

HARDNESS OF CORRUGATED BOARD REVISITED

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ABSTRACT

In 1968, Crisp, Stott and Tomlinson [Tappi 51(5):80] defined corrugated board hardness which became an Australian standard in 1978 (AS 1301.445). They showed that hardness was a more sensitive measure for board damage from crushing than other common board properties (e.g. thickness) and that the flat crush test (FCT) was unsatisfactory for this purpose.

Hardness represented the first yield peak of the flat crush test (FCT) force-displacement curve of ‘undamaged’ corrugated board. The hardness peak was observed to fall within the first 0.25 mm of crushing for the A, B and C flute boards tested. Prior to this point, the corrugated board resists damage and the hardness can even increase slightly with small amounts of crushing. Beyond this point, the corrugated board undergoes permanent damage, which can make the board feel softer. This can occur without a significant reduction in thickness (due to a degree of recovery post crushing).

The typical laboratory FCT crush testing equipment of the time did not capture the full force-displacement curve. The solution was to use a modified flat crush jig/holder in concert with a flexible beam crush tester. This work revisits and expands on some of this original corrugated board hardness work of Crisp, Stott and Tomlinson with reference to the full FCT force-displacement curves that are now more readily available through more modern crush testers.

Hardness is an extension of the standard flat crush test requiring no extra equipment or changes to the procedure, just software to analyse force-displacement curves (corrected for machine set-up compliance). Hardness peaks were observed in all undamaged singlewall boards tested from E-flute through A-flute. All singlewall hardness peaks fell within the first 0.2 mm of compression displacement, double wall near this value but triplewall outside this range. Flute geometry is the dominant factor in the hardness peak displacement, with the platen surface also having an effect, while the medium furnish appears to have limited impact.

This work proposes the following approach to define hardness: For a displacement less than 0.2 mm (in order of priority), hardness is the force at the (a) first yield peak, (b) inflection point/first plateau (i.e. first minimum of the derivative of the force-displacement curve) or (c) maximum. Zero displacement is also redefined. This worked well for singlewall boards and may be sufficient as an internal quality control measure for multiwall boards. Ideally more study is required to better understand and more robustly define hardness for multiwall boards.

INTRODUCTION

Corrugated board is an elegant sandwich structure with linerboard facings separated by a core fluted medium, typically glued together with a starch-based adhesive. The linerboard facings provide board with high bending rigidity, analogous to the flanges in an I-beam, with the linerboard resisting tensile and compressive loads. The fluted medium acts like the web of an I-beam, maintaining separation of the linerboards by resisting crushing and shearing forces.

Corrugated board has been used as a packaging material for over 100 years. For much of that time, one of the main methods used to assess the performance and integrity of the fluted mediums has been the Flat Crush Test (FCT). It measures the maximum crushing load carried by the board in the thickness direction before the complete collapse of the flutes occurs. Flat crush resistance was introduced as a tentative Australian standard (AS 1301.429) in 1961 and became an official standard in 1989.

In 1968, at the Products Laboratory, Australian Paper Manufacturers (now Opal Research & Development), Crisp, Stott and Tomlinson [1] defined corrugated board hardness. They had noticed that corrugated board could be damaged by flat crushing loads when passing between rollers or belts during the container-making processes. However, it was observed that while such processing often caused the board to lose thickness and/or to feel softer, the flat crush resistance was not correspondingly reduced, suggesting that the flat crush resistance was not a good indicator of such damage. They defined hardness as the ‘first yield point’ of the flat crush load displacement curve. Due to equipment limitations of the day (lack of full load-deflection curve), it was practically implemented as the maximum load within the first 0.25 mm displacement after a pre-load of 40 N. Hardness was thought to be a better indicator of crushing damage than FCT [1, 2, 3]. Hardness of corrugated board became an official Australian standard (AS 1301.445) in 1978.

Recently there has been a renewed interest in the performance of the fluting medium in both the combined board and the paper tests used to assess fluting medium quality. In particular, the S-Test (ISO 7763) has been developed as a proxy for hardness in both CMT (AS 1301.429, Concora Medium Test) and FCT. [4, 5, 6, 7].

Hardness has been used internally by Opal R&D as a quality control measurement to assess fluting medium performance ever since Crisp et. al coined the term in our laboratory in 1968, although its exact form has changed slightly due to the changing nature of test equipment over that period. The original equipment used in the work of Crisp et. al. and referenced in the Australian standards (AS 1301.445: 1978, 1989 and 2006) is now obsolete (e.g. flexible beam crush tester and modified crush test jig) and hence the standard, as of December 2019, has ‘withdrawn’ status. Since the change to the fixed platen crush tester, Opal R&D has been capturing the load-displacement curve and applying a similar methodology to Crisp et. al [1] to determine board hardness.

Although the full FCT force-displacement curve is not required in the flat crush standards, some crush testers on the market now can provide this information. This work revisits and expands on some of the original corrugated board hardness work of Crisp, Stott and Tomlinson [1] with reference to the full FCT force-displacement curves that are now more readily available through more modern crush testers.

Crisp et. al. implemented hardness as the maximum load within the first 0.25 mm displacement. It is difficult to accurately measure the true specimen compressive displacement over small spans, as with the flat crush test, without external extensometers (either contact or non-contact). The platen displacement of the crush tester alone is likely to contain extra non-specimen displacement due to other factors such as frame/machine set-up deformation, contact gaps and strain concentrations [8, 9]. This work also considers this issue of machine and set-up compliance (i.e. inverse stiffness).

With the trend for light weighting of boxes, along with the corresponding cost savings and environmental benefits, boards with lighter/weaker mediums are becoming more susceptible to crushing damage. Bick concludes [10] that “Crush is difficult to measure and commonly understated”. As the title of Bick’s work makes clear, “The Cost of Crushing Flutes is High”, as typically a reduction in box strength is compensated for by additional fibre (along with other possible economic impacts). Hardness offers one highly sensitive method of quality control for maintaining fluting medium performance (by minimising crushing) through the manufacturing and converting process.

METHOD

Crush testers

Two types of fixed platen compression crush testing equipment, both complying to AS 1301.449:2017, were used in this study: (a) a Zwick Roell Z100 materials testing machine (Zwick) using a 5 kN Load Cell fitted with stainless steel compression platens and (b) a rigid platen Lorentzen & Wettre (L&W) crush tester (No. 48). The L&W crush tester was modified with an LVDT displacement sensor. The loadcell and LVDT voltages were processed via National Instruments hardware and in-house MATLAB software to produce and analyse full FCT force-displacement curves. The L&W crush tester was used both with and without emery cloth adhered to crush tester platen surfaces (as allowed by AS 1301.449:2017 to prevent specimen slippage).

Crush tester compliance corrected displacement

Both crush testers were assessed for machine set-up compliance by measuring load-displacement curves, at the standard rate of 12.5 mm/min, for both (a) the no specimen case i.e. platen-on-platen and (b) a rigid specimen in lieu of the corrugated board flat crush test piece. In the latter case, discs of acrylic, brass and stainless steel were substituted. All had stiffnesses two to four orders of magnitude, or more, higher than the corrugated boards tested. The L&W crush tester compliance was also assessed both with and without emery cloth adhered to crush tester platen surfaces.

Full flat crush force displacement curves for various flutes

An investigation into the full FCT load-displacement curves for a wider range of flutes than the original work of Crisp et. al. was conducted. Board samples from E-flute, through to multi-wall, including Xitex (X-flute) were tested. Board sample details can be found listed in Table 1. Although not all listed boards were used in every part of this study.

Table 1. Sample details of boards tested

Sample #	No. Walls	Flute Type	Flute Pitch mm	Board Thickness mm	Nominal Board gsm	Nominal Medium gsm	Medium Furnish
1	Single	E	3.50	1.6	415	90	recycled
2	Single	I	4.85	2.1	380	100	recycled
3	Single	B	6.50	2.9	495	135	recycled
4	Single	C	7.79	4.0	560	165	recycled
5	Single	C	7.79	4.1	660	140	semi-chem
6	Single	C	7.95	4.6	795	185	recycled
7	Single	X	5.00	4.9	810	135 / 135	recycled
8	Single	A	8.66	5.2	575	165	recycled
9	Double	BE	--	4.3	670	140 / 100	recycled
10	Double	IB	--	4.6	700	120 / 135	recycled
11	Double	BC	--	6.5	765	135 / 135	recycled
12	Triple	CCA	--	13.2	1,575	135 / 135 / 165	recycled

The load-displacement curves for the various flutes were tested in triplicate in both 'uncrushed' and 'crushed' form. The flat crush tests were first conducted on an 'uncrushed' specimen then immediately re-tested without removing the specimen from the crush tester and re-crushed, now as the 'crushed' specimen. Hence a total of six load-displacement curves (three 'uncrushed' and three 'crushed') were tested for each flute type.

