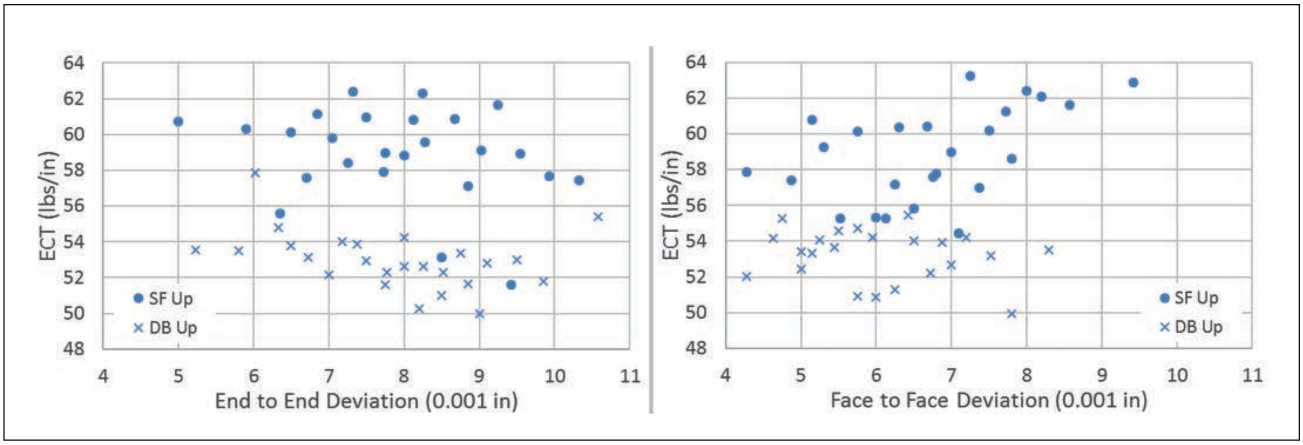
| | | Nominal Height | | Absolute Variation | | | |
|---|---|---|---|---|---|---|---|
| | | | | End-to-End | | Face-to-Face | |
| Lab | Cutter | in. | mm | mil | mm | mil | mm |
| B | 4 | 1.25 | 31.75 | 6.08 | 0.154 | 1.58 | 0.040 |
| A | 1 | 1.50 | 38.10 | 3.31 | 0.084 | 0.07 | 0.002 |
| C | 2 | 1.50 | 38.10 | 3.08 | 0.078 | 0.46 | 0.012 |
| G | 2 | 1.50 | 38.10 | 6.17 | 0.157 | 0.17 | 0.004 |
| G | 2 | 1.50 | 38.10 | 8.46 | 0.215 | 0.63 | 0.016 |
| A | 4 | 1.50 | 38.10 | 0.42 | 0.011 | 1.17 | 0.030 |
| B | 4 | 1.50 | 38.10 | 4.73 | 0.120 | 0.35 | 0.009 |
| A | 5 | 1.50 | 38.10 | 0.10 | 0.003 | 2.60 | 0.066 |
| E | 5 | 1.50 | 38.10 | 2.60 | 0.066 | 1.20 | 0.030 |
| E | 5 | 1.50 | 38.10 | 2.95 | 0.075 | 1.83 | 0.046 |
| E | 5 | 1.50 | 38.10 | 2.50 | 0.064 | 0.60 | 0.015 |
| E | 5 | 1.50 | 38.10 | 2.75 | 0.070 | 2.65 | 0.067 |
| E | 5 | 1.50 | 38.10 | 2.75 | 0.070 | 1.55 | 0.039 |
| E | 2 | 2.00 | 50.80 | 3.10 | 0.079 | 0.50 | 0.013 |
| E | 2 | 2.00 | 50.80 | 4.75 | 0.121 | 0.25 | 0.006 |
| E | 2 | 2.00 | 50.80 | 5.37 | 0.136 | 0.27 | 0.007 |
| E | 2 | 2.00 | 50.80 | 6.40 | 0.163 | 0.50 | 0.013 |
| E | 2 | 2.00 | 50.80 | 5.70 | 0.145 | 0.40 | 0.010 |
| D | 4 | 2.00 | 50.80 | 0. 92 | 0.023 | 2.67 | 0.068 |
| D | 4 | 2.00 | 50.80 | 1.23 | 0.031 | 0.77 | 0.020 |
| F | 4 | 2.00 | 50.80 | 2.29 | 0.058 | 4.86 | 0.123 |
| F | 4 | 2.00 | 50.80 | 3.79 | 0.096 | 0.64 | 0.016 |

***II. Parallelism measurements on specimens of different sample materials supplied by various industry laboratories. The first sample (1.25 in.) was B-flute. All other samples were C-flute. Samples were cut to different heights by the supplying laboratories, in line with their needs. We find meaningful deviation of nearly all specimens from true parallel in at least one direction, independent of laboratory, cutter type, blade used, or nominal specimen height (ECT = edgewise compressive strength).***

tory or preparation equipment, typical specimens produced for ECT testing are not truly rectangular.

