Shear measurement of board crushing effects

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Abstract

Corrugated board in production endures varying degrees of crushing from stacking, transfer, die cutting, printing, and other corrugating and converting operations. Thus production corrugated board has a measurable loss of shear stiffness from converting operations which reduces its potential buckling load resulting in loss of box performance and lifetime. Yet the level of the impact of crush on board properties and ultimately box performance cannot be accurately detected by the usual measurement of caliper loss which is disproportionately small compared to the loss of shear stiffness. Instead, measurements of flat crush hardness or transverse shear stiffness have been shown to be greatly affected by board crushing. A newly available and convenient non-destructive method using sonically induced shear (Board Quality Measurement or BQM) is compared to a known torsion pendulum technique for validation. The results indicate that the effect of board crushing can be sensitively detected using these methods. Shear measurement can provide clear information regarding the effects of converting operations on board mechanical quality and provide an opportunity to minimize the impact of these operations

Background:

Transverse shear stiffness is the resistance to relative sliding motion of the inner and outside linerboard facings. When a box is loaded vertically, the side panels of the box bulge outwardly in response to the load causing a relative motion of the inside and outside liners principally in the MD or perpendicularly to the flutes. The amount of panel bulging is governed in part the MD transverse shear stiffness. A greater amount of panel bulging for a given load increases the stress concentrations at the corners of a loaded box such that failure will occur sooner in time at a lighter load. Shear stiffness is governed by the strength properties of the medium which is determined partly by material properties and partly by geometry. The material properties of influence are basis weight, fiber strength and fiber bonding. Geometry properties of influence here are flute shape, flute size. Should any measurable amount of board crushing occur, the caliper is usually observed to recover however, the flutings will suffer the formation of a kink at their flanks. These kinks compromise the rigidity of the corrugated medium structure to transverse shear.

Application of transverse shear measurement

Converting operations apply various out of plane loads to the boards in scoring, folding, printing, all of which crush the corrugated board to some degree. To maximize the strength potential of corrugated board it is useful to monitor the impact of the converting operations which is realized through the measurement of transverse shear rigidity.

The simplest method to measure this property is through an adaptation of the tensile strength test where opposite faces of the corrugated board are pulled in opposite direction [1]. However, an out-of plane displacement complicates this measurement. Other researchers have realized the component of transverse shear in three point bending measurements or have adopted a torsion pendulum measurement to infer the transverse shear rigidity from measurements of the twisting stiffness [2, 3]. All of these mechanical measurements require the preparation and mounting of samples in destructive tests and are thereby inconvenient to implement in a production environment.

XQ Innovations [4] have recently devised a sonic based method which requires only that the sample under test be placed between supports. The brick sized device placed on the supported sample vibrates along its length through a range of sonic low frequencies. A transducer on the underside of the BQM is in contact with the board and detects the amplitude and frequency of the detected board vibration. The amplitude and frequency of the MD induced board vibration is then computed to an equivalent transverse shear stiffness.

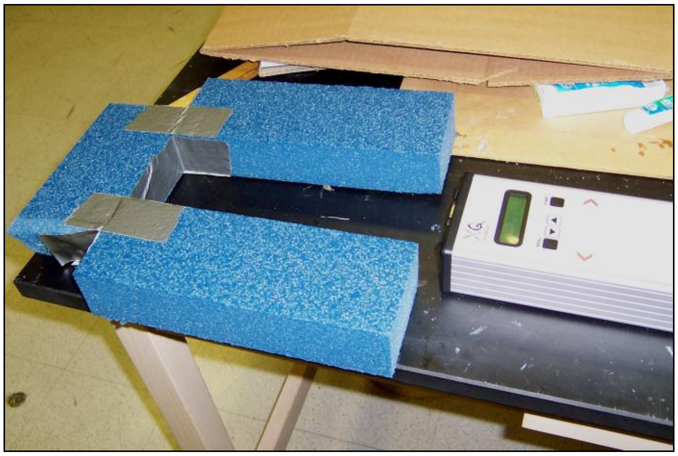

Figure 1. Improvised foam sample support and BQM used in the measurements. Boards are placed with flutes perpendicular to the length of the BQM, the BQM is placed on top of the samples suspended by the foam blocks. Test boards are vibrated along their MD by the BQM, the frequency and amplitude of the test board's sympathetic vibration is converted to a shear stiffness numeric output.

Description of the experiments

IPST has developed a torsion pendulum method [5] for determining the transverse shear rigidity of board specimens. The system is calibrated using a steel bar which is subjected to known torques using a system of weights and a pulley to twist the steel beam to various angular deflections. Computerized analysis of the detected oscillating twisting frequency of 2.5 x 12" test specimens is converted to a torsional stiffness. Coupled with measurements of the 4 point bending stiffness of corrugated board the transverse shear rigidity of boards is determined. More details of the technique are available in the May 2007 Appita paper physics conference.