Progressive crushing and hardness methodology

The Zwick crush tester was used to progressively crush a C-flute board (sample #4, Table 1) in increments of 0.2 mm in order to investigate the nature of the measured hardness and its sensitivity to the applied analysis methodology.

Application of hardness methodology to a crushed C-flute

Following the crushing work of Crisp et al., a heavy C-flute board (sample #6, Table 1) was crushed to six different levels, relative to the original thickness (i.e. 0%, 5%, 10%, 15% 20% and 50%). Samples were compressed to a set thickness in a Zwick compression tester to a load set to 10% higher than the flat crush of the board. Feeler gauges of the required thickness were inserted beside the board, between the test platens to control the crush level. A compression rate of 10 mm/s was used. The crushed boards were tested (10 specimens per crush level) for hardness and a range of other properties: thickness, FCT, edge crush test strength (ECT), bending stiffness and MD shear stiffness [12, 13].

RESULTS AND DISCUSSION*Crush tester compliance corrected displacement*

To apply a testing machine compliance correction, the specimen and testing machine set-up are assumed to be two springs in series [8, 9]. This gives the platen displacement (δ_p) as the sum of both the specimen and testing machine set-up displacements (δ_s and δ_T respectively) while the loading force (F) remains the same for both elements. i.e.

$$\delta_p = \delta_s + \delta_T \quad (1)$$

Taking the testing machine set-up stiffness (inverse compliance) as k , then $\delta_T = F/k$ and the corrected specimen displacement becomes:

$$\delta_s = \delta_p - F/k \quad (2)$$

Two typical methodologies used for estimating the testing machine set-up stiffness (k) are (a) directly, by moving the compression platens together (with no specimen) and measuring the load-displacement curve or (b) indirectly, measuring the load-displacement curve of a reference FCT specimen made from a material of known stiffness and subtracting its theoretical load-displacement curve.

Both of these approaches were tried for the Zwick with results plotted in Figure 1. The direct method load-displacement curve (with no specimen) gave a stiffness of 22.7 MN/m (fitted slope between 1500 N-4500 N) while discs of acrylic, brass and stainless steel (in lieu of an FCT specimen) gave much higher stiffnesses of ~35 MN/m. At face value this did not make sense as theoretically the presence of a specimen should add to the displacement i.e. lower the stiffness, not increase it. The platens used in this work were much larger than the FCT specimens (i.e. 300 mm vs. 79.8 mm) but were only checked for adequate parallelism and flatness (following AS 1301.449:2017) in the centre region where the FCT disc is placed. It is possible, even likely, that the significant regions outside of this did not have adequate parallelism and/or flatness, artificially reducing the observed stiffness.

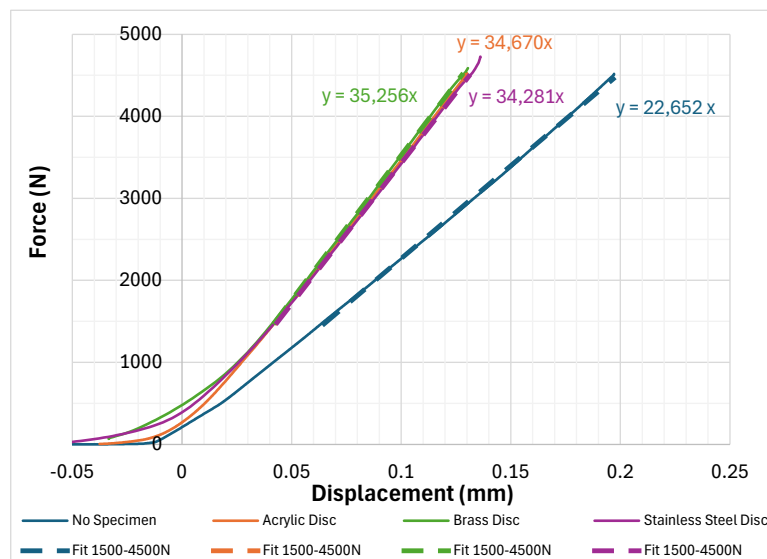


Figure 1. Force displacement curves for Zwick compliance correction.

The measured stiffnesses of the acrylic, brass and stainless-steel discs are given in Table 2. Back calculating the estimated Zwick set-up stiffness using the assumptions behind equations 1 and 2 gives similar results (within 0.6%) for the acrylic, brass discs. However, the stainless-steel disc gave a result a few percent lower. Given the rigidity of the stainless-steel, it would be expected to have given the greatest measured stiffness, but this was not the case as it was lower than both the acrylic and brass (34.3 vs 34.7 and 35.3 MN/m respectively). One explanation is that the stainless-steel disc was measured on a different day, post removal and replacement of platens, producing subtle changes in machine compliance that were even more significant than the greater modulus of the stainless-steel. The corrugated board samples tested on the Zwick were done on the same set-up as the tests on the acrylic and brass discs so a stiffness value of $k = 35.3$ MN/m was used for the machine compliance correction of displacement (in equation 2).

Table 2. Summary of estimated Zwick set-up stiffness using known material.

Disc	E modulus GPa	Stiffness MN/m		Ratio (±Brass)
		Total	Est. Zwick	
Acrylic	~3	34.7	35.1	99.4%
Brass	~100	35.3	35.3	100.0%
Stainless Steel*	~190	34.3	34.3	97.2%

* Measured on a different day, post removal and replacement of platens

Using this estimated Zwick set-up stiffness to correct displacement can have a significant impact on the observed hardness peak displacement location, especially for boards that experience high force/hardness levels. This is illustrated for an E-flute board (sample #1, Table 1) in Figure 2. Note that the location of the hardness peak has been corrected from 0.16 mm down to 0.07 mm displacement¹.

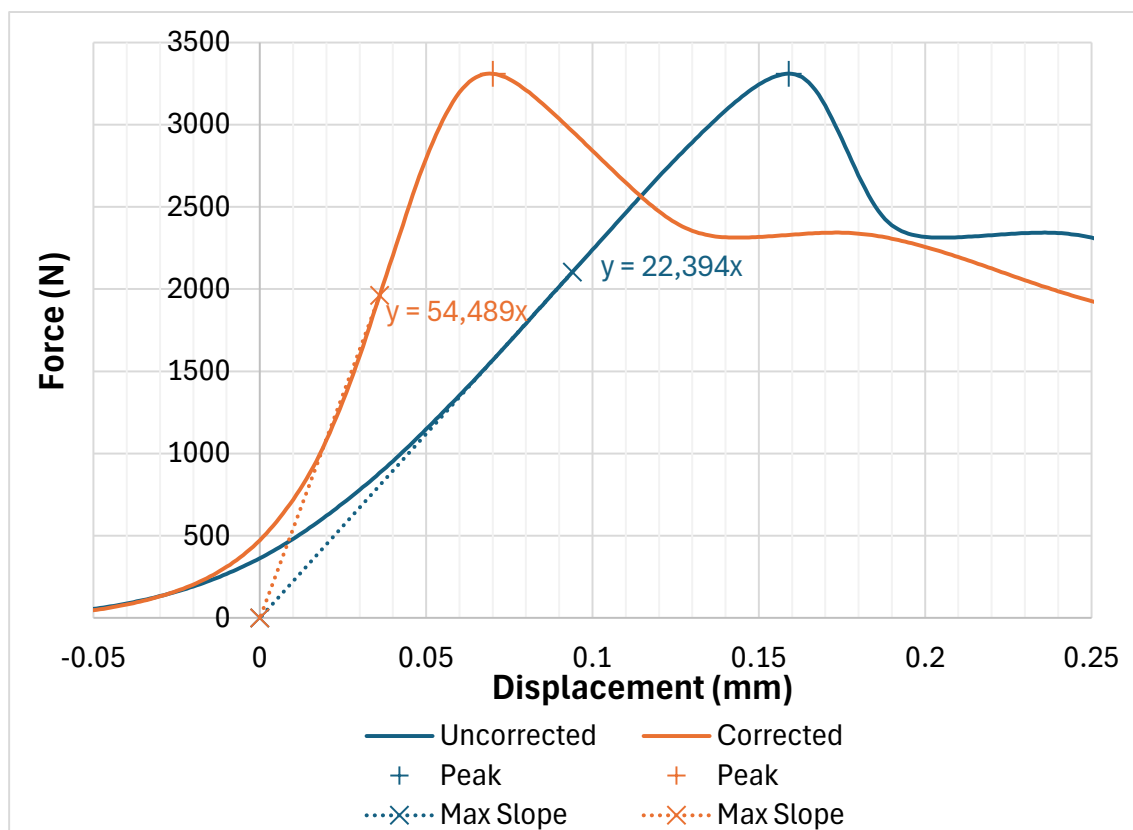


Figure 2. E-Flute – before and after crush tester compliance displacement correction.

