An evaluation of ECT sample height for small flute board grades and Box Manufacturer's Certification compliance

CORY JAY WILSON AND BENJAMIN FRANK

ABSTRACT: TAPPI test T811 is the specified method to ascertain ECT relative to box manufacturer's certification compliance of corrugated fiberboard under Rule 41/ Alternate Item 222. T811 test sample heights were derived from typical board constructions at the time of the test method's initial development. New, smaller flute sizes have since been developed, and the use of lighter weight boards has become more common. The T811 test method includes sample specifications for typical A-flute, B-flute, and C-flute singlewall (and doublewall and triplewall) structures, but not for newer thinner E-flute or F-flute structures. This research explores the relationship of ECT sample height to measured compressive load, in an effort to determine valid E-flute and F-flute ECT sample heights for use with the T811 method. Through this process, it identifies challenges present in our use of current ECT test methods as a measure of intrinsic compressive strength for smaller flute structures. The data does not support the use of TAPPI T 811 for ECT measurement for E and F flute structures, and demonstrates inconsistencies with current height specifications for some lightweight B flute.

Application: This paper will help readers understand the mechanics behind ECT measurement, and examines the relationship between specimen sample height and compressive load values in order to determine valid ECT sample heights for E and F flute to meet BMC compliance.

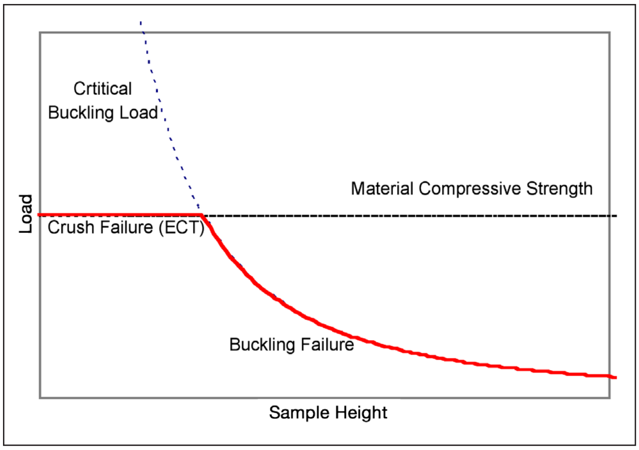
The edge crush test measures the magnitude of force necessary to cause material failure of a specimen of corrugated fiberboard under compressive load. Results from the test, the combined board ECT values, nominally indicate a fundamental material property of corrugated board, a value important because it is directly related to the expected box compression strength and thus the stacking performance of the finished corrugated fiberboard box.[1,2] The measurement of ECT can be impacted by various factors including premature failure of the sample's loading edges, sample buckling, or structural damage sustained during handling and processing, all of which can shift the value obtained away from the true intrinsic material property of the corrugated board. While several different measurement approaches (codified in different TAPPI and ISO test methods) attempt to address these challenges using different geometry and/or restraint to limit the sample failure modes, they do not all produce the same numerical assessment of a corrugated board's intrinsic strength.[3]

Certain carrier specifications require a guarantee of ECT performance under Rule 41/Item 222. Rule 41 and Item 222 are freight classification rules that include requirements for corrugated fiberboard boxes. Boxes that meet performance certification requirements can display a box manufacturer's certification (BMC) consisting of circular printed stamp that guarantees that all denoted structural requirements for the applicable freight classification have been identified and met by the box manufacturer. Rule 41/Item 222 specifies the use of the original TAPPI T811 method for ECT certification.[4]

Compressive failure of a column depends on the geometry, strength and stiffness of the material. The geometry of a column can be described using its slenderness ratio – the effective length of the column to the radius of gyration of the cross section.[5] The critical load (P_{crit}) is the load at the proportional limit of the material, where an unstable equilibrium occurs.[6] Beyond this limit, it is likely buckling or a mixture of buckling and compression failures modes will occur. Euler's formula of beam theory, $P_{crit} = EI\pi^2/L_{eff}^2$, relates the critical load to the bending stiffness of the specimen (EI), and the effective sample height (L). From Euler's formula we can deduce that for a given board (where EI is constant), as the height of the sample (column) increases, its stability decreases.