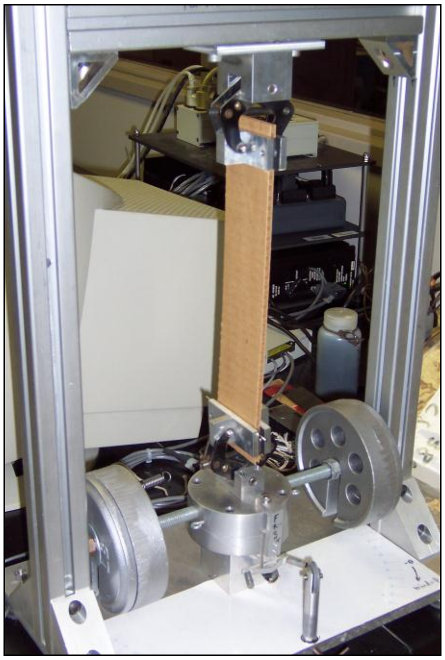

Figure 2. IPST torsion pendulum with specimen mounted between clamping jaws.

A series of boards were prepared using facilities at IPST using the pilot corrugator and manually double-backing as described if reference [6]. One set consisted of a series of lab made A flute corrugated boards where the medium basis weight was varied from 14# to 42#.

Table 1. List of relevant properties of the A flute set. Linerboards are all 42#, medium basis weight varied from 14# to 42#.

sample	ECT (lbf/in)	MD - 4 pt Bending (Nm)	CD - 4 pt Bending (Nm)	Torsion constant N/m	Average BCT lbs	Shear stiffness R55 (metric)	BQM stiffness kN/m
14A	20.6	18.5	9.2	0.89	614.7	2866	1.2
16A	30.1	20.8	9.4	1.34	679.2	4672	1.7
18A 723D	26.5	19.3	8.7	0.96	670.1	3120	1.4
18A 726E	38.3	17.2	8.8	1.18	720.1	4115	1.5
20A	52.4	17.7	11.3	1.46	931.0	5186	1.9
26A	50.4	19.5	12.2	1.81	1013.8	6742	2.8
33A	61.7	19.8	13.1	2.18	1022.6	8569	3.7
42A	53.6	19.4	9.9	1.24	933.3	4237	2.9

Another set of boards used for transverse shear analysis were made by crushing the commercially made or IPST made boards through a rolling nip set at various fraction of the nominal caliper ranging from 90 to 60%. Boards were sent through twice the rubber/chrome roll nip, with the second pass having the board flipped over and rotated 180 degrees from its original direction through the nip.

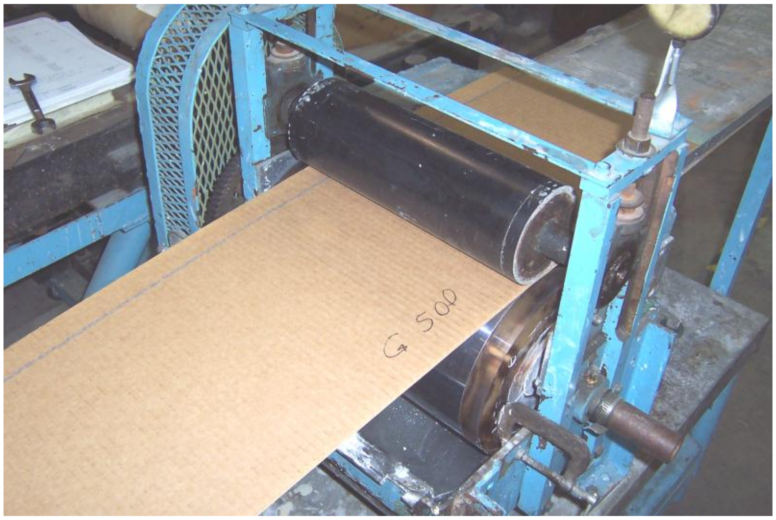

Figure 3. Corrugated board blank being sent through a double backing glue applicator nip to crush the board to a preset fraction of the original caliper.

Table 2 . Relevant properties of the crushed board set for comparative transverse shear measurements.