At its extreme, deviations from parallel along the length of the specimen can result in a significantly trapezoidal specimen, end-to-end, causing one end of the specimen to load to failure before the other end supports any load. Based on the literature discussed previously [14-16,18], that might occur if the size difference end-to-end was on the order of 0.5%-1% of the height of the sample specimen. Few, if any, of the ECT specimens measured here appear to have variations large enough to lead to that effect explicitly. However, it is reasonable to expect a continuum of impact from a specimen where one end loads to failure (and the test stops) before the other end loads at all, up to the point where the specimen truly is perfectly parallel and the entire specimen loads uniformly and fails as such. These samples collected from across the industry are all somewhere along that continuum, with an unknown reduction from the true inherent compression strength of the material in each case.

Similarly, deviations from parallel along the thickness of the specimen, from one face to the other, can cause one liner to carry proportionally more load than the other. We can imagine that a perfect compression failure would have both the singleface and doubleback liners reaching their maximum carrying capacity simultaneously. If, however, the specimen is cut so that one facing is slightly larger than the other, it might cause that facing to reach its failure strain first, thus ending the test at a lower measured strength than if both of the liners failed together. (Conceptually, this is not unlike a load-sharing situation with a corrugated box and divider — the system reaches its highest peak strength when the box and divider reach their maximum carrying capacity at the




***4. The effect of end-to-end and face-to-face variation, averaging sets of 10 specimens cut from a single lot of material using cutter 3. The orientation in the cutter dominates the data, even above the relatively high variability arising from this cutter. (Standard deviations on each point are on the order of 8%–10%.)***

same overall deformation.) As with end-to-end deviations, the samples in Table II are all somewhere along the continuum between simultaneous failure of all structural components and loading of one component to failure before the other picks up any load. We have the ability to begin to identify the effect of those deviations.

## EFFECT OF TRAPEZOIDAL SPECIMENS

ECT is conceived as a bulk material property with uniform failure throughout the material. However, from our observations, total specimen failure actually occurs only a small fraction of the time. We commonly find that a group of sample specimens cut from a single lot of material in a consistent manner exhibits a failure bias, collapsing predominantly on one side of the specimens. While at first glance this implies that the structure is unbalanced, we find the size of this bias depends not only on the board structure but also on the equipment used to cut the specimen. Thus, the cutting equipment can force failure to one face or the other, with the potential to shift the ECT value.

### *Unbalanced material*

In an attempt to more clearly quantify the effect to ECT values, we cut 500 ECT specimens from an individual singlewall C-flute board sample (nominal combination 42-23-69), using cutter 3. Likely because of the flexibility of the blades during the cutting process and their freedom to move in their tracks, this cutter produced some of the more significantly trapezoidal specimens in our explorations, both end-to-end and face-to-face. Half the specimens were cut with the singleface side oriented face up during cutting and the other half with the singleface oriented down, creating specimens with one or the other liner slightly larger. We measured the edges (A-D) on each specimen and compressed them individually. We then sorted the samples in order of deviation from parallel, and grouped them in sets of 10 to form ECT averages with average deviations from parallel.

Plotting these average ECT values against either the average end-to-end or face-to-face deviations for each set shows that the dominant factor governing the ECT measured is which side of the board was face up in the cutter (**Fig. 4**). When the doubleback side of the board was facing up, all the specimens exhibited failure at maximum load on the doubleback side and not on the singleface side. When the singleface side was up, more than 75% of the specimens exhibited failure only on the singleface side. While we might expect the weaker doubleback liner to reach collapse first, it is clearly the orientation of the sample strip in the cutter, not the strength of

