Preferred citation: C. Rydefalk, A. Hagman, L. Yang and A. Kulachenko. Mechanical response of paperboard in rapid compression – the rapid ZD-tester, a measurement technique. In *Advances in Pulp and Paper Research*, Cambridge 2022, Trans. of the XVIIth Fund. Res. Symp. Cambridge, 2022 (D. Coffin and W. Batchelor, eds), pp 311–331. FRC, Manchester, 2022. DOI: 10.15376/frc.2022.1.311.

MECHANICAL RESPONSE OF PAPERBOARD IN RAPID COMPRESSION – THE RAPID ZD-TESTER, A MEASUREMENT TECHNIQUE

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ABSTRACT

Paperboard is a common material for packages and other carriers of information. During rotary printing processes, the paperboard is subjected to rapid deformations in the out-of-plane direction as it passes through the nip between the rolls of the printer. Being viscoelastic in nature, the mechanical response of the material to high deformation rates differs from what is measured with conventional testing conducted at slower deformation rates. In this work, a device called the rapid ZD-tester is used to show the response of paperboards subjected to a rapid pressure pulse and compare this to measurements made at lower strain rates in a common universal testing machine. All the tested paperboards show complete recovery within 5 s when being rapidly compressed, while the slower compression to the same pressure leaves a deformation that remains after 5 s. The stiffness response differs between the paperboards, but does not consistently increase or decrease between slow or rapid compressions. The difference in response between slow and rapid compression appears larger for the low-density paperboard in the study. The time scales

in the rapid ZD-tester are comparable to those in a printing press, and, therefore, evaluation of the material response of the paperboard measured by this device is relevant in the context of printing applications.

INTRODUCTION

One of the fundamental uses of paper and paperboard is as carriers of information printed on the surface. This feature is utilized even when the paperboard, in the form of packages, is primarily a carrier of goods. Several methods of rotary contact printing exist, but within the context of packaging printing, flexography is one of the most common, primarily owing to its unmatched printing quality. A modern flexographic printing process can run with a web-speed of several hundreds of meters per minute, meaning that the substrate is only in contact with the print nip for a few milliseconds during ink transfer. The pressure profile of a soft nip has been shown both experimentally [1]–[5] and numerically [6]–[9]. The impression or pressure in a flexographic print nip is very soft in comparison to other contact printing methods. Therefore, the ideal pressure is sometimes referred to as kiss impression [10] or kiss print [11]. The pressure in a printing press is controlled by the cylinder distance and in studies on the influence of pressure on different printing parameters, it is common to refer to the impression in terms of distance or engagement rather than pressure measured in MPa [12]–[15]. The low pressure in flexography is advantageous when printing on e.g corrugated boards where the fluting can become flattened at pressures as low as 0.23 MPa [16]. While for paperboard the pressure in a flexographic print nip have been measured up to 1–2 MPa [2]. Due to the viscoelastic properties of paperboard, and inhomogeneous nature of material, the out-of-plane mechanical characterization at high strain rates and low pressures is therefore of interest in this context.

Another rotary process where much work has been done on the out-of-plane compressive properties of paper and board is calendaring. There are studies specifically looking at the material behaviour under compression in a rolling nip [17], [18] and many of them are concerned with calendaring in particular [4], [5], [19]–[21]. However, the purpose of calendering is to induce permanent deformation (smoothing and compacting) of the board. Although calendaring is also done under rapid conditions, it is concerned with much higher pressures than flexographic printing to achieve this permanent deformation. In a printing context the purpose of applied pressure is to achieve a good printing quality on a substrate that might be uneven in both thickness and compressibility.

Experimental studies and characterization of paper in the out-of-plane direction, as well as reports on out-of-plane models that include experimental data, are generally measured under much slower rates than the operational speed of a printing press [22]–[26] and are often made at pressures in the range of 10–20 MPa, or much higher which makes the resolution around 1 MPa poor. The most common method for out-of-plane compression testing of paper in the mentioned studies is to use a universal testing machine (UTM), compressing the material between two clamps and recording force and displacement at relatively slow rate. Furthermore, the compression clamps are usually large compared to the variations in the paper thickness to avoid the influence of individual flocks. The use of large test areas in compression testing can therefore not reveal spatial variation of the compression properties of the paperboard relevant in the printing context.