¹ Note for this illustration a pre-load of 40 N (as per Crisp et.al) was not used, but zero displacement was defined by the extrapolation of the force at the maximum slope back to zero load. This will be discussed in more detail in the next section.

Methodology and hardness sensitivity

The hardness methodology of Crisp et. al. was, at the time, limited by the lack of readily available quality FCT force-displacement curves for standard laboratory crush testers. They solved this short coming by applying an electro-mechanical approach along with two main criteria:

1. Zero displacement was set at a 40 N pre-load.
2. The maximum load within the first 0.25 mm displacement was considered the 'hardness'.

This current work suggests a modified approach to that taken by Crisp et. al. as full FCT force-displacement curves are now more readily available through modern crush testers.

By way of illustration, Figure 3a shows a single C-flute FCT specimen (sample #4, Table 1), crushed under incrementally decreasing platen separation (see legend labels) in a Zwick testing machine. For comparison, the full flat crush curve of a previous C-flute specimen from the same corrugated board sample was overlaid (see dashed grey curve labelled FCT). Figure 3b shows the compliance corrected curves processed using the original two criteria, namely the 40 N pre-load and the hardness defined as the maximum force within the first 0.25 mm (as indicated by the crosses). This seems problematic as, particularly for the 'lightly' crushed boards in this series, the methodology appears better suited to picking up the second yield peak, not the first.

The zero-displacement defined by the fixed 40 N pre-load seems incongruous when used for both light weight recycled mediums with larger flutes that generate very low compressive forces (of which the 40 N pre-load can be a considerable percentage) and heavy weight semi-chemical mediums used in smaller flutes that can produce very high forces (of which 40 N can be a small percentage). This work adopted the technique used in tensile property standards (e.g. AS 1301.566:2019) i.e. zero displacement is the point where the tangent to the curve, with a slope equal to the maximum slope of the curve, intersects the displacement axis (schematically shown in Figure 4 and previously shown in Figure 2). The difference between these two 'zero' methods can be seen in Figure 3c with three selected curves, where 'steeper' curves have a higher effective pre-load while 'shallower' curves have a lower effective pre-load. This change, possibly combined with machine displacement compliance correction, can reduce the displacement location of the hardness peaks significantly below that of the 0.25 mm used by Crisp et. al. and in the 'withdrawn' Australian standard.

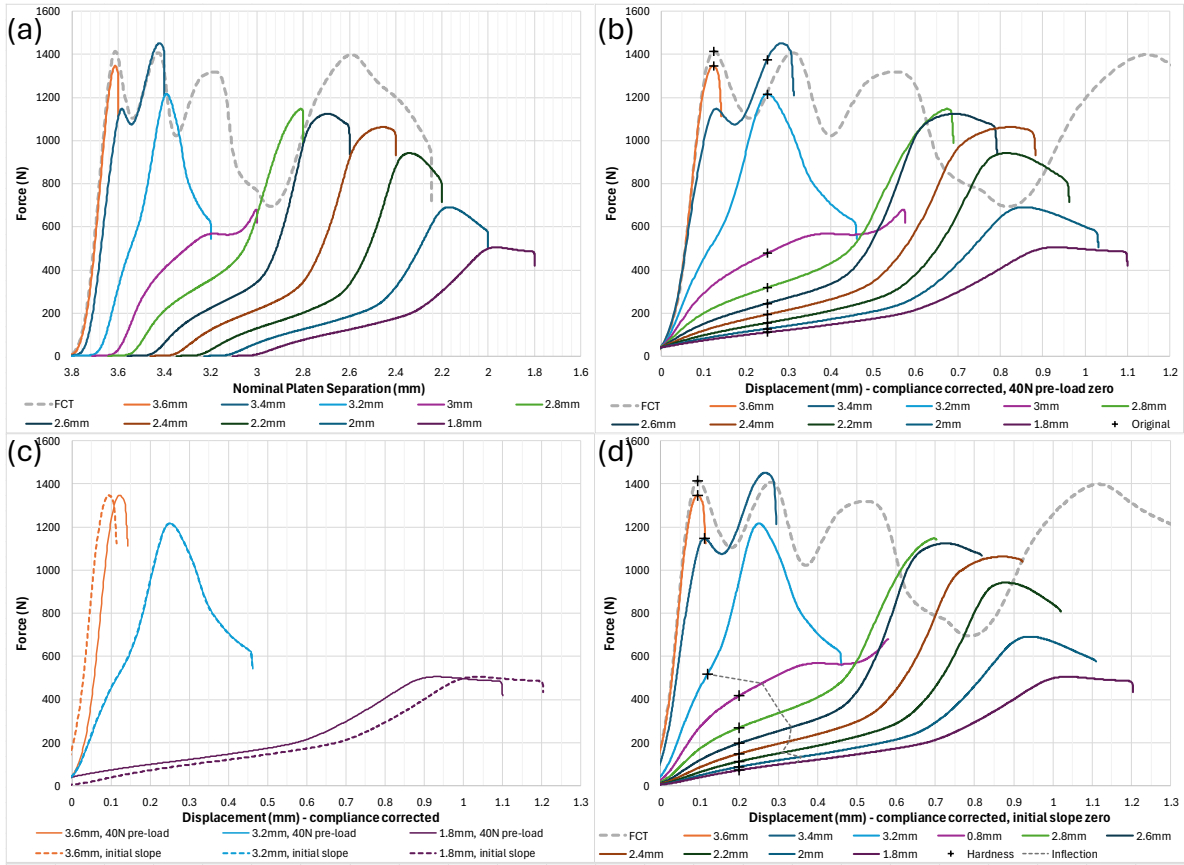


Figure 3. (a) Incrementally increasing compression loading behaviour of a single C-flute FCT specimen. (b) Curves processed and hardness marked (+) based on original Crisp et. al. method (c) Difference in zero-displacement method illustrated. (d) Curves processed and hardness marked (+) based on proposed method.

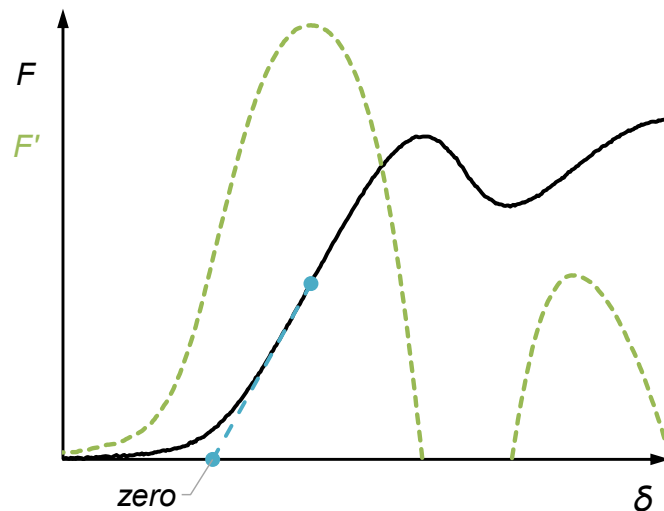


Figure 4. Schematic force (F) - displacement (δ) curve (and derivative F') with extrapolation to zero.

Ideally the hardness should be defined by the force at the displacement of the first yield peak, or for crushed boards at the displacement where the first peak would have been for the original uncrushed board. For an arbitrary crushed board, where the original location of the first peak is unknown, this is not possible. This work proposes the following approach to define hardness:

For a displacement less than 0.2 mm (in order of priority), the hardness be defined as the force at the:

1. First yield peak.
2. Inflection point/first plateau (i.e. first minimum of the derivative of the force-displacement curve)
3. Maximum.