| Cutter | Average Variation | | Doubleback (DB) up ECT | | | Singleface (SF) up ECT | | | ECT | |
|---|---|---|---|---|---|---|---|---|---|---|
| | End-to-End | Face-to-Face | Fail on SF | Average ±STD | | Fail on SF | Average ±STD | | Difference | |
| | mil | mil | | lbs/in. | N/mm | | lbs/in. | N/mm | lbs/in | N/mm |
| 1 | 4.7 | 0.4 | 25% | 61.4±1.8 | 10.8±0.3 | 83% | 63.4±2.2 | 11.1±0.4 | 2.0 | 0.3 |
| 3 | 7.9 | 6.3 | 0% | 52.9±5.3 | 9.3±0.9 | 75% | 58.9±6.8 | 10.3±1.2 | 6.0 | 1.0 |
| 4 | 0.5 | 3.1 | Edge | 54.8±2.9 | 9.6±0.5 | Edge | 58.2±2.0 | 10.2±0.4 | 3.4 | 0.6 |
| 5 | 1.4 | 2.5 | 0% | 57.8±2.2 | 10.1±0.4 | 100% | 60.1±5.4 | 10.5±0.9 | 2.3 | 0.4 |

***III. Side of failure and TAPPI Standard Test Method T 811 ECT values for a single material (42-23-69) across multiple cutters.***

the papers, that governs the failure and controls the ultimate ECT measured. The average ECT when the failure occurs on the stronger singleface liner was more than 10% higher than when the failure occurs on the doubleback liner. Beyond this primary factor, we also find end-to-end variation to be statistically significant (p=0.006) over the level of testing variation when we run an analysis of variance on the entire 500 data point set. (Face-to-face variation is overpowered by the orientation in the cutter and noise in the data, and is not independently resolved.)

This behavior on unbalanced material from our designed experiment persists across cutters. The difference in cutting orientation can lead to an ECT difference of 5%-10% or more (**Table III**). The larger the face-to-face difference in size, the larger the ECT difference. Importantly, no cutter we examined was entirely free from sidedness bias. Although cutter 1 appeared to give the least bias, none seem capable of consistently producing truly parallel samples. We can hypothesize that the edge curl discussed previously (Fig. 3) arising from the blades impacting one side of the sample material first during cutting might be influencing the distribution of load on the loading surfaces of each specimen, potentially explaining the edge failure bias connected with cutting orientation.

### *Designed experiment, balanced and unbalanced*

We can further clarify how cutting affects ECT by analyzing test results from a separately designed experiment. In one production run we produced four C-flute board combinations with either light or heavy liners on each side of the board, then sampled across the corrugator at five positions for each combination. Using cutters 1 and 5, we prepared ECT specimens for each combination at each corrugator position, cutting specimens with the singleface side up or the doubleback side up. We then tested the specimens in two orientations in our test equipment (singleface side oriented to the right or left). In the full factorial experiment (4 × 5 × 2 × 2 × 2 = 160 sets of ECT) we recorded not just the average ECT of 10 specimens for each combination of conditions, but also identified explicitly which side failed on each specimen during testing. We later repeated a subset of this testing on the same material, producing samples using cutter 3.

Analysis of the ECT values and the typical side of failure (failure mode) found no dependence on either the orientation of the specimen in the test equipment (the crush tester, during compression) or the sampling position across the corrugator, neither as individual factors nor as significant factors in combination with others. This is good; our conclusions are robust to variation from the compression equipment and corrugator. Board combination was the primary contributor to ECT, as would be expected. Stronger papers should lead to higher ECT values, and the heavier papers had about twice the ring crush of the lighter papers.

We again expect that for a balanced combination, where the two liners have very similar strength and the specimen was cut squarely (with the two sample faces parallel and of the same size), that the ECT specimens should fail on the singleface side about as often as on the doubleback side. The specimen should reach critical strain first on one side or the other based on random variation in the materials. Instead, we found a sidedness dependence to the failure for cutters 3 and 5, notably less so for cutter 1 (**Table IV**), similar to our observations for the 500 specimens of unbalanced board produced on cutter 3 discussed previously. Despite this sidedness bias, ECT values were statistically independent of the failure side in these balanced materials, regardless of the cutter used, as would be expected given the similar strength of the faces for each specimen. The values measured do have some dependence on the cutter, which might arise from the propensity of each cutter to produce samples trapezoidal in the end-to-