As load is applied to a sample, we would expect the sample to fail at the lowest applied load that exceeds the ability of the sample to support the load. When a sample would otherwise buckle at an applied load greater than the critical load, the sample instead fails first (at a lower load level) by compression at roughly the critical load. Since P_{crit} decreases as specimen height increases for a given bending stiffness, this relationship defines the point at which a measurement is identifying the intrinsic compression strength as a material property versus where failure is influenced by sample bending (**Fig. 1**). Note that in practice, the transition between pure compression and bending failures is influenced as well by other factors, including axial uniformity of applied load, and is not expected to be as crisp as in the idealization presented in Fig. 1.

In T811, sample heights are specified by combined board



1. Load characteristics for a column of corrugated board under compression.

flute size for A-, B-, and C-flute singlewall, as well as for doublewall and triplewall. Early research in the 1950s and 1960s indicated that sufficient sample heights for determining the edgewise compression strength of corrugated board fall within a height range of 1 to 3 inches.[7] The present T811 method defines these heights as 1.25 in. for B-flute, 1.5 in. for C-flute and 2 in. for A-flute and all double/triplewall combinations. These are the heights used by McKee et.al. in their development of a box compression model.[1] However, newer singlewall flute structures such as E- and F-flute are not defined in T811. To evaluate BMC compliance of ECT for E- and F-flute, it is necessary to identify sample heights at which the inherent compression strength can be accurately measured.

This research examines the relationship between specimen sample height and compressive load values in order to determine valid ECT sample heights for E- and F-flute to meet BMC compliance. The test can be considered valid when sample failure is dominated by compressive failure and is relatively free of bending. We examine compressive load using the approach of the T811 test, for sample heights ranging from 0.5 inches to 3 inches. Samples one inch high or larger were prepared and tested following the test method procedure[8], with sample edges waxed to a depth of about ¼″ and tested using the standard guide blocks. Samples 0.5″ and 0.75″ high were waxed to a depth of about 1/8″ to maintain a test area in the middle of the sample that was free of wax, and corrugated board guides or machined aluminum plates ~3/16″ high were used for sample support to ensure vertical alignment until the sample began to carry the applied load. Samples of all heights were examined after failure to ensure that failure occurred in the body of the sample, between the waxed edges. As well, we used the TAPPI T839 method as a reference for comparison to all T811 data, using a standard commercially available test fixture that applied 4-6.5psi to clamp the samples under study.

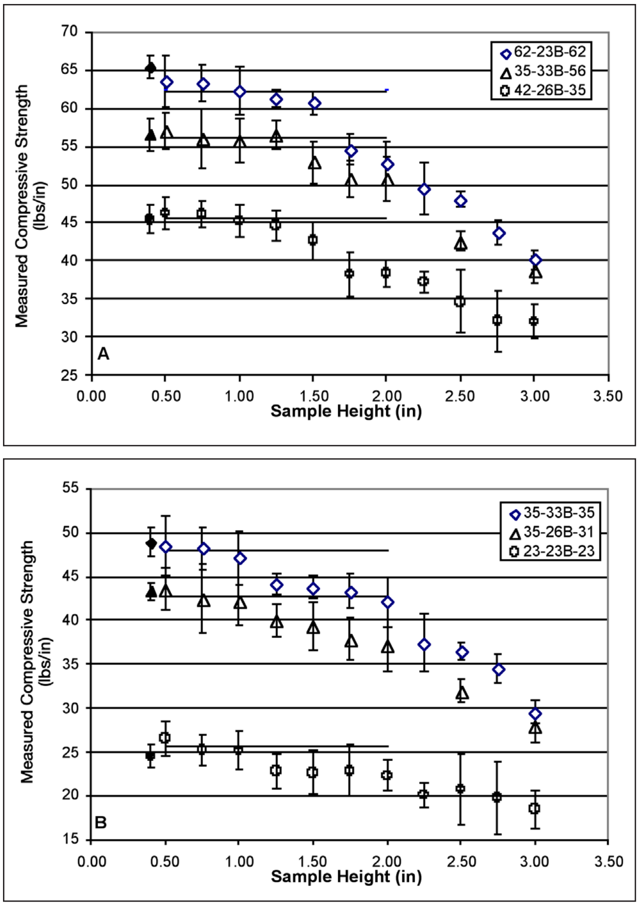
The critical height for a sample is the maximum height at which the measured load agrees with measurements at lower heights. For sample heights below some critical height, the load measured should be constant, consistent with a pure compression failure as discussed above, while for heights above some critical height the measured load will continually decrease as the height increases. To accurately assess the intrinsic compression strength needed for accurate compression estimation, we would want to define the test height for the material such that the test height consistently falls at or below the critical height and in the range of pure compression failure for all paper combinations used in the board structure. We examine B-flute before proceeding to E- and F-flute, and then discuss in more detail the impact of P_{crit} on ECT measurement.