Figure 3d applies this new approach for defining both the zero displacement and also the hardness value, as indicated by crosses. The thin dotted grey line joins the first inflection points for a number of the crushed FCT curves, one of which is inside 0.2 mm displacement and is used to define the hardness for this curve (3.2 mm final platen separation, light blue line). The hardness displacements via this method are better aligned with the displacement position of the uncrushed board hardness peak than applying the original methodology of Crisp et. al. on these FCT force-displacement curves.

Figure 5 looks at the sensitivity of the applied hardness methodology with the various crushing levels (as a percentage of board thickness) shown in Figure 3. The blue line (labelled 'Peak Position') indicates the retained hardness (hardness as a percentage of the uncrushed value) in the ideal situation where the exact displacement of the original uncrushed hardness peak position is known (in this case 95 μm , for the 3.6 mm platen separation, orange line in Figure 3d). Unfortunately, this is almost never the case in practice. The black line (labelled 'Original') shows the original Crisp et. al. approach (from Figure 3b). It is obvious that there is a significant loss in sensitivity from the 'ideal' blue line compared to the 'Original' Crisp et al. black line, especially in the region around 5% - 10% crushing for this C-flute board. Using the new zero displacement (initial slope) combined with using the maximum force less than 0.2 mm (orange line), rather than the original 0.25 mm, improves the sensitivity somewhat. However, a substantial improvement in sensitivity is achieved (dashed purple line, labelled 'Peak, Inflection or Max < 0.2 mm') when using the new methodology proposed in this study (as outlined above).

In short, the blue line is the expected result. The black curve uses the old calculation method, which overestimates, sometimes dramatically. The purple curve reflects the new approach, which while not perfect, is an improvement.

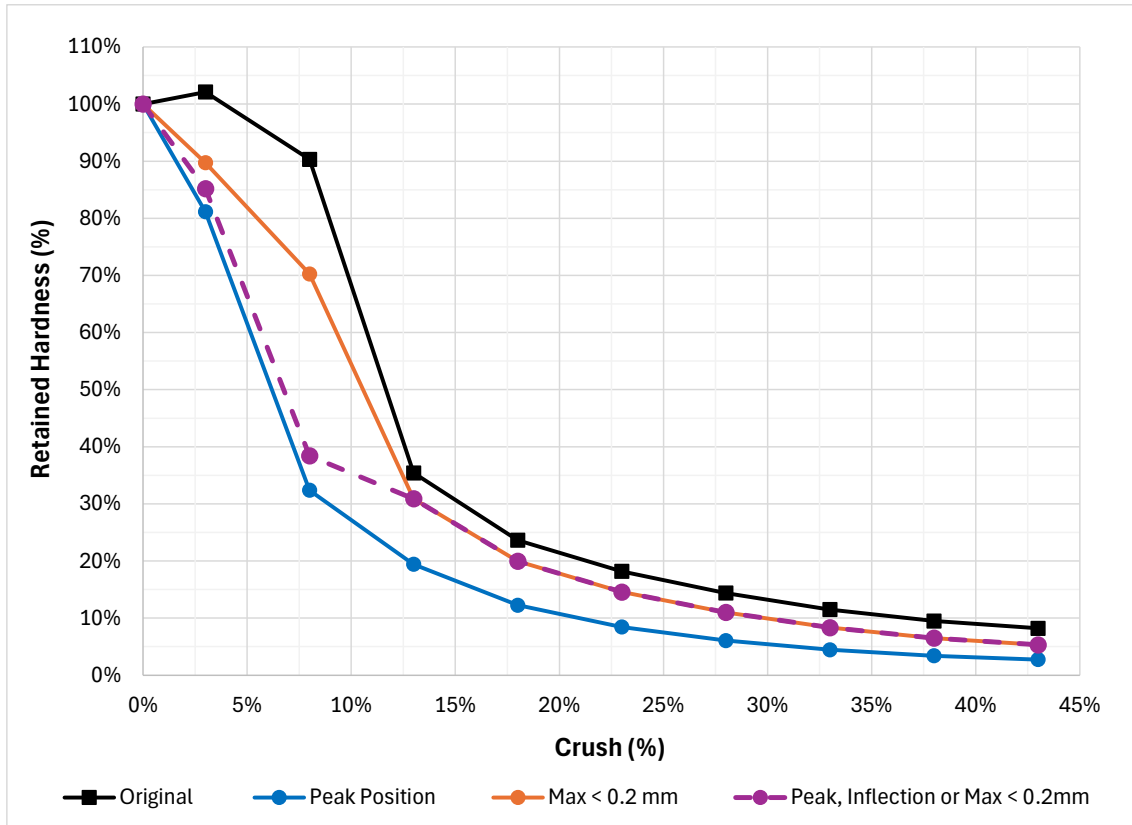


Figure 5. Retained hardness with crushing via various applied methodologies

Flat crush force-displacement curves for various flutes

The original work of Crisp et. al was on A, B and C flute board only, which were the predominant singlewall flutes at the time. The Australian standard for hardness (AS 1301.445) did not specify flute type. This is unlike the flat crush standard (AS 1301.429) which limits the method to single-faced and single-wall board only. Double-wall and microflute boards are excluded from the flat crush test as the endpoint is not clearly defined or observable. Opal R&D has applied this hardness method since 1968, internally for quality control purposes, to boards ranging from E-flute to triple-wall. It has been a useful measure to infer relative board crushing damage, even if the original definition may be less applicable in some of these situations.

For this study, a wide range of flute types (Table 1) were tested in flat crush using the Zwick (Figure 6). The C-Flute board shown in Figure 6d is sample #4, Table 1. Each flute type was first tested on an 'uncrushed' specimen then immediately re-tested as the 'crushed' specimen. This occurred in triplicate. The first yield peaks or inflection points are indicated via crosses. The Inflection point or first plateau has been used in terms of hardness for studies on CMT and FCT [2, 4, 5, 6] where no first yield peak exists. The displacements were corrected for machine compliance and zero displacement was defined by the extrapolation of the force at the maximum slope back to zero load.