Sample	caliper	Torsion Pend.	ECT	Flexural Stiffness (N-m)		Flat Crush	BQM	shear
	mm	(N/m)	lb/in	MD	CD	N	kN/m	R55
C-flute								
Control	4.15	1.90	41.0	15.5	6.45	15.34	3.65	9219
90%	4.11	1.78	42.1	14.9	6.34	14.55	2.9	8369
80%	4.04	1.28	38.4	14.4	6.08	6.90	2.05	5110
70%	3.93	0.98	38.8	13.4	6.01	5.29	1.5	3545
60%	3.65	0.56	32.3	10.7	5.17	4.25	1.05	1837
Waxed C								
Control	4.28	1.84	49.5	16.5	8.97	15.71	3.5	7676
90%	4.09	1.64	52.0	16.2	8.79	11.05	2.95	6545
80%	4.09	0.95	50.9	14.6	8.12	3.87	1.8	3231
70%	4.02	0.84	46.1	13.5	7.82	2.33	1.4	2787
60%	3.83	0.57	48.3	11.4	7.25	0.09	1.15	1814
A-Flute								
Control	5.13	2.06	49.9	23.7	13.96	18.14	4.05	7565
90%	5.12	1.88	47.5	23.7	13.21	12.53	3.45	6736
80%	4.98	1.13	44.6	20.5	12.88	6.00	1.9	3658
70%	4.92	0.89	47.0	19.6	12.43	4.96	1.85	2784
60%	4.86	0.79	44.1	17.9	12.11	3.01	1.4	2437
B-Flute								
Control	3.02	1.50	52.9	8.0	4.29	40.06	5.5	10079
90%	2.99	1.44	50.7	7.5	4.29	27.69	4.65	9530
80%	2.95	1.25	49.4	7.5	4.14	20.99	4.1	7113
70%	2.85	0.89	45.8	6.9	3.82	11.95	2.7	4045
60%	2.73	0.63	46.7	6.1	3.48	6.72	2	2525

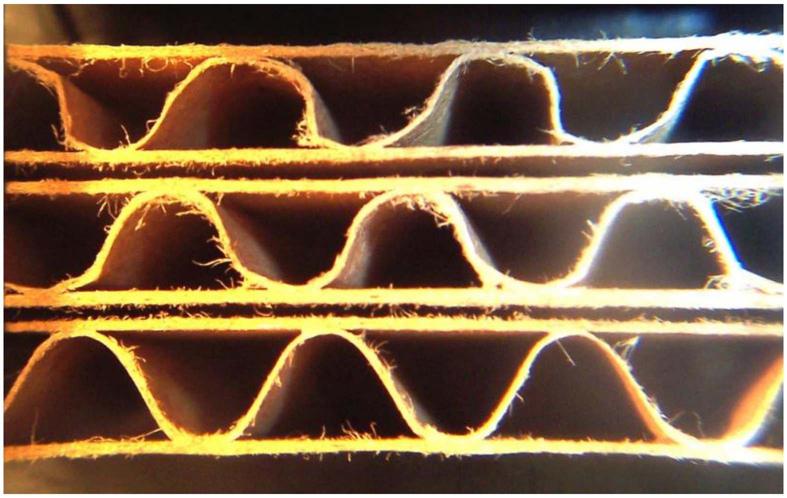

Figure 4. Magnified cross section of C flute boards: bottom board uncrushed, Middle: sent through nip gap set at 70% of original caliper, top board: board sent through nip set at 60% or original caliper. Note that despite the large amount of crushing, the permanent caliper reduction is 10% or less in these extreme circumstances.

Results

The first comparison was made using the A flute series of laboratory made boards were the basis weight of the medium ranged from 14 to 42 lb/msf. Comparison of the transverse shear rigidity obtained from the torsion pendulum and the results of transverse shear stiffness from the BQM are shown in Figure 5. The BQM is not calibrated to read A-flute so readings were taken using its C flute setting. The one outlying point is the A -flute board using 42# linerboard as the medium. In this case, the flutes were observed to be fractured since the corrugating labyrinth is set to accept small range of fluting calipers. Damaged flutes will lead to an anomalously low shear resistance measurement. In Figure 6, if we remove the fractured flute specimen the correlation between instruments and methods become unambiguous. Thus we have an indication from this data that medium quality or damage can be detected through transverse shear measurement.