Other novel compression test methods for paper and paper-like materials have been suggested, e.g. using a lab printing press and strain gauges to extract out-of-plane compressibility data [17] in a rolling nip or using Split-Hopkinson [27] to get rapid compressive measurement data.

In order to extract relevant spatial variability of the compression properties, this study uses a device called the rapid ZD-tester [28], [29] to measure out-of-plane properties. The rapid ZD-tester subjects the substrate to a rapid pulse of the same order of magnitude as in a modern printing press and with a probe having a diameter comparable to the length of a printing nip thereby providing a force-displacement relation under conditions not easily achievable by traditional means. Additionally, the machine has the benefit of easily exploring the dynamic material behaviour across a surface of a thin substrate in the out-of-plane direction, providing a map of the lateral variations in compression properties.

The mapping feature of the rapid ZD-tester is used to ascertain that the behaviour is consistent over the sheet and not due to "weak spots". This method is also utilized to reveal differences between the boards hidden in the force-displacement curves, but which could be of interest when printing on the paperboard.

MATERIAL

The materials used in the present study are commercial, coated paperboards meant for printing. Three different paperboard grades from different manufacturers were used in the study named in the text as Thick multi-ply, Thin multi-ply and Single-ply. The three investigated materials were selected to include both single-ply and multi-ply paperboards having comparable grammages but different densities, thereby being expected to show differences in compressive behaviour.

Table 1 Summary of the investigated paperboards

	Thick multi-ply	*Single-ply*	*Thin multi-ply*
Grammage [g/m^2]	280	270	270
Ply	Multi	Single	Multi
Structural thickness [μm]*	433	391	380
Density [kg/m^3]	646	690	710
Calliper thickness [μm]**	436	397	385

* Measured in accordance with SCAN P88:01.
** Measured at 100 kPa using a L&W Micrometer with probe of 16 mm in diameter.

METHOD

The difference in material behaviour between the slow and the rapid pulse is investigated by approximating the conditions in pure compression. The nip of a flexographic printer is estimated to be a few millimetres long, and the pressure pulse approximately 1 MPa. The duration of the pulse is in the millisecond range. In this study, a pressure probe 5 mm in diameter exerts a pulse of approximately 0.7–0.85 MPa on the paperboard, for a duration of roughly 1 s and 1.5 ms respectively, using a standard UTM and the rapid ZD-tester. The maximum pressure is chosen to be comparable but on the lower side of the estimated pressure in a printing press so that permanent, irrecoverable deformations can be excluded from the study.

Two methods have been used to compare the material behaviour in out-of-plane compression: the rapid ZD-tester [28], [29] and a conventional universal testing machine (UTM).[1] All measurements were performed at standard climate (23 °C and 50% RH) after conditioning the samples for a minimum of 24 hours. In both methods, the sample is resting flat on a surface larger than the measurement probe. The surface can be considered rigid in comparison to the paperboard. The measurement probe is a cylindrical compression clamp 5 mm in diameter, starting at a distance from the paperboard surface. The trigger pressure used here to denote impact on the surface is 18 kPa, for both methods.

UTM-measurements

The UTM compresses the paperboard with a constant piston speed of 60 μm/s to maximum pressures of approximately 0.7 MPa. The maximum pressure in the UTM-measurements is purposefully kept on the lower side of the mean maximum pressure from the rapid ZD-tester measurements. This results in a pulse of approximately 1 s. The compression clamp is set to start and stop a distance above the paperboard so that the delay between contact with the sheet is approximately 5 s. The gap between the underlying surface and the piston at start position is fixed for each paperboard quality to 200 μm above the mean structural thickness.[2] The displacement was measured with an extensometer attached to the rigid clamps.

Four different measurement procedures were used, listed below. All of them have three compression cycles, where the maximum pressure differs between the procedures. Each measurement procedure is tested in a new point on the sheet.

(a) 3 repeats to a maximum pressure of 0.7 MPa (to compare with the maximum pressure in the rapid ZD-tester).