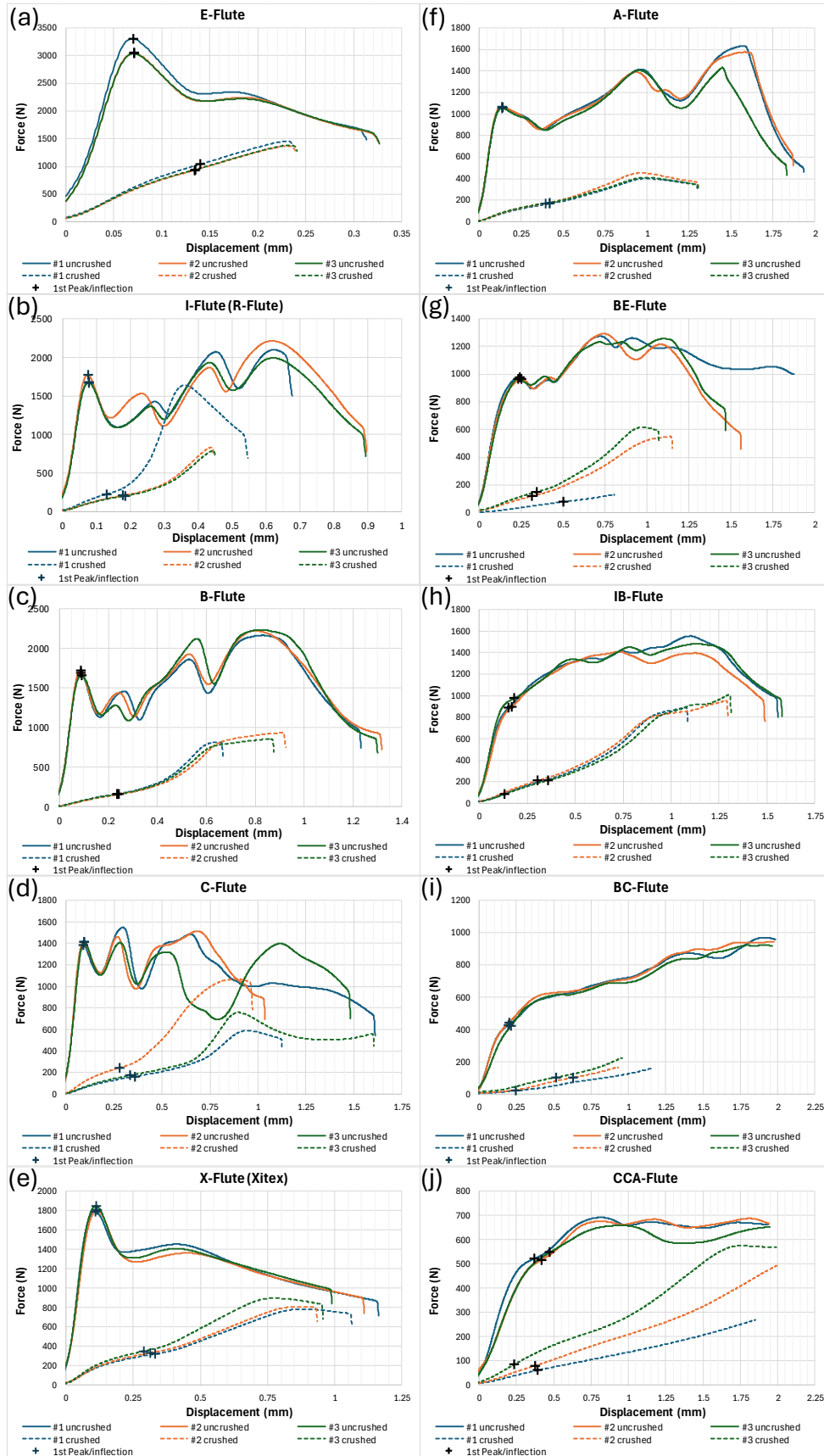


Figure 6. Flat crush force-displacement curves for various flutes, both uncrunched and crunched, and either the first peak or first inflection point marked (+).

All singlewall boards and the BE doublewall board tested (BE, Figure 6g) had clear first yield peaks. The IB and BC doublewall and CCA triplewall boards did not, so inflection points are indicated (Figure 6h-j). The reason for this lack of first yield peak in these multiwall boards warrants further investigation but was not done as part of the scope of this work. It is surmised to be due to either (a) a degree of damage during production or (b) the geometry of the flutes so that the tips are not aligned in the different layers, which are only separated by thin relatively flexible internal lightweight liners [11].

The hardness peaks for all the ‘uncrushed’ singlewall boards fall well within the first 0.2 mm of crushing and the doublewall peaks/inflection points are close to this value. This was not the case for the triplewall board that was tested. This is illustrated in Figure 7 where first yield peaks or inflection points are plotted against corrugated board thickness. The ‘uncrushed’ singlewall board first yield peak positions are approximately linear with board thickness ($r^2=0.88$) as highlighted by the dotted line in Figure 7.

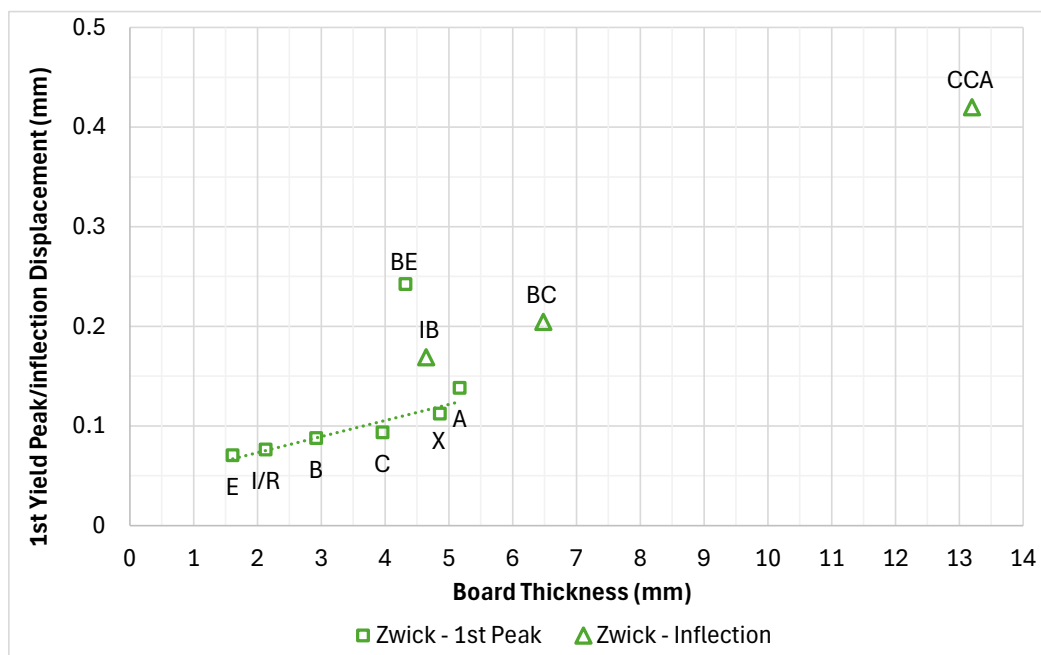


Figure 7. Flat crush first yield peak/inflection points with corrugated board thickness for various flute geometries.

The effect of platen surface and medium furnish

The standard AS 1301.449:2017 allows the use of emery cloth adhered to crush tester platen surfaces to prevent specimen slippage for some test methods. It is a common practice to use emery cloth (or similar e.g. magnetic sandpaper) to prevent leaning flutes in FCT and/or CMT. To test the effect of such surfaces, a rigid platen L&W crush tester was used with the displacement corrected for the machine set-up stiffness separately for both the emery cloth

($k = 23.3 \text{ MN/m}$) and no emery cloth scenarios ($k = 26.3 \text{ MN/m}$) i.e. the emery cloth set-up was less stiff than the no emery cloth set-up.

The L&W crush tester with bare platens (no emery cloth) gave very similar first peak displacements to most of those measured on the Zwick tester for the same board samples (Figure 8a)². The main difference was the inflection points for the multiwall boards. The quality of the force-displacement curves was superior on the Zwick compared to the modified in-house crush tester set-up. The extra ‘noise’ experienced on the later, made curve processing more challenging, especially second derivatives relating to inflection points of curves with fewer obvious ‘features’ (peaks and troughs).

The board samples tested with emery cloth showed noticeably greater first peak displacements to those measured on the Zwick and the no emery cloth crush tester case. This is despite all test scenarios being individually corrected for machine set-up compliance. It is speculated that the abrasive grit of the emery cloth, penetrating the liners of the test specimen, adds extra displacement not seen in the other cases. Despite this ‘extra’ observed displacement for the emery cloth case, all singlewall first yield peaks fell well within 0.2 mm displacement (Figure 8).

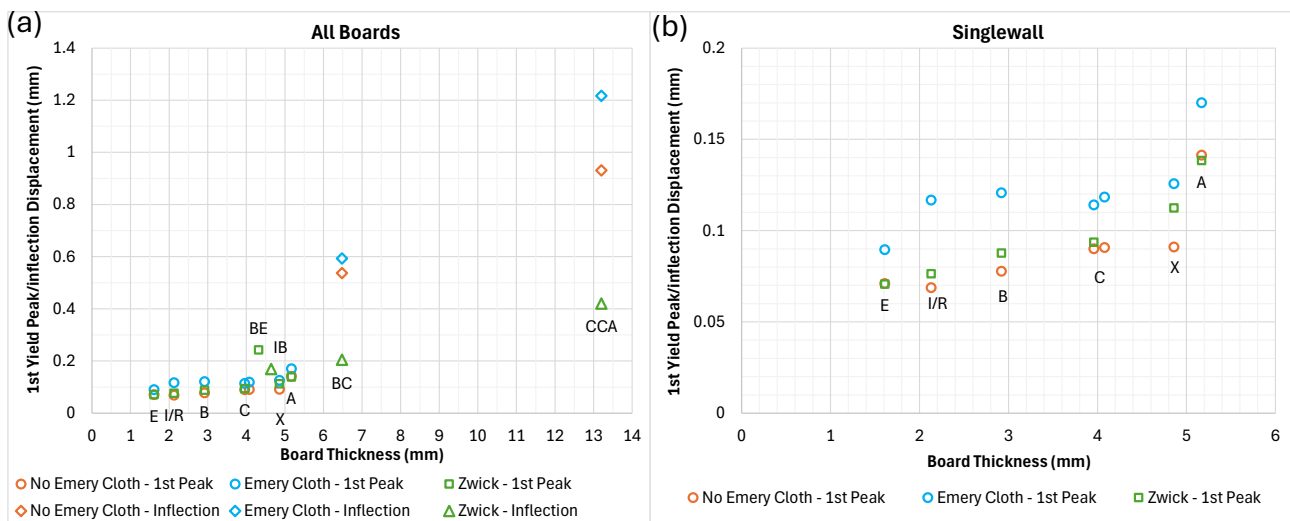


Figure 8. Flat crush first yield peak/inflection points with board thickness with and without emery cloth for various flutes.