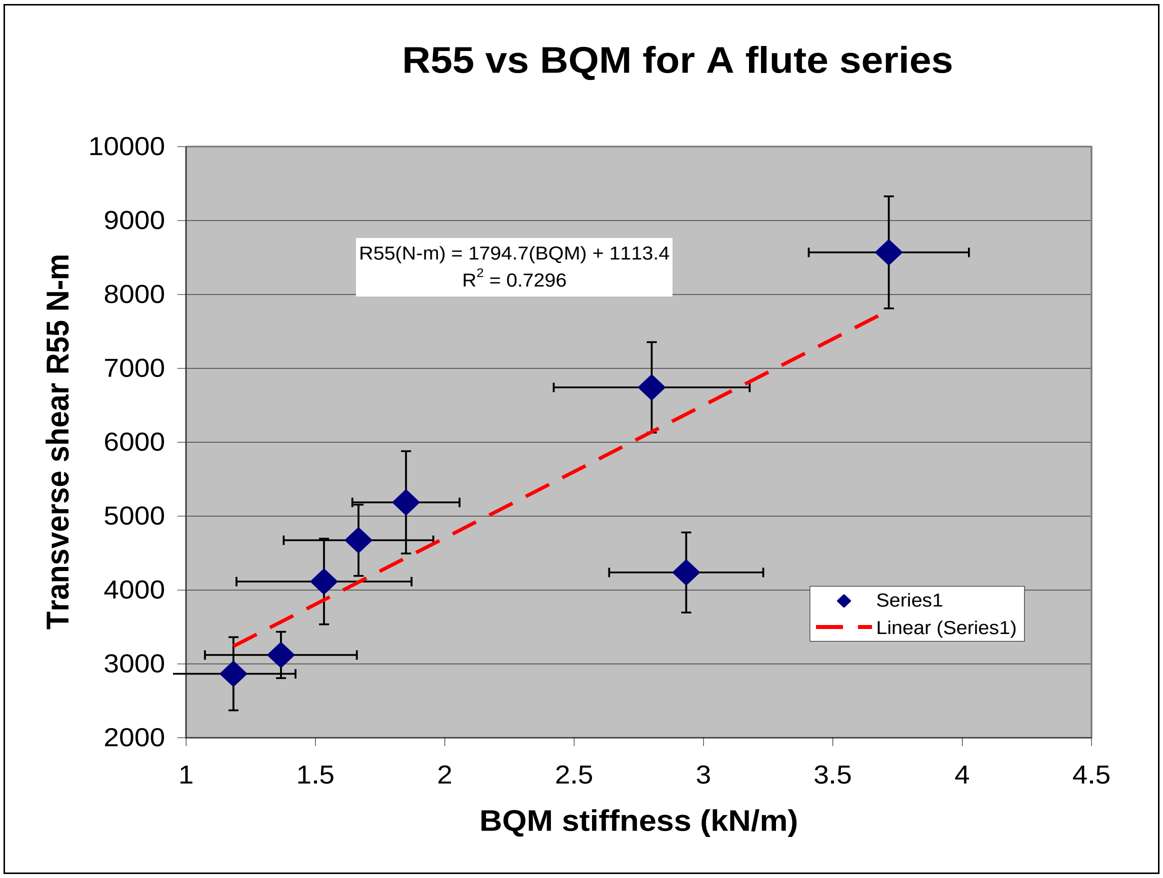

Figure 5. Torsion pendulum determined transverse shear rigidity versus the BQM measurements of stiffness. The BQM was set on its "C" flute setting. The one outlying point is 42A which is a fractured flute caused by the corrugator gap not accommodating this thickness of medium.