Measurements using this procedure are used to compare the paperboards to each other and to compare with the results from the rapid ZD-tester measurements. The results from this procedure are reported in the Result-section.

(b) 3 repeats to a maximum pressure of 0.36 MPa (approximately half of the above maximum pressure).
(c) Increasing maximum pressure of 0.25, 0.35 and 0.7 MPa.
(d) Decreasing maximum pressure of 0.8, 0.4 and 0.2 MPa.

The last three procedures are only used as a confirmation of general behaviour of slow out-of-plane compression of paperboard, and that all three boards exhibit these. Mainly that the non-recovered thickness between the first and second pulse, is not only due to the maximum pressure level in the first procedure. The characteristics are demonstrated in the Result-section, but a full quantitative comparison between the paperboards is not made in this study.

Rapid ZD-tester Measurements

The rapid ZD-tester, Figure 1, works by dropping a probe in free-fall on the paperboard while an eddy-current sensor underneath records the position of the probe as it falls, impacts on the paperboard, and bounces. The velocity and acceleration are obtained from the numerical time derivative of the position,[3] see Figure 2. From the acceleration *a* the force *F*, and pressure σ exerted by the probe are calculated as:

$$F = ma$$

$$\sigma = \frac{F}{A}$$

where *A* is the probe area and *m* is the mass of the probe. The mass of the probe is 200 g (±1 g) and the contact area 5 mm (±1 μm) in diameter. The surface of the probe is polished steel. Repeated measurements on mylar with comparable stiffness to paperboard shows a standard deviation in the thickness measurements performed by the Rapid ZD-tester to be approximately 0.6 μm.

The maximum pressure depends on drop height and material properties in that specific point. In the present study, the drop height is set to 80 μm which results in a mean maximum pressure of approximately 0.8 MPa. The cut-off pressure of 0.7 MPa, used to provide a maximum pressure in the UTM-measurements, was selected as the highest pressure all points had at least been subjected too.

To get the same drop height in each point an initial thickness measurement is performed at 50 kPa,[4] and the probe is raised to 80 μm from this reference position. Two consecutive drop-releases from the same height were performed for each point on the paperboard. Each drop produces a pulse having a duration of approximately 1.5–2 ms and the time delay between the drops is approximately 5 s. The procedure of the rapid ZD-tester is found in Table 2. The probe is allowed to bounce multiple times in each drop-release (measurement) with the probe's position is continuously recorded. This is performed in a 16 × 20-grid providing measurement data in 320 adjacent points, thereby covering an area of 8 × 10 cm.

Results and Discussion

The present study utilized a common compression measurement method to characterize the paperboards in slow compression. This was performed to confirm that they exhibited behaviour typical of paperboard; to provide specific information of each paperboard quality and to provide a comparison to the rapid measurements.

A demonstration of all four procedures of slow compressive pulses of the UTM-measurements are depicted in Figure 3. Compression to the same maximum

Table 2. Measurement procedure for the rapid ZD-tester

```
for each measurement point on a sheet do
    Thickness measurement;
    Slowly lower the probe to rest on the material at a pressure of 50 kPA;
    Record the probe-sensor distance as thickness H;
    ZD-position measurements;
    for two drop-heights do
        Raise the probe to a set drop-height 80 μm above H;
        Drop the probe and record the distance between probe and sensor until the probe
        is still
    end
end
```

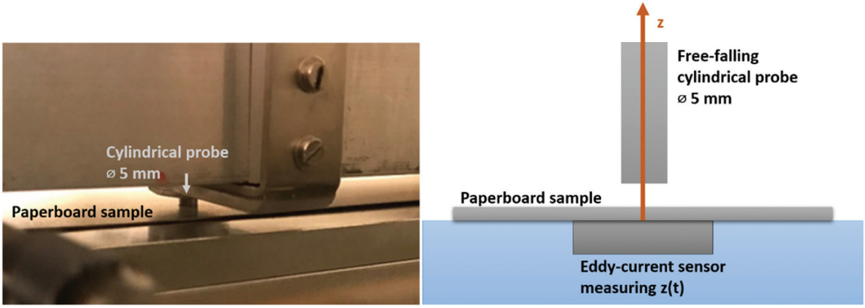

Figure 1. Photograph and schematic of the rapid ZD-tester. The paperboard is mounted in a frame in an xy-table.