B-Flute

B-flute is the lowest caliper flute type presently specified in TAPPI T811, with the lowest typical bending stiffness, so it should serve well as an initial point to begin to explore the applicability of testing approaches to E- and F-flute. In TAPPI T811, B-flute sample height was established at 1.25 inches, based on the initial work on the ECT test.[7,9] While the original ECT development and box compression modeling focused primarily on “200lb” and “275lb” B-flute (with a few additional samples at “175lb”), we have access to a broader range of B-flute board combinations to explore.

We begin by mapping out compressive load values relative to sample height for several B-flute board combinations. As one might expect, when observing “175lb” (42-x-33) or higher B-flute board combinations we observe the load dropping meaningfully at sample heights greater than the 1.25 inch TAPPI specification for sample size (**Fig. 2a**). At first the decrease is gradual, indicating a transition between pure compression and pure buckling, before obvious buckling failures occur. For some heavier B-flute combinations the first significant drop in measured ECT occurs at 1.75 inches, leading to a critical height of at least 1.5 inches. In other cases the critical height is at least 1.25 inches, in line with the test height in the standard. Since larger samples are easier to fabricate and handle, this height was likely selected in the initial development based on this type of data analysis of the board combinations available. However, as we decrease liner weights, and thus bending stiffness, below those evaluated in the initial definition of the method (**Fig. 2b**), we find critical heights at lower sample heights. Some of the test materials demonstrated an observed 6-10 percent load drop off for 1.25 inch high samples from the likely intrinsic compression strength measured at lower sample heights. This drop off percentage is statistically significant. Sample heights below 1.25 inches (0.5-1.0 inches) had consistent load results. This implies that 1.0 inches may be a better height to incorporate into the standard, although changing the test standard, and thus the definition of ECT, in this way may cause changes in various empirical models (e.g. the McKee equation) for box strength based on ECT.

For our lightweight B-flute samples, T839 ECT values are equal to or higher than the observed T811 values at 1.25 inches. The T839 test clamps the samples, providing a free span



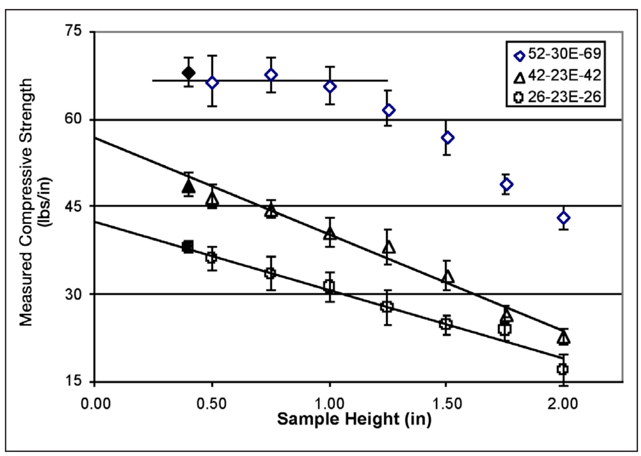
2. Comparison of compressive strength values at various sample heights for selected B-flute combinations. Samples tested using a wax-dip method (T811) are represented with open symbols, while the clamp method test (T839) is represented with closed symbols. The solid lines provide a guide as to the likely material compressive strength for each combination. Note that for heavier combinations (2A) the test performed at the current standard specimen height for B flute (1.25") is in line with the intrinsic strength, while for lighter combinations (2B) it is not.

of about 0.4 inches. Despite some established interactions between the clamping force used in T839 and the test specimens, which may impact test results[10], the T839 test method can provide an indication of the ultimate compressive strength on uncrushed material like that in this study. The fact that the T839 value exceeds the value of the T811 test applied at 1.25 inches for some samples further indicates that this specified height may not actually capture the true compression strength for these lightweight samples. If we reduce the sample height we find better agreement between these two ECT test methods and load values; the T839 value is statistically similar on average to the value measured at 0.75". This behavior, particularly for lightweight B-flute, further supports the hypothesis that, while the current specimen height is appropriate for many board combinations, a lower sample height may be more appropriate to universally assess the full B-flute spectrum.