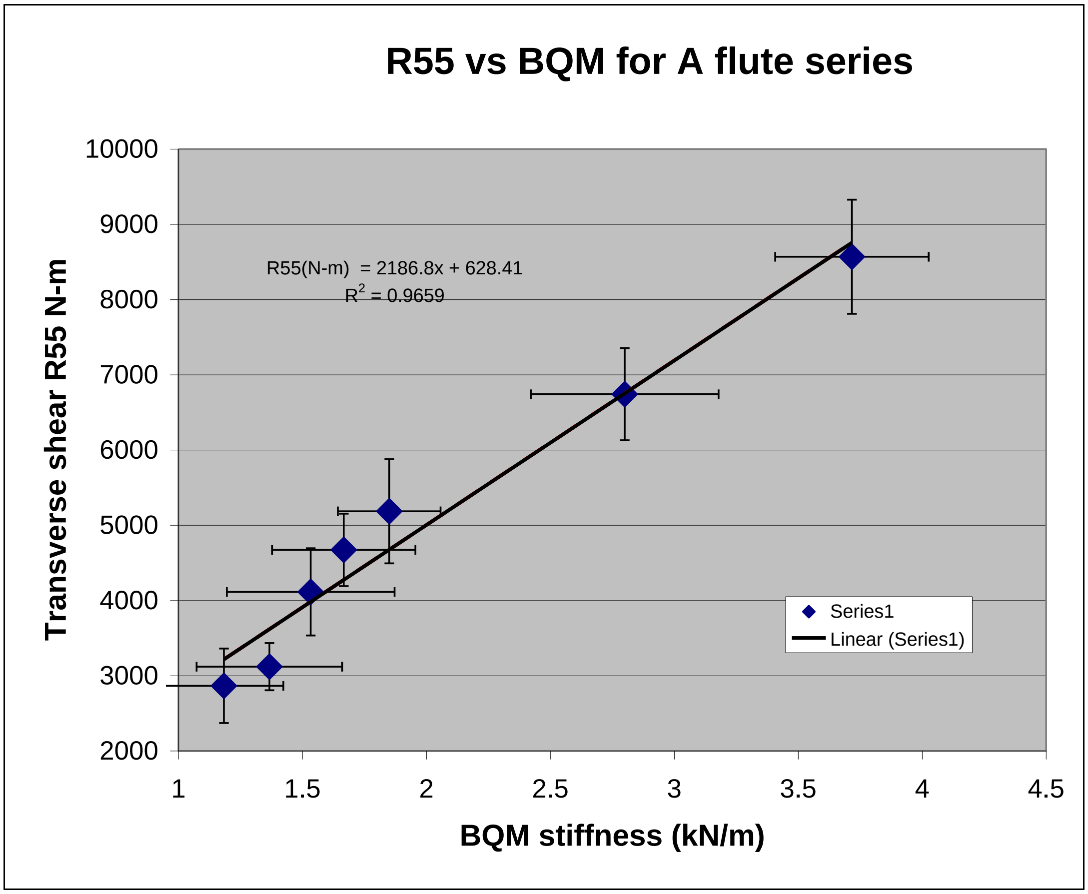

Figure 6. Same as Figure 4 but with the 42A outlier point removed.

Crushed boards

Crisp et al described how changes in the load displacement curve for flat crush occur once a board is crushed. They dubbed the first load peak in the curve as the medium "hardness" and noted that it was the most sensitive measured property that responded to board crushing. Other investigators found that many physical properties are insensitive to board crushing. Recently the studies by Batelka [7] and Kroeschell [8] show that board caliper recovers within minutes of crushing to 90% or more of its original caliper. However, there is a loss of performance properties (vertical stacking strength and lifetime) when crushed board is converted into a box which goes largely undetected through routine caliper measurements in box plants.

Flat crush test instruments are usually set to set to record maximum peak load value and thus do not detect the drop in the first peak in the load displacement curve. Recording the hardness through a recording compression tester is possible but tedious. Shown in Figures 7 and 8 below are load displacement curves of uncrushed A flute board and A flute board crushed to 70% of its original caliper. Figure 8 graphically shows the dramatic decrease in the first peak of the load displacement curve. The alternative to measure the effects of crushing on board by measurement of transverse shear is suggested as a means to conveniently monitor and control crushing effects on board.

Results of the hardness versus permanent caliper reduction are shown for a variety of laboratory crushed boards in Figure 9. The permanent loss in caliper for all cases is less than 10% of the original caliper however the corresponding change in the hardness values in some cases as much as 800%! The caveat is however, that the selection of the hardness value if based on load alone involves a subjective evaluation of the load displacement curve and is therefore subject to operator variability. A combination of the curve inspection alongside with a comparison of the displacement value where the first peak was known to occur as found to be the best method to reduce error. However, the care that must be taken to ensure the starting point of the compression cycle for each series of specimens is appropriate to minimize offset is another barrier for making this a routine quality test measurement.

Measurements of transverse shear stiffness or rigidity offer a similar sensitivity to board crush level with a much higher level of convenience and ease of use. Shown in Figure 9 are the results using the BQM device on the series of crushed boards which indicates a good range and correspondence with flat crush hardness. Thus a measurement of the transverse shear of the medium with the BQM is much more convenient and is comparably sensitive as flat crush hardness to detect and damage to the medium from crushing.

Comparison of the same crushed board hardness results with the torsion pendulum are indicated in Figure 11. Here, the transverse shear rigidity R_{55} is the shear stiffness multiplied by the board thickness. Moreover, the measurement here is influenced by the twisting stiffness of the board which is governed by the tensile stiffness of the linerboards. Hence, in Figure 11 we see a larger separation between the points of different types of board. However, the ranges of transverse shear rigidities are similar to those for shear stiffness as measured by the BQM which confirms the measurements of transverse shear strength to be a sensitive measure of board crush.

Effect of transverse shear strength of board

The question arises that if crush were to be eliminated in a box plant what would be the potential increase in box performance. Chalmers [9] recently has shown preliminary evidence of the influence of reduced transverse shear on box lifetime. The effects of crushing on BCT are expected to be smaller than that on lifetime which can be gleaned from the following considerations.

Recall that the McKee equation [10] for the BCT of the board takes the form:

$$BCT \propto ECT^{0.75}\left\{\sqrt{D_{11}D_{22}}\right\}^{0.25}W^{0.5}$$

with ECT being the edge compression strength, $\sqrt{D_{11}D_{22}}$ is the geometric mean of the flexural rigidity of the corrugated board commonly approximated by a 4 point bending stiffness measurement and W is the perimeter of the box. Since for a sandwich panel the flexural rigidity is proportional to the caliper of the board squared, the McKee equation is further approximated by this substitution resulting in the more familiar form of the McKee equation which is proportional to the square root of the board caliper.