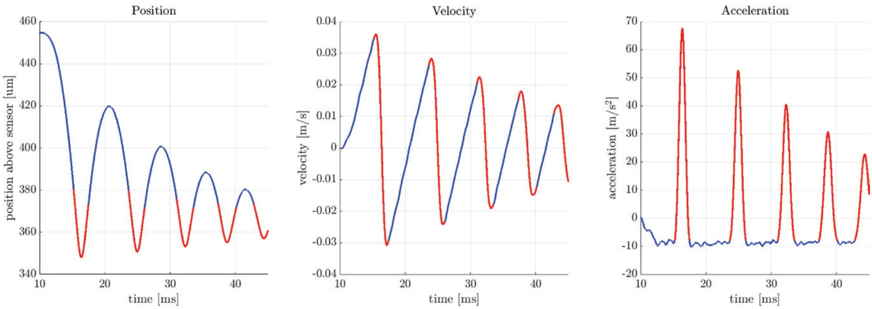

Figure 2. Position (probe position above the sensor z(t)) [µm], velocity [m/s] and acceleration [m/s^2] in the rapid ZD-tester for a single point on a paperboard. Red lines are filtered as parts where the acceleration is larger than –8 m/s^2 (equivalent to a pressure larger than 18 kPa).

pressure as in the rapid ZD-tester, Figure 3a, compression to a lower maximum pressure, Figure 3b, increasing the maximum pressure with each pulse, Figure 3c, and decreasing the maximum pressure with each pulse, Figure 3d. It should be noted that the zero-point is set at 18 kPa for later comparison to the rapid ZD-tester, and the displacement is shown in micrometres rather than strain since a rotary printing press is set by adjusting the gap in micrometres, not by any relative strain measurement of the materials involved.

In the time frame (5 s recovery between pulses) there is unrecovered thickness between the first and second pulse, when the maximum pressure (σ_{max}) of the first pulse is equal to, or larger than the second pulse ($\sigma_{max_1} \geq \sigma_{max_2}$) as pointed out in blue in Figure 3a, b and d. When successively increasing the maximum pressure with each pulse ($\sigma_{\max_3} > \sigma_{\max_2} > \sigma_{\max_1}$) they form a connecting line down (during compression), pointed out in green in Figure 3c. A typical behaviour shown in other studies of out-of-plane compression of paper and paperboard [23]–[25], [30]. The third type of behaviour shown in all three paperboards is the collapsing of the curves for pulse 2 and 3 when the maximum pressure in a pulse is either equal to or smaller than the first one ($\sigma_{\max_1} \geq \sigma_{\max_2}$) and the third pulse has a maximum pressure equal to or smaller than the second one ($\sigma_{\max_2} \geq \sigma_{\max_3}$), pointed out in orange in Figure 3a, b, d.

All three paperboards in the present study exhibited the three types of behaviour described in Figure 3 in slow compression with 5 s recovery and are therefore assumed to be paperboards with common compressive behaviour. Additionally, the non-recovered thickness between first and successive pulses when cycling to 0.7 MPa cannot be merely attributed to the maximum pressure, since the same behaviour is seen when cycling to lower maximum pressures, as demonstrated in Figure 3b.

The measurement procedure illustrated in Figure 3a (three consecutive pulses to 0.7 MPa) was performed on 40 measurement points on each of the three paperboards. The mean pressure-displacement curves from these 40 points are shown in Figure 4. In terms of total compression between 0.018–0.7 MPa the thinner multi-ply paperboard is the softest (largest total compression) and the single-ply is the stiffest (smallest total compression).

The limitation of the slow compression testing is that the unrecovered material between the pulses could either be due to a permanent deformation of the material or a delayed recovery due to the slow compression. The time between compressions is only around five times the duration of the pulse and might not be enough. Additional measurements would be required to resolve the question of recovery in slow compression.