The effect of medium furnish was explored via comparisons with two C-flute boards, one with a 140 gsm semi-chemical medium (SC140), the second with a 165 gsm recycled medium (RM165). The full FCT force-displacement curves for both the emery cloth and no emery cloth crush tester cases are shown in Figure 9a, with a detail of the first yield peaks within the first

² Note that IB and BE samples were not tested on the L&W crush tester and SC140 C-flute samples were not tested on the Zwick.

0.2 mm in Figure 9b. The first yield peak locations are marked with crosses in both plots. It is clear that the lighter 140 gm semi-chemical medium has superior hardness to that of the heavier 165 gm recycled medium. Also, that both the semi-chemical and recycled medium first yield peaks occur at essentially the same displacement. However, these displacements are slightly different for the with and without emery cloth scenarios.

This work suggests that the flute geometry is the dominant factor in the first yield peak displacement, with the platen surface also having an effect, while the medium furnish appears to have a limited impact. All singlewall boards had their first yield peak displacement well within 0.2 mm, while the double wall boards had peaks/inflection points near this value.

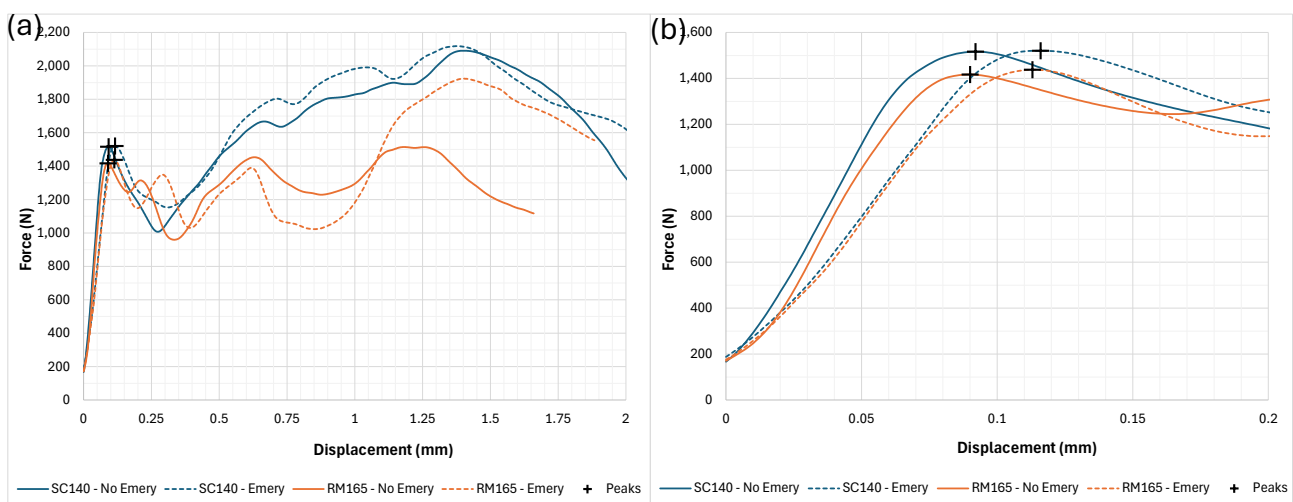


Figure 9. (a) C-flute FCT curves for SC140 and RM165 boards with and without emery cloth. (b) First 0.2 mm of FCT curves.

Application of new methodology

As an example, following some of the original experimental work of Crisp et. al, the new hardness assessment methodology (as outlined above, Figure 3d) was applied to a heavy C-flute board (sample #6, Table 1). Six crush levels, relative to the original thickness, were chosen (0%, 5%, 10%, 15%, 20% and 50%). The crushed boards were tested for hardness and a range of other properties (thickness, FCT, edge compression test (ECT), bending stiffness and MD shear stiffness) and the performance with crushing level is compared in Figure 10. The reduction in measured mechanical properties at 20% crush level are compared in more detail in Figure 11. Scanned board cross-sections at the various board crushing levels are also shown in Figure 12.

The average FCT force-displacement curves (Figure 10a), and the hardness, followed a somewhat similar form to those discussed above (Figure 3d). The hardness was described by the first yield peak for the low crush levels (0% and 5%) and by the maximum force less than

0.2 mm displacement for the higher crush levels. Hardness was the most sensitive to crushing of the properties measured, particularly between the 5% - 20% crush range (Figure 10b). The next most sensitive tests were MD shear stiffness related tests involving twisting [12, 13] and short span three-point bend [14]. This is not surprising as any damage to the medium would likely impact such shear behaviour. The remaining properties were significantly less impacted, particularly at moderate to low crush levels. Also shown are two calculated values for Box Compression Test (BCT) strength as the crushed board samples were not large enough to construct full size boxes. The first was based on a McKee-like equation [15] (labelled ‘BCT McKee’) using ECT and bending stiffness, while the second BCT calculation was expanded to include the effect of shear stiffness, in a similar manner to Garbowski [16] (labelled ‘BCT inc. shear’). Crisp et. al. [1, Fig.9] included two BCT measures, a standard box and a tube (box without flaps), which gave similar drops in performance to the calculated values displayed in Figure 10b. Historical unpublished work in our laboratory on crushed board BCT has also shown similar reductions in performance.

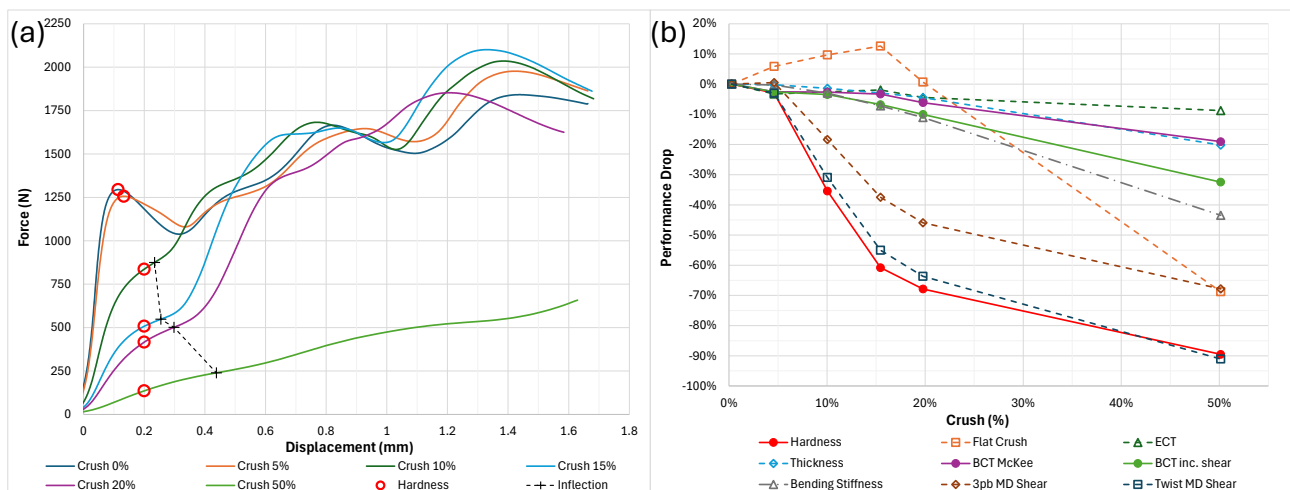


Figure 10. Application of new methodology (a) hardness (b) various properties with crush level.

Even at 20% crushing (Figure 11), the FCT, ECT and thickness were only marginally affected (a change of +1%, -4% and -4% respectively). The bending stiffness performance drop (-11%) mostly reflects the reduction in thickness (i.e. $\sim 2 \times -4\%$). The drop in BCT, calculated via McKee (-6%), is obviously intermediate between the ECT and bending stiffness (from which it is derived), however once the reduction in shear stiffness is taken into account, the drop in calculated BCT almost doubles to -10%. The two MD Shear stiffness measures show significant performance drops (-46% and -64% for 3 point-bend and twist respectively). Such measures are not pure shear but influenced by the board bending stiffness which is more strongly dependant on the liners. The most sensitive measure to crushing was the hardness (-68%), which is a medium dominated property, with little contribution from the liners. This is

illustrated by the fact that at the 50% crush level, the hardness is reduced by 90% but the ECT only by 9%, with no visual or other indication of any significant liner damage.