| Doubleback (DB)/ Singleface (SF) | Orientation | % Fail SF | | | ECT (Average ±STD) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Cutter 1 (n=100) | | Cutter 5 (n=100) | | Cutter 3 (n=10) | |
| | | Cutter 1 (n=100) | Cutter 5 (n=100) | Cutter 3 (n=10) | lbs/in. | N/mm | lbs/in. | N/mm | lbs/in. | N/mm |
| Light/Light | DB up | 63.5 | 6.5 | 0.0 | 38.1±1.2 | 6.7±0.2 | 36.3±1.3 | 6.4±0.2 | 32.1±2.6 | 5.6±0.5 |
| | SF up | 61.0 | 88.5 | 90.0 | 37.9±1.4 | 6.6±0.2 | 36.8±1.4 | 6.4±0.2 | 33.9±1.9 | 5.9±0.3 |
| Heavy/Heavy | DB up | 58.8 | 15.5 | 0.0 | 58.0±2.0 | 10.2±0.4 | 55.7±3.3 | 9.8±0.6 | 55.9±2.7 | 9.8±0.5 |
| | SF up | 72.0 | 98.0 | 90.0 | 57.3±2.2 | 10.0±0.4 | 55.0±2.9 | 9.6±0.5 | 55.1±0.9 | 9.6±0.2 |
| Light/Heavy | DB up | 1.5 | 1.0 | 0.0 | 44.7±1.5 | 7.8±0.3 | 41.3±1.6 | 7.2±0.3 | 38.9±2.6 | 6.8±0.5 |
| | SF up | 3.0 | 57.5 | 65.0 | 45.5±1.8 | 8.0±0.3 | 48.2±1.8 | 8.4±0.3 | 44.6±4.9 | 7.8±0.9 |
| Heavy/Light | DB up | 99.0 | 70.5 | 90.0 | 41.9±1.4 | 7.3±0.2 | 48.8±1.7 | 8.5±0.3 | 47.3±2.2 | 8.3±0.4 |
| | SF up | 98.5 | 100.0 | 100.0 | 44.6±1.4 | 7.8±0.2 | 44.1±2.1 | 7.7±0.4 | 40.4±2.1 | 7.1±0.4 |

***IV. Results of a designed experiment exploring cutting orientation, cutter, and failure mode on ECT values. The initial rounds of testing included just cutter 1 and cutter 5. Cutter 3 was added in at a later time, on a small subset of the material.***

| Cutter | Average Variation | | Doubleback (DB) up ECT | | | Singleface (SF) up ECT | | | ECT | |
|---|---|---|---|---|---|---|---|---|---|---|
| | End-to-End | Face-to-Face | Fail on SF | Average ±STD | | Fail on SF | Average ±STD | | Absolute Difference | |
| | mil | mil | | lbs/in | N/mm | | lbs/in | N/mm | lbs/in | N/mm |
| 1 | 4.1 | 0.3 | 55% | 50.3±1.7 | 8.8±0.3 | 55% | 48.5±1.6 | 8.5±0.3 | 1.7 | 0.3 |
| 2 | 4.0 | 0.2 | 45% | 54.6±0.9 | 9.6±0.2 | 50% | 52.8±1.0 | 9.2±0.2 | 1.8 | 0.4 |
| 4 | 0.4 | 1.7 | 45% | 50.3±1.7 | 8.8±0.3 | 45% | 48.5±1.6 | 8.5±0.3 | 1.7 | 0.3 |
| 5 | 1.5 | 2.7 | 35% | 50.4±3.0 | 8.8±0.5 | 35% | 50.8±1.3 | 8.9±0.2 | 0.4 | 0.1 |
| 1 | 5.4 | 1.0 | 55% | 66.6±1.7 | 11.7±0.3 | 55% | 66.6±4.9 | 11.7±0.9 | 0.0 | 0.0 |
| 3 | 8.6 | 7.7 | 35% | 64.1±1.4 | 11.2±0.2 | 65% | 63.7±1.4 | 11.2±0.2 | 0.4 | 0.0 |
| 4 | 0.1 | 3.1 | 50% | 63.3±2.2 | 11.1±0.4 | 45% | 66.7±1.9 | 11.7±0.3 | 3.4 | 0.6 |
| 5 | 1.8 | 2.1 | 25% | 63.1±3.5 | 11.1±0.6 | 80% | 64.8±2.7 | 11.3±0.5 | 1.7 | 0.2 |

***V. Side of failure and TAPPI T 839 ECT values for two materials across multiple cutters. Ten specimens were cut with each cutter. ECT values are statistically independent of which side was cut facing up for all cutters except cutter 4. The first set of data is from the "heavy/light" materials in Table IV, with the heavier liner on the DB side. The second set is from the same set of materials as Table III, with the heavier liner on the SF side. For both materials, the ECT value tends to be higher when the heavier liner is impacted first by the cutting blades, though the difference is generally smaller than for the TAPPI T 811 ECT test (Tables III and IV).***

end direction. Cutter 1, with less sidedness bias, produced higher ECT values, indicating an area for future study in the development of optimal cutting methodology.