To achieve a good resolution of the results at low pressures a sensitive load cell is required. This prohibits extending the pressure range within the present study to higher loads. The materials used have been tested in other contexts and beyond the 0.7 MPa they behave predictably at pressures up to several MPa with compaction-increased stiffness.

Since paperboard is inhomogeneous, the initial compression behaviour, at pressures lower than 0.1 MPa, is strongly affected by topology and local thickness. In the context of contact printing the topology and local thickness, and in extension its effect on the compression behaviour of the paperboard, is a factor to take under consideration.

Rapid out-of-plane compression of paperboard is a part of several common processes that involves paperboard. The rapid ZD-tester drops a probe in free fall on the substrate and the material being tested slows the probe and (depending on the elasticity of the material) bounces the probe back into the air. Thereby the deformation due to a millisecond pressure pulse can be recorded.

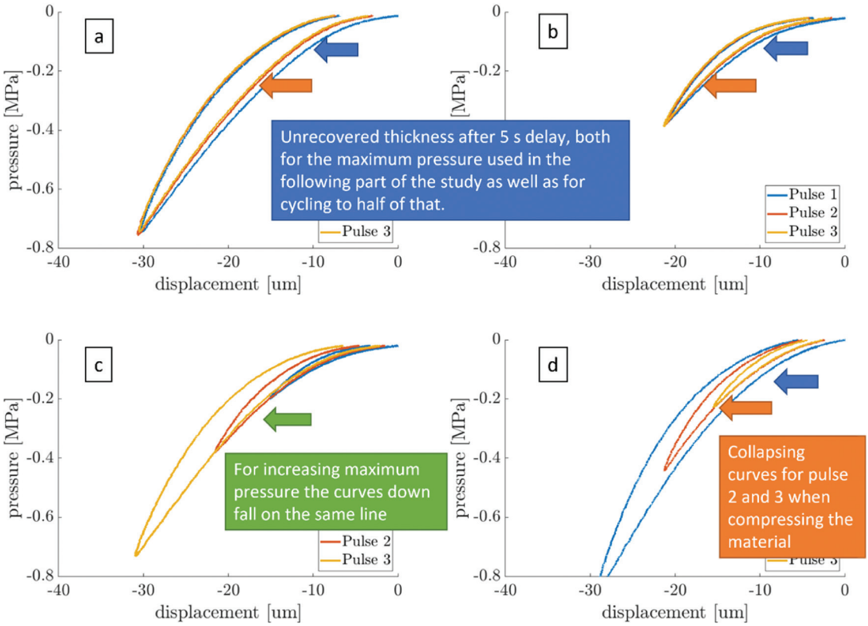

Figure 3. General behaviour of the thin multi-ply paperboard in slow out-of-plane compression. All three paperboards in the study exhibit the pointed-out behaviour in slow compression.

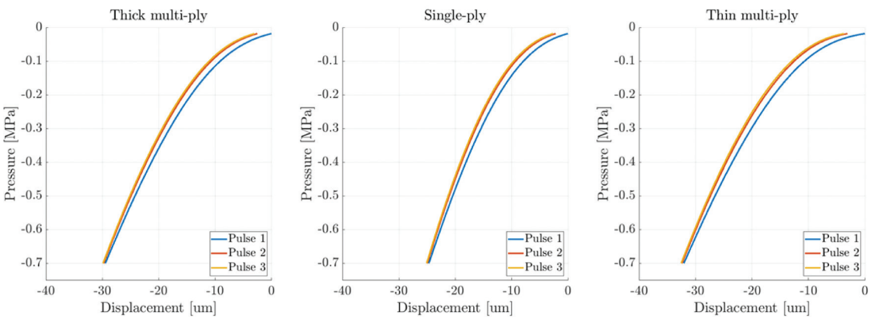

Figure 4. Mean pressure displacement-curves from the UTM-measurements with a delay of approximately 5 s between the pulses. The mean is calculated from 40 measurements. The trigger pressure of 18 kPa is used as zero position in the first compression.