However, it should be noted that the flexural rigidity term arises for the derived analytical expression for the buckling of a vertically loaded orthotropic plate and as approximated, is neglecting the effect of transverse shear rigidity. Estimates for the decrease in panel critical buckling load can be made from several available analytical and numerical models [11, 1, and 6]. A typical calculation is shown in reference [6] where for the case of 70% caliper crush reductions in ECT are 10% and reductions in bending stiffness are 20% so that the predicted loss in BCT is 12%. But with the inclusion of the loss of transverse shear at this level of crushing, the panel critical buckling load is actually reduced by 32% leading to a predicted BCT loss of 16%. Therefore the neglect of transverse shear will lead to an overestimate in BCT by a few percent by this calculation. Ultimately, if crush were to be eliminated a gain in BCT of 15% can be expected. Measurement of transverse shear strength is a sensitive method to determine what stages in operations cause the crush.

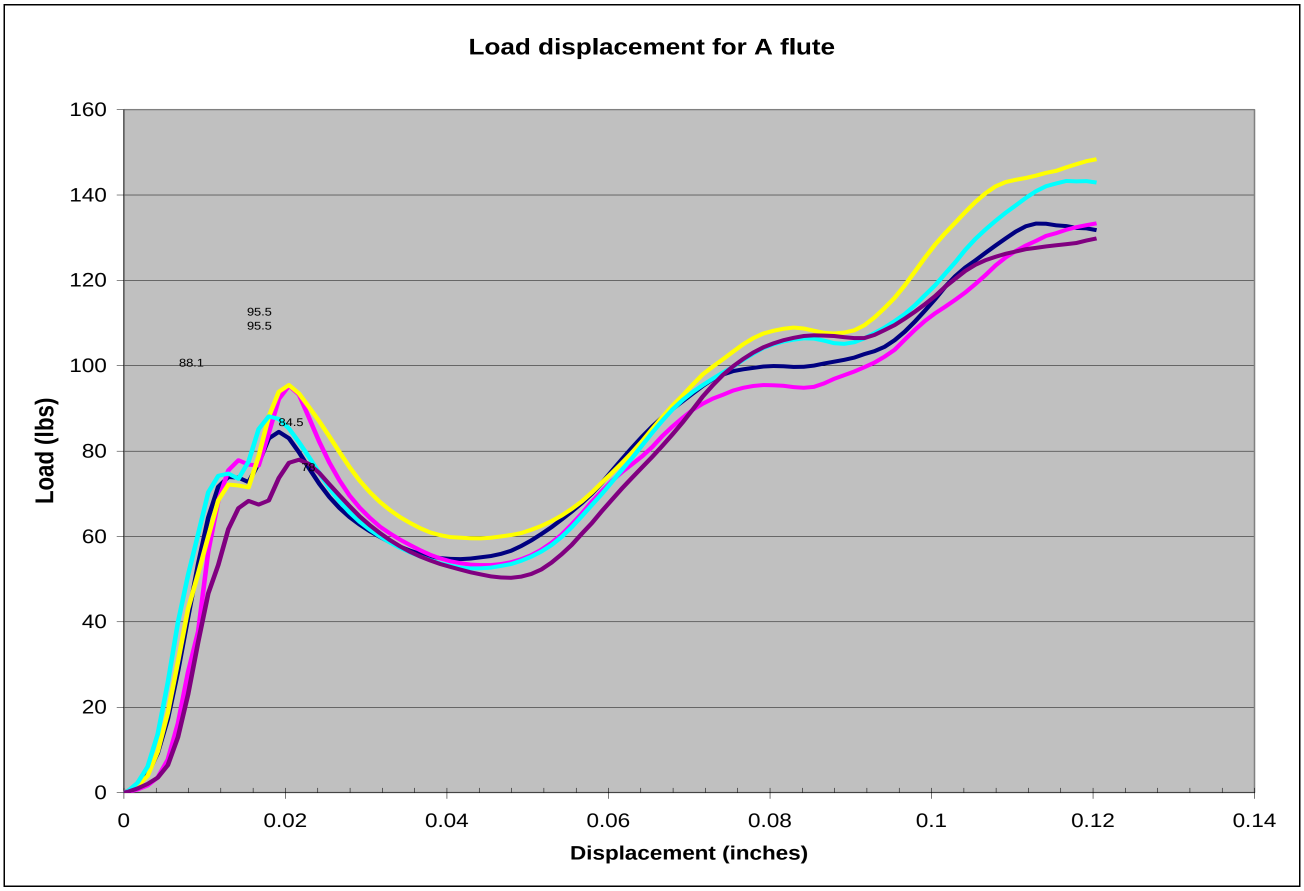

Figure 7. Flat crush load displacement curves for 2 x 2" Uncrushed A flute specimens.