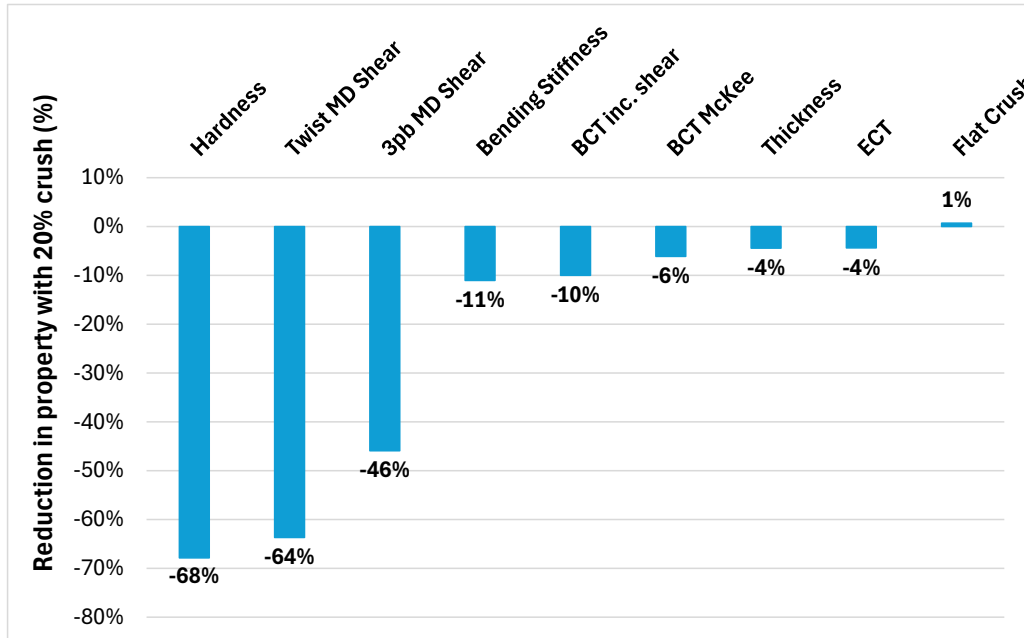


Figure 11. Reduction in various properties with 20% crush.

Figure 12 shows images of flatbed-scanned, laser cut, board cross-sections of the heavy C-flute board (sample #6, Table 1), with various levels of crushing. Very limited damage is visually observed until 20% crush, when a small amount of shearing of the flutes is noted. At 50% crush, a large amount of shearing (leaning flutes) is seen, as is not uncommon for heavy fluting mediums. Note that random variations in the nature of the leaning flutes are the likely explanation for the FCT (Figure 10b) initially increasing up until 15% crush levels, before decreasing with further crushing. In any case, FCT does not describe well the degree of board damage (crushing) experienced by this sample.

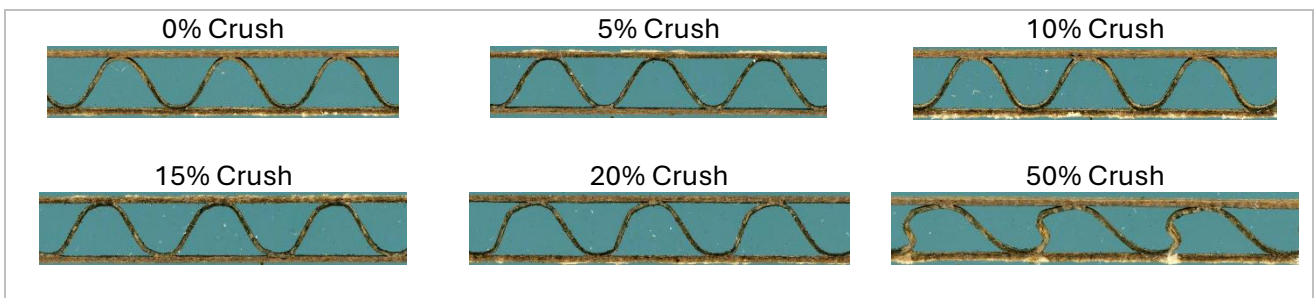


Figure 12. Crushed cross-sections of a heavy C-flute board

All the other flute types from Table 1 displayed similar behaviour and features with crushing (not shown here) as found with the heavy C- flute example examined above (Figure 10 through Figure 12) and were consistent with the original work of Crips et. al for A, B and C flutes.

This new approach to determining hardness worked well for the singlewall boards. The first 0.2 mm displacement for multiwall boards FCT curves is also quite sensitive to crushing, as evidenced in Figure 6 (g – j). Applying this approach to multiwall boards also offers the same quality control ability for maintaining performance through the manufacturing and converting process but with the caveat that there is not necessarily a first yield peak/inflection point within this 0.2 mm displacement range.

Comments

Hardness could be defined as the force at either the first yield peak or alternately the inflection point of the load displacement curve [2, 4, 5, 6]. This would reduce the need to define the zero displacement and correct the displacement for machine compliance etc., as hardness is then identified by features of the ‘curve’ only. However, for certain crushed boards the inflection point can be a substantial distance from the original location of the first yield peak of the uncrushed board, making it less relevant as a measure of board damage. Defining an initial displacement region within which the hardness must fall, as done originally by Crisp et al, alleviates this issue. Ideally this displacement should be corrected for non-specimen influences, such as crush tester compliance. An initial hardness displacement region of 0.2 mm for singlewall boards (E-flute or thicker) is supported by this work. For multiwall boards, a 0.2 mm region may be sufficient as an internal quality control measure, but ideally further investigation is required to better understand and more robustly define hardness for such boards.

This work shows that the platen surface finish of fixed platen crush testers can impact the ‘apparent’ specimen displacement, even if corrected for machine compliance (e.g. emery cloth vs no emery cloth). For any future standards, to allow cross laboratory hardness comparisons, the exact nature of the platen surface and/or any compliance corrections would need to be well defined.

CONCLUSIONS

Hardness is an extension of the standard flat crush test requiring no extra equipment or changes to the procedure, just software to analyse force-displacement curves (corrected for machine set-up compliance). Hardness peaks were observed in all undamaged singlewall

boards tested from E-flute through A-flute. All singlewall hardness peaks fell within the first 0.2 mm of compression displacement, double wall near this value but triplewall outside this range. Flute geometry is the dominant factor in the hardness peak displacement, with the platen surface also having an effect, while the medium furnish appears to have limited impact.

This work proposes the following approach to define hardness: For a displacement less than 0.2 mm (in order of priority), hardness is the force at the (a) first yield peak, (b) inflection point/first plateau (i.e. first minimum of the derivative of the force-displacement curve) or (c) maximum. Zero displacement is also redefined. This worked well for singlewall boards and may be sufficient as an internal quality control measure for multiwall boards. Ideally further investigation is required to better understand and more robustly define hardness for multiwall boards

Hardness is a medium dominated property, with little contribution from the liners. It is the most sensitive of common board properties to crushing damage, offering a quality control and troubleshooting method for maintaining performance through the manufacturing and converting process.

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APPENDIX

Force-Displacement Curve analysis

The raw FCT force-displacement curves were first corrected for machine compliance. This produced unevenly spaced displacement values which was undesirable for ease of analysis. Hence, displacement corrected curves were linearly interpolated to an even 1 μm spacing.

The first (y') and second (y'') derivative of the force-displacement curve were derived by a running quadratic regression analysis over a number of corresponding force-displacement values, i.e.:

$$y = ax^2 + bx + c \quad (1a)$$

$$y' = 2ax + b \quad (1b)$$

$$y'' = 2a \quad (1c)$$

where a , b and c are fitted quadratic parameters and x is the compliance corrected displacement. The smoothed force-displacement curve (y) (1a) was not used in the hardness calculations.

A centred running displacement window of $\sim 50 \mu\text{m}$ was chosen for the analysis (25 data points each side of the centre-point, a window of 51 points in all). This window size was judged by eye and is approximately half of the displacement to the hardness peak for C-flute board. It is likely that smaller flutes (thinner boards) are slightly 'overfitted' while larger flutes (thicker boards) are slightly 'underfitted'. One other possibility is to size the window on the board thickness (i.e. half the values of the dotted line fitted through the hardness peak locations in Figure 7). However, in this case, the simplicity of a single size for the running least squares window was chosen over the complexity of a variable window requiring knowledge of the board thickness. As typically the derivatives are used for approximate locations on the force-displacement curve, for a more thorough search for the appropriate curve feature (e.g. hardness peak), this almost always had little bearing on the final result.