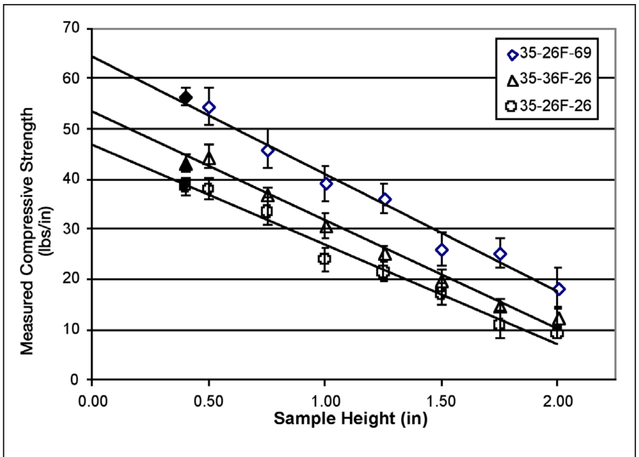
E- & F-flute

With our B-flute results as background, we can begin to examine E- and F-flute in more detail. Sample width for all specimens tested was kept at two inches, consistent with current practice in T811, with the expectation that this specimen width would produce reasonable and reproducible results.[11] We observe a similar strength vs. height relationship between lightweight combinations of B-flute and the heavier combinations of E-flute (**Fig. 3**), with a drop off starting around the 1.25 inch sample height. These materials can have similar bending stiffness, as the increased caliper of the B-flute samples can have a similar impact on bending as the increased weight in liners in the thinner E-flute samples. The major difference with the E-flute samples is that their strength decreases rapidly once the sample height reaches the cross-over point where the specimens begin to demonstrate failure by visual bowing or buckling, rather than compression, at heights greater than 1.5 inches. As the basis weight of the samples decreases, we progressively lose the "plateau" region at low sample heights indicating that the test never probes the pure compression region. For these samples, even the clamped ECT value from T839 falls on the line of ECT to sample height formed by the waxed ECT data, implying that the clamp method is also not measuring the intrinsic compression strength and that the pure compression load would need to be measured by a specimen shorter than ~0.4".

F-flute duplicates the trends observed for lightweight E-flute. Three samples of F-flute were evaluated and demonstrated a similar linear downward trend as height increased (**Fig. 4**). Consistent values or a plateau region for short samples are not apparent, again indicating that the test never probed the pure compression region. F-flute specimens also began to bow outward at a height as low as 1 inch.



3. Measured load values at various heights for E-Flute board combinations. Samples tested using a wax-dip method (T811) are represented with open symbols, while the clamp method test (T839) is represented with closed symbols. The line associated with the heaviest sample provides a visual guide to the likely inherent compression strength. The lines for the lighter samples are best fits to the wax-dip method data.



4. Measured load values at various heights for F-flute board combinations. As with figure 3, open symbols indicate samples tested using a wax-dip method (T811) while closed symbols indicate use of the clamp method test (T839). The lines indicate best fits to the wax-dip method data.

The impact of critical load

The critical load depends on the caliper of the material (as it relates to bending stiffness). For lower caliper materials (like small flute), the bending stiffness and thus critical load decreases, and we are more likely to find our compressive strength measurement impacted by bending rather than pure compression at various heights.