Figure 8. Load displacement curves for A flute boards crushed though nip passage gap set at 70% of the original caliper.

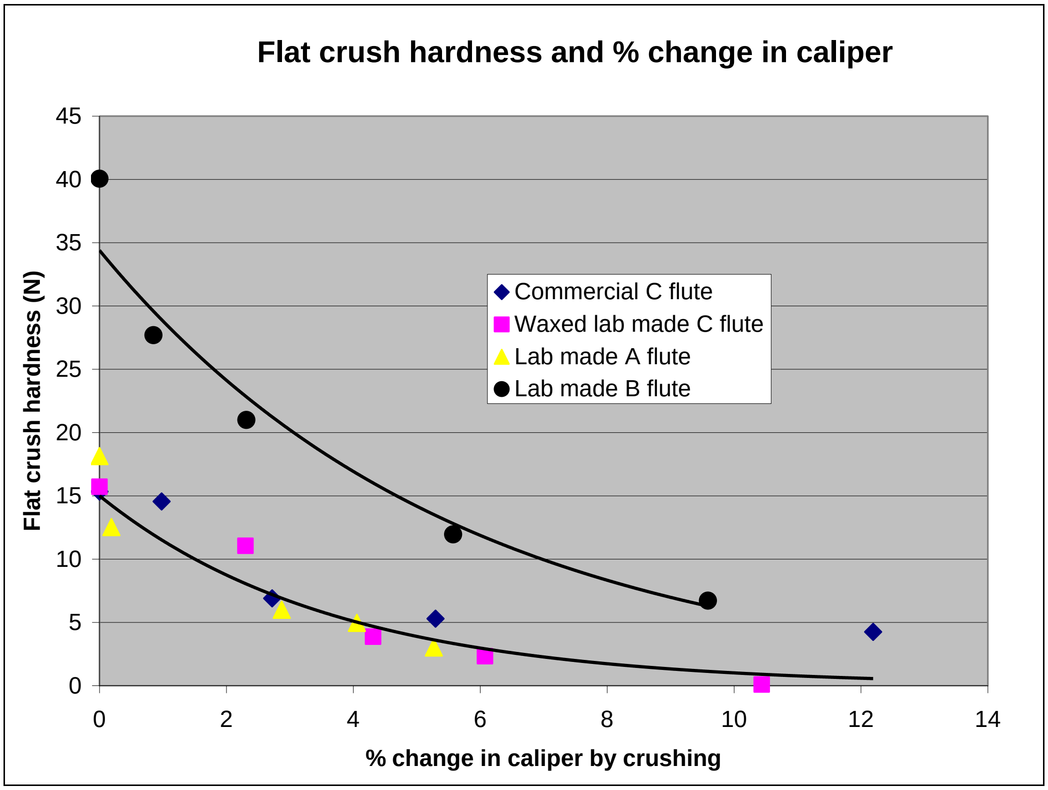

Figure 9. Hardness is the value of the first peak in the load displacement curve in the flat crush test. Although the % change in caliper is about 10% or less, the change in hardness is a factor of 4 to 6 times. The hardness was measured through examination of the load displacement curves using an Instron universal tester and a compression load cell. Thus a measure of hardness is a sensitive detector of board crushing.