For the unbalanced combinations in this experiment, we found that orientation in the cutting apparatus shifted the failure mode from the weaker paper for two of the three cutters. When the singleface side was oriented up in the cutter, a significant fraction of the specimens failed on the singleface side for those two cutters, regardless of which liner was stronger (Table IV). Similarly, cutting with the doubleback side up increases the propensity of specimens to fail on the doubleback side, and again appears to shift the ECT values. Specimens could be influenced to fail on whichever side was oriented up in the cutting process, to different degrees, depending on the cutter used. This had a notable effect on the measured ECT value, with higher measured values occurring when the stronger liner failed first under load.

Although the previously mentioned data has focused primarily on the waxed ECT test, we can repeat these types of measurements with other ECT methods. With the clamp method (TAPPI T 839), for example, we find that the effect of cutting bias is reduced, but not necessarily eliminated, especially for dual blade cutters designed to cut 2 in. specimens with a single cut (Table II and **Table V**). In this method, ECT values are generally independent of cutting orientation. This observation might also support the development of a test method that, along with adjustments to our cutting, can help us dramatically reduce the potential for bias and variation in ECT values.

## A TEMPORARY PATH FORWARD

Together, these observations provide a standard that a new cutting process must reach to truly meet the criteria of "parallel" test specimens presented in TAPPI T 811. We must clearly find a cutting method that avoids influencing the side on which the specimens fail.

The literature is replete with ECT data, with dozens of papers [18] discussing ECT measurements, modeling, and utility. The many models for estimating ECT from paper strength [19] provide similar functional forms, but fundamentally different constants. The same issue arises with box compression estimations that rely on ECT. Few of these studies mention the cutters used, or make mention of end-to-end or face-to-face size variations. The differences discussed here apparently provide a hidden contribution to the variations measured, and might well account for some or perhaps even all of the differences between models. Furthermore, these differences might also account for a meaningful fraction of between-laboratory differences, as in the industry collaborative round-robin testing program [20].

We clearly need a more detailed and extensive study that includes finished boxes to determine what effect these differences might have on estimation equations for BCT. Without revising any of the existing equations, simply shifting the ECT values by changing cutting preparation methods might shift our estimate of BCT by as much as 10% or more. Clearly, the box strength is whatever it is, and this shift in estimation is not inherently helpful. A more consistent ECT method might lead to estimation equations with less variability, and it might help us more accurately predict performance of boxes in the field.

To make the methodology more robust and reduce the effect of variation, our industry's technical committees will have to explore how to specify and measure parallelism, and at what accuracy. Until we have a better specimen preparation method, we might mimic the instructions for some of our paper tests. For example, the ring crush test (TAPPI T 822) specifies alternating specimen orientation in the test fixture to minimize the issue of edge influence. By the same token, we may choose to specify alternating sample orientation in today's cutting equipment to at least average out the cutting bias arising from cutting blades impacting the top of the material first. That would not eliminate the effect of end-to-end bias, but it might help address the specimen edge curl challenge and establish a clearer comparison, avoiding face-to-face bias from cutting. Additional work exploring this issue for the standard referee method (TAPPI T 811) and other ECT methods would be extremely valuable.

The underlying physics and mechanics are robust; paper strength contributes to combined board strength, and the inherent compression strength of the combined board contributes to box performance. Our challenge is in measuring that strength as accurately as possible. Although our current level of ECT test variation might have been acceptable historically, as our industry moves toward true performance packaging, we must do more to reduce the variation in our testing methodology so that we can improve and optimize the boxes we provide to our customers. **TJ**

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## ABOUT THE AUTHORS

We chose this topic to research because we were intrigued by variations in our ECT data. We believe this is the first work of this type to examine parallelism in detail. Perhaps the most difficult aspect of the study was the sheer quantity of test materials required to build a statistically robust signal from the noise. The results show that we have a lot of work to do to improve standard test methods.

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