All displacement values were re-zeroed to where the tangent to the curve, with a slope equal to the maximum slope of the initial portion of the curve, intersects the displacement axis (Figure 2, Figure 4). This is also illustrated by the red dotted line in Figure 13 (a, b, e, f) and Figure 14a. Care must be taken in selection of the maximum slope of the 'initial portion of the curve'. This work searched for the local maxima in the 1st derivative curve within the displacement window of $\sim 50 \mu\text{m}$ centred on the location of the first inflection point ($y'' = 0$) that traverses from positive to negative. The partially crushed C-flute (Figure 14) has 'lost' the first yield peak making it easy to select the maximum slope adjacent to the second yield peak, which is higher

than the first local maxima in the 1st derivative curve. This can lead to erroneous hardness values i.e. effectively selecting the second yield peak and not the inflection point pertaining to the 'erased' first yield peak. This error can be avoided if the search for the local maxima in the 1st derivative curve is centred on the location of the first inflection point ($y''=0$, inflection +/-).

Once the displacement values were re-zeroed the determination of the hardness progressed as follows:

- a. The 'region of interest' (ROI) was restricted to a:
 - i. Lower displacement value equal to the location of the maximum slope ascertained for the re-zeroing.
 - ii. Upper displacement value equal to the minimum of 0.2 mm or the location of the first minimum of the derivative of the force-displacement curve i.e. inflection point/first plateau ($y'' = 0$, see the point labelled 'inflection -/+ ' in Figure 13 and Figure 14).
- b. If a hardness peak existed within the ROI (e.g. Figure 13a-d) i.e. the 1st derivative changes sign from positive to negative ($y' = 0$) a local maximum in the force-displacement curve was searched for within the displacement window of $\sim 50\mu\text{m}$ centred on the location of this 1st derivative zero.
- c. Else, if no hardness peak existed within the ROI (e.g. Figure 13e-h) then the force at the upper end of the ROI (minimum of 0.2 mm or inflection-/+ location) was chosen as the hardness.

This methodology is illustrated in Figure 13 and Figure 14 and is applied throughout this work, unless otherwise stated.

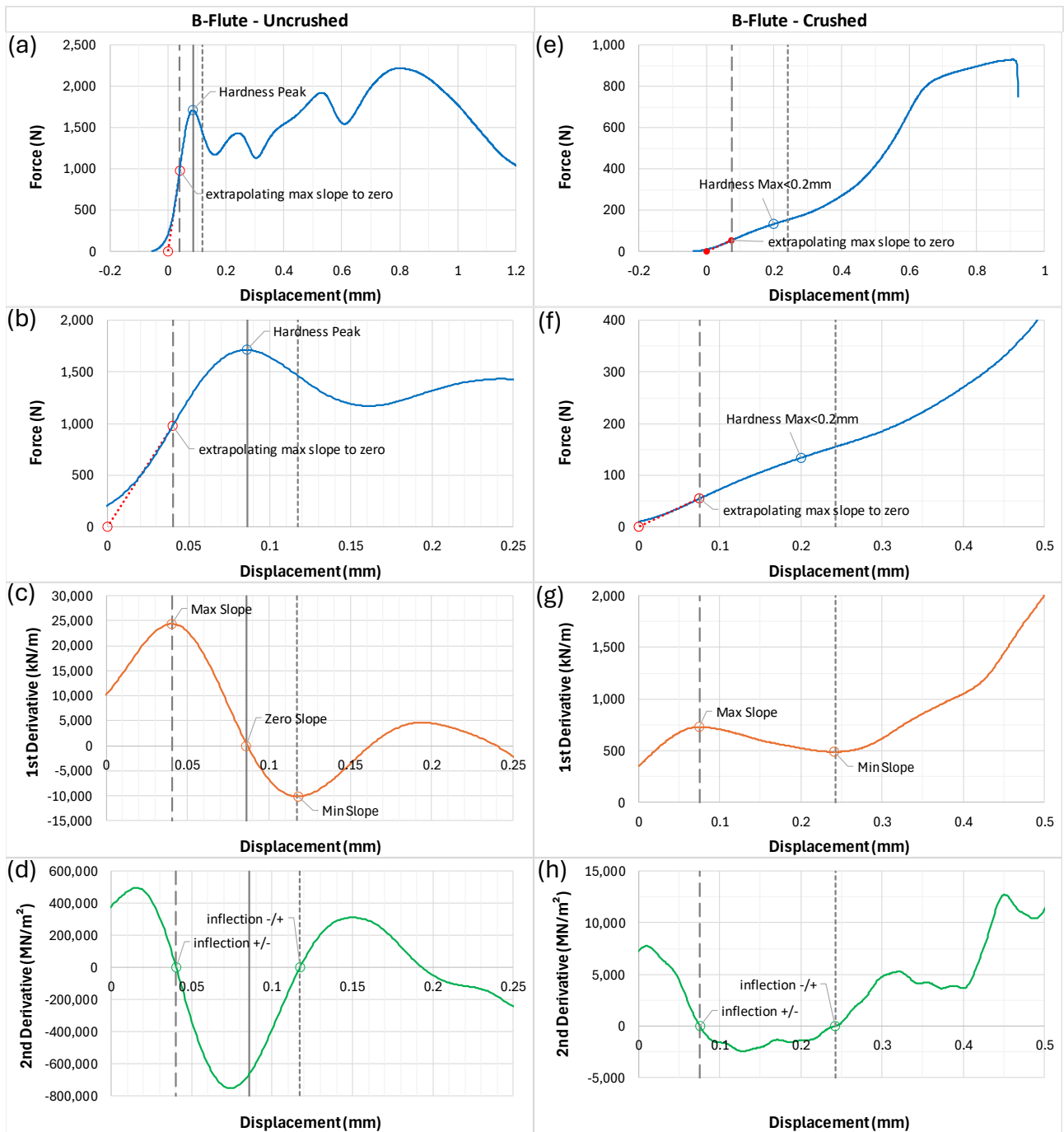


Figure 13. FCT, 1st and 2nd derivative curves for B-flute #2 (Figure 6c) used to determine hardness.

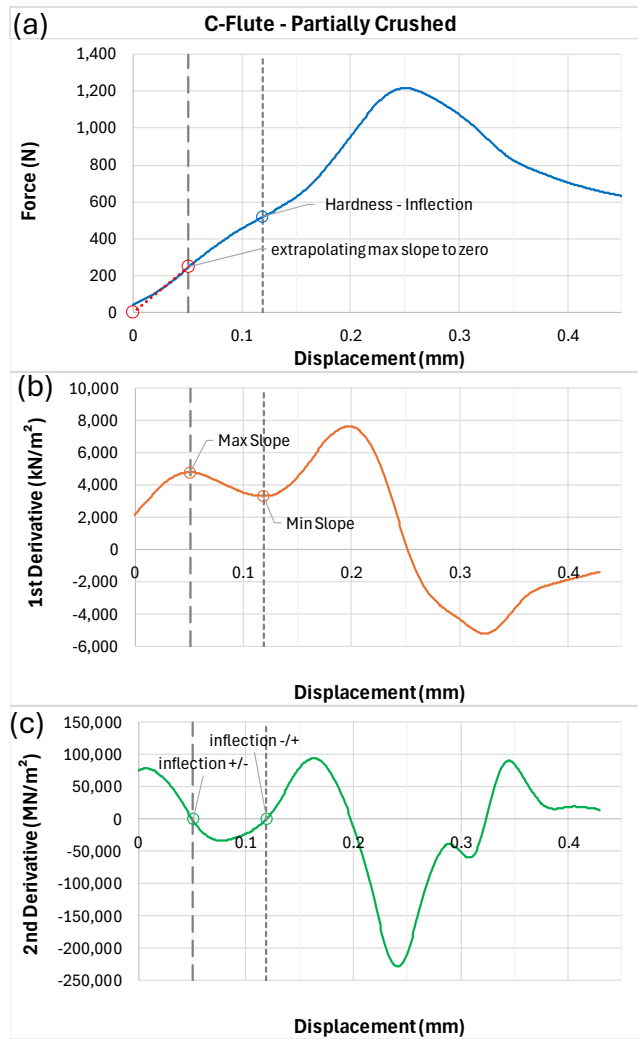


Figure 14. Curves from a partially crushed C-flute (Figure 3d, 3.2 mm) used to determine hardness.