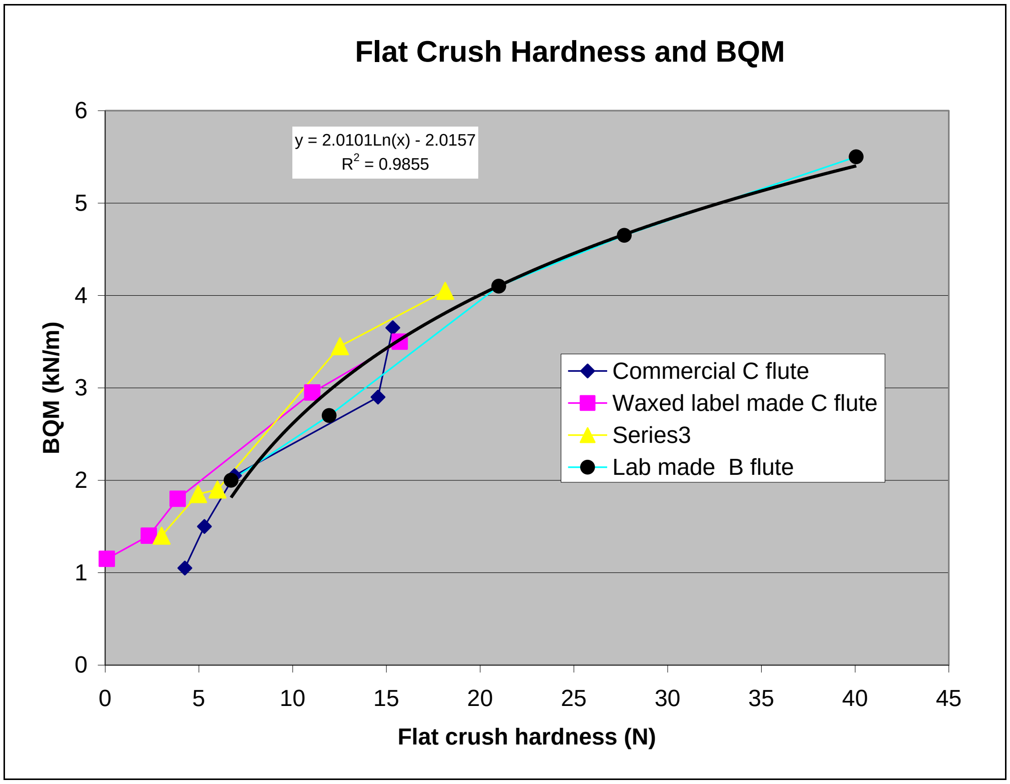

Figure 10. Correspondence of the BQM to the flat crush hardness. A non-linear relationship appears to be the best generalized fit for the data. The large range in BQM values corresponds well to the large range in hardness, thus BQM measurements can substitute for hardness to detect levels of board crushing with more sensitivity than caliper measurements.

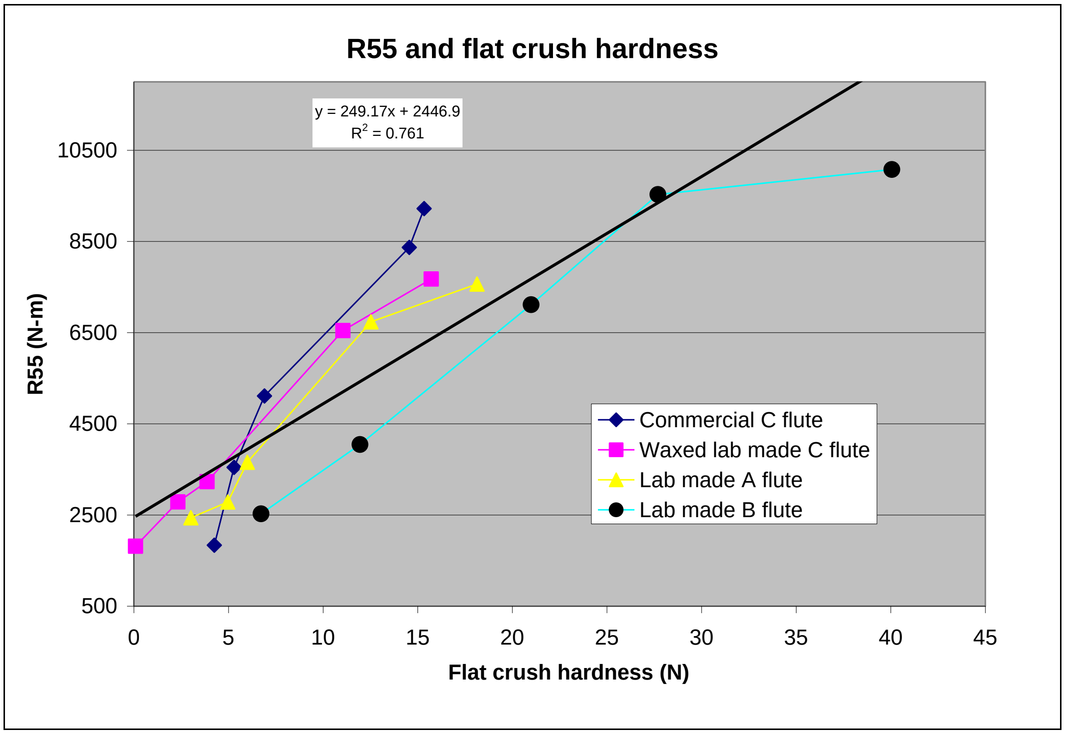

Figure 11. Similar to Figure 11, except the R55 as determined from the torsion pendulum and bending stiffness tester is plotted versus flat crush hardness.

Summary

Board crushing occurs to some degree in nearly all box plant operations however the availability of convenient instrumentation to characterize crush with sufficient sensitivity has been limited. This paper advocates measurement of transverse shear strength as a means to detect board crush. A new non-destructive sonic method was shown to correlate well with measured values of medium hardness and results from a calibrated laboratory torsion pendulum method. These methods have a much greater dynamic range than the corresponding board caliper values thus offer the opportunity to survey box making operations to source and eliminate the cause of board crush. The calculated gains in box compression strength from the elimination of crush is of the order of 15% which should provide an incentive for the industry to incorporate transverse shear measurement of board as part of its regular manufacturing practice.

Acknowledgement

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