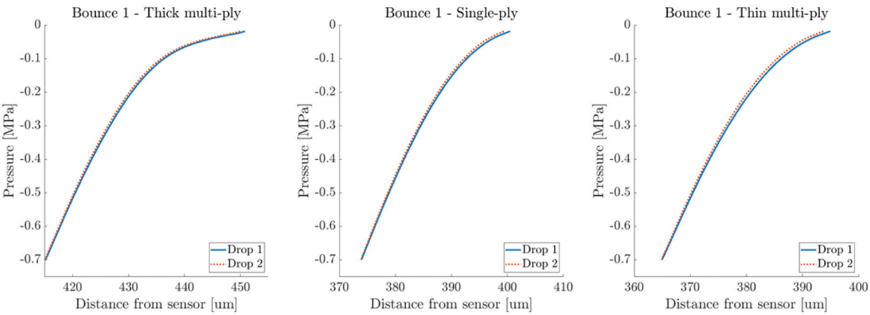

Figure 5. Mean pressure-displacement curves from the rapid ZD-tester with a delay of approximately 5 s between the drops. The mean is calculated from 320 measurement points. The x-axis shows the distance from the sensor underneath the paperboard.

When performing the measurement with the rapid ZD-tester on the three paperboards the initial curves from two consecutive drops overlap or fall very close to each other, as seen in Figure 5. The unrecovered deformation seen in the slow measurements is not present. Thereby implying that the material properties return to almost their original state withing 5 s after the first drop. This behaviour is consistent despite the different ply-structures of the material. The duration of a pulse is 1.5–2 ms, which makes the 5 s delay long in comparison to the duration of the pulse. While the compression in the rapid ZD-tester elicited a more elastic response, as seen in the recovery in Figure 5, the slower loading in the UTM triggered the viscoelastic behaviour which explains the slower recovery in Figure 4.

When displaying the results from the slow and rapid compressions together in Figure 6 the change in material response between the slow and the rapid pulse differs among considered paperboard grades. The stiffness response of the board (in terms of total deformation achieved between 18 kPa–0.7 MPa) does not consistently increase or decrease between slow or rapid compressions but differs between the paperboards. However, the total deformation in the rapid ZD-tester between measurements ranks with the density of the material and the low-density thicker multi-ply paperboard appears to be the most sensitive to the rapid compression. This is further quantified in Table 3 where it also can be seen that the thick multi-ply paperboard has a slightly higher standard deviation than the other two in the rapid measurement results. It should be noted that the actual zero pressure impact position is beyond the range of the measurement data and that the sparse thicker multi-ply paperboard might have reached the trigger pressure of 18 kPa faster in rapid compression due to its low stiffness.

To provide an additional comparison independent of the zero position in Figure 6, the tangential stiffness at the pressure level 0.5 MPa is presented in Table 4. The tangential stiffness at 0.5 MPa is similar for all three paperboards when compared to each other, but slightly higher for the single-ply paperboard. The tangential stiffness is also similar for the two methods, but it is not consistently so for both methods. The multi-ply paperboards show a small increase in tangential stiffness with the rapid method, while the single-ply instead has a steeper slope in the slower measurements. The standard deviation is also very similar between both paperboards and methods.

Although the difference between the tangential stiffness when comparing the two methods is present, it is small. The biggest difference occurs in the initial part of the curve where the behaviour is strongly influenced by the topography or local thickness. The results therefore suggest that the major influence of the rapid compression is both the recovery time, and the initial material response.

The two methods do not work the same way. The UTM compressed the material with a constant speed to a fixed pressure, while in the rapid ZD-tester the paperboard breaks the free-fall of the probe slowing it down until it bounces back up. The velocity drops to zero before the probe is accelerated back up. However, when the probe impacts the surface, it is still accelerating, and the maximum velocity is achieved when reaching pressures close to 0.1 MPa. The maximum velocity of the first bounce is approximately 30 mm/s (see Figure 2) which can be