This behavior explains why we see different board combinations of B-flute exhibiting load drop off points at different sample heights. Board using heavier liners has higher bending stiffness, and thus a larger region of pure compression failure. Typical B-flute bending stiffness in the cross direction (relevant for ECT test specimen orientation) ranges from about 1.8-5.6 Nm (16-50 lb-in) with caliper values from about 2.7-3.3 mm (105-130 mil). For a sample height of 1.25″, this leads to an estimated critical load between 25-78lbs/in. The lower end of this range is in the neighborhood of the typical ECT strength of lightweight B-flute, consistent with the decreasing strength observed in our testing. The standard B-flute specimen height for heavy liner B-flute is thus just about at or perhaps even somewhat higher than the necessary height to capture pure compression failure in these corrugated specimens.

When we extend our observations to board combinations where the bending stiffness is sufficiently small (in the range of E- and F-flute), we see more clearly how the bending stiffness becomes a critical variable for the rate at which column stability declines. If we compare failure modes for samples of 52-30-69 E-flute and 35-36-26 F-flute at one inch height, we observe that the latter fails by clear buckling while the former appears to be close to pure compressive failure. This behavior suggests the stiffer E-flute sample is more stable than the F-flute configuration. CD Bending stiffness for E-flute typically falls in the range of 0.7-1.4 Nm (6-12 lb-in) and for F-flute in the range 0.4-0.8 Nm (3-7 lb-in). Comparing B-flute failures to those of E-flute samples we again see a difference in failure mode associated with stability. E- and F-flute's considerably low bending stiffness (0.4-1.4 Nm) impacts the proportion ratio of bending stiffness to sample height more readily than B-Flute (1.8-5.6 Nm) or thicker board combinations. Thus in the range of E- and F-flute, the stability of the column decreases more rapidly as the column height increases. This helps explain why the ECT drops rapidly for E-flute once we leave the plateau region at short heights, while it drops more gradually for B-flute. B-flute columns at 1.5 inches are more stable structurally than 1.5 inch E-flute columns. Similarly, E-flute is more structurally stable than F-flute, with F-flute strength dropping at a proportionally higher rate with increasing sample height. Thus, the critical load of a column is the crucial element for determining optimal ECT sample height of corrugated board, with a particularly significant role for small flute board.

Recognizing this dependence we can better understand why E- or F-flute cannot realistically be specified in TAPPI T811. While using the waxing approach can produce test data, because of the influence of sample bending this test data does not reflect the true inherent compression strength of the material. In most cases the inherent compression strength cannot be measured accurately with the clamping approach (T839) either. Since "ECT" is intended to mean the inherent compressive strength of the material, our inability to accurately measure that strength for most E- or F-flute combined board using these methods means that ECT cannot be truly defined for most of these materials. And since we cannot define ECT accurately, we cannot apply an ECT-based BMC.

CONCLUSION

We have seen that the inherent material properties of different B-flute board combinations yield different optimal T811 ECT sample heights to capture the intrinsic compression strength of the material. The current TAPPI specification of a 1.25 inch sample height appears to apply well to most but not all B-flute, underestimating the true compression strength of the material for lighter weight combinations. For some of the lightest B-flute combinations, the standard sample height may allow a component of bending failure into the compressive test result. In that case, a height of 0.75 or 1.0 inches would appear to be more appropriate.

For E- and F-Flute, testing using the T811 approach did not produce consistent ECT load values for most samples. For the average small flute board, there is no easily attainable sample height at which one can reliably measure pure compression failure using this testing method. As T811 is the only specified method to determine ECT as required by Rule 41/Item 222 for BMC compliance, based on these findings E- and F-flute board combinations cannot be stamped with an ECT-based BMC under current specifications. **TJ**

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INSIGHTS FROM THE AUTHORS

Frank

Wilson

We chose this research because we wanted to better understand how to model small flute behavior and its real-world implications for industry applications. This research suggests that the current T811 sample height specification for B-flute underestimates the true compression strength for certain lightweight B-flute board combinations. Moreover, for E- and F-flute board there is no easily attainable sample height at which one can reliably measure pure compression for E- and F-flute board.

The most challenging aspect was interpreting small flute behavior. This was addressed by letting the data shape and tell the story. More research on small flute behavior under compression, as well as a valid approach for accessing the true compression strength of E- and F-flute needs to be carried out.

Frank is Manager, Materials Optimization and Development for Packaging Corporation of America, Mundelein, IL, and Wilson is a graduate student at Michigan State University, East Lansing, MI.
Email bfrank@packagingcorp.com. wilso279@msu.edu.