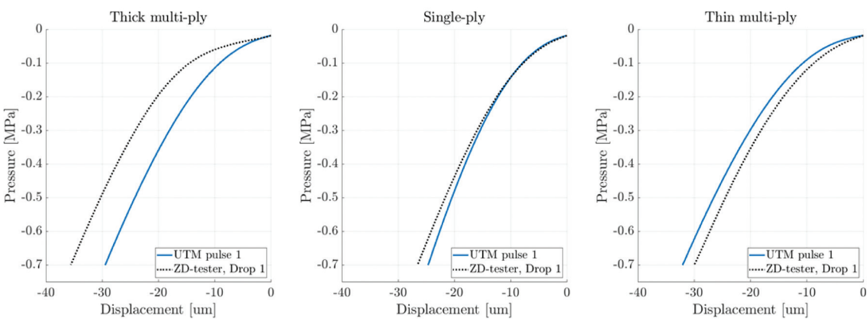

Figure 6. Combination of the mean curves in Figure 4 and Figure 5 to show the differences between the board in slow and rapid compression. The trigger pressure of 18 kPa is used as zero position in the first compression for both methods. The rapid ZD-tester mean curves are calculated from 320 measurement points, and from the UTM the mean is calculated from 40 points.

Table 3. Total deformation [µm] between 18 kPa–0.7 MPa. The rapid ZD-tester mean curves are calculated from 320 measurement points, and from the UTM the mean is calculated from 40 points

	Rapid ZD-tester		*UTM*	
	Mean total deformation [µm]	*Standard deviation* [µm]	*Mean total deformation* [µm]	*Standard deviation* [µm]
Thick multi-ply	36	6	29	2
Single-ply	25	3	25	2
Thin multi-ply	30	4	32	3

Table 4. The mean tangential stiffness at 0.5 MPa and the standard deviation for all three boards and both methods. The rapid ZD-tester mean curves are calculated from 320 measurement points, and from the UTM the mean is calculated from 40 points

	Rapid ZD-tester		*UTM*	
	Mean tangential stiffness at 0.5 MPa [MPa/mm]	*Standard deviation* [MPa/mm]	*Mean tangential stiffness at 0.5 MPa* [MPa/mm]	*Standard deviation* [MPa/mm]
Thick multi-ply	36.0	2.6	35.3	2.4
Single-ply	39.0	2.7	43.8	3.1
Thin multi-ply	35.4	2.4	33.8	2.8

compared to the 0.06 mm/s in the UTM. The probe in the rapid ZD-tester is slowed the same velocity as the UTM shortly before the turning point.

Since the rapid ZD-tester works by releasing its probe in free fall, it is possible to allow it to bounce several times on the paperboard surface before lifting it for the second drop, as illustrated in Figure 2. When the probe bounces on the surface, the maximum height the probe reach after a bounce, and the impact speed of a bounce subsides with each consecutive bounce. This procedure enables some additional information to be extracted about the paperboards.

Figure 7 depicts the pressure-displacement curves of five strike-bounce cycles of the first drop. As shown, the maximum pressure and displacement decreased with each cycle. The shift in impact position at the same trigger pressure to a lower position for the consecutive bounces is much larger than the difference between the pulses in the slower measurements. Due to the full recovery between the drops which we observed in Figure 5, we know that this is not permanent.

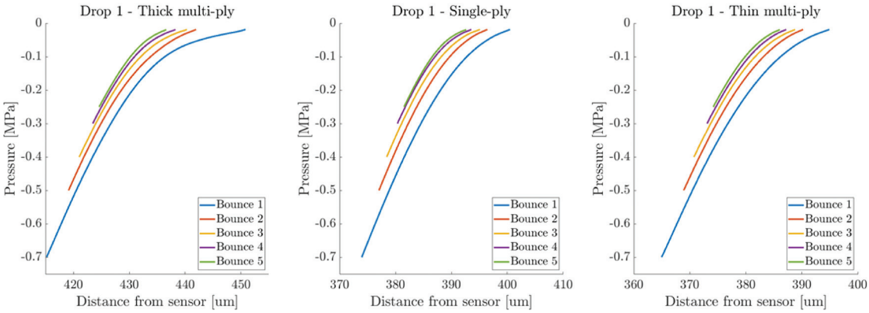

Figure 7. Mean pressure-displacement curves from the rapid ZD-tester from the bounces between the drops in Figure 5.

A possibility is suggested here to explain the lowered impact position for each bounce. It is possible that the milliseconds between impact from each bounce is not enough time for the material to recover in. The recovery time between the first and second bounce is <10 ms, and for each bounce the recovery time decreases. The full recovery that is gained in the 5 s it takes to lift the probe and drop it a second time cannot be achieved in such a short time frame as a few milliseconds, despite the pulse duration also being in the millisecond range. However, since the material response at pressures below 18 kPa are not available, it cannot be completely ruled out that there might also be other mechanisms at work.

Mapping of the Lateral Variations

In the previous sections the results were presented mainly in the form of mean pressure-displacement plots. This last result section will go into the variations, but expand on them a little bit wider than only reporting on the standard deviation tables (Table 3 and Table 4) for the data in Figure 5, Figure 6 and Figure 7. Since the rapid ZD-tester performs the measurements in a grid of 16 × 20 adjacent points, it provides the option of studying the lateral variations in thickness at a given pressure, or the pressure response at heights from sensor of interest.

The colour maps can also be used to ascertain that the mean results are not due to any "weak spots". The lowered probe position at impact at the trigger pressure 18 kPa, seen in Figure 7, is mapped in Figure 8 and show the same lateral patterns in the initial static thickness measurement (described in Table 2) at 50 kPa (left-most column) as in the probe position at 18 kPa for each bounce (columns 2–6). Some distinct structures can be observed, especially in the single-ply paperboard. The white grid-points in the later bounces are rejected measurements. They are due to loss of energy in the bounces where eventually the probe does not leave the surface of the paperboard and the data thereafter is rejected. These points are set as not a number in the calculations of the mean pressure.

In the same manner the pressure distribution can be visualized. In Figure 9 the pressure distribution is presented for each bounce at a fixed height above the sensor set at the mean structural thickness, indicated by the grid line in the mean pressure-displacement curve in the leftmost column of Figure 9. The colour maps echo the height patterns in Figure 8 for all bounces indicating a strong influence of the local thickness on the pressure response at a fixed height. The additional influence of variations in compressibility due to e.g. flocks cannot be ruled out by Figure 9.

A different way of presenting the same data, is shown in Figure 10 and 11. In a printing press, the imprint, or pressure, is controlled by changing the distance between the cylinders in the printing units. And in this printing context, the lateral variations in out-of-plane properties are important.

A starting position above the sensor is calculated as the point where 10% of the paperboard height is detected. This position is indicated by the rightmost *x*-axis grid line on the mean curve in the leftmost column in Figure 10. The position is also noted underneath the pressure maps in the second column of Figure 10 that shows the points in contact and the pressure. From this point, the pressure maps are plotted for each step down of 5 μm at a time. The white areas in Figure 10 are non-contact areas. Their values are counted as zero pressure in the mean and standard deviation calculations, but displayed in white for better contrast and visibility.

As can be observed in Figure 10 the number of steps needed to reach full "contact" varies between the boards and once in full contact, so does the pressure variation. The distinct structure of the single-ply paperboard is again very present. However, comparing the two seemingly smoother multi-ply paperboards to each other shows that it takes longer to reach full contact on the thicker one of the two. Nonetheless, the thin multi-ply paperboard has a larger standard deviation at each step despite reaching full contact sooner than the thick multi-ply board.

Due to the difference in thickness between the paperboards it is not straightforward to compare the materials at the same fixed heights. However, the single-ply and the thin multi-ply share some steps (with an offset of 1 μm). Starting at 397 μm in the second row fifth column for the single-ply and at 398 μm in the third row second column for the thin multi-ply. At the same heights from the sensor, they have different levels of both contact build-up and variations on the sheet, despite their comparable average thickness.

For comparison to the pressure maps in Figure 10, Figure 11 shows the same data, but the steps of 5 μm start at the local height at 18 kPa. The heights above the sensor are indicated as grid-lines in the mean pressure displacement plot in the leftmost column. Zeroing at the local position at trigger pressure erases the patterns from the thickness. At the lowest step, the standard deviation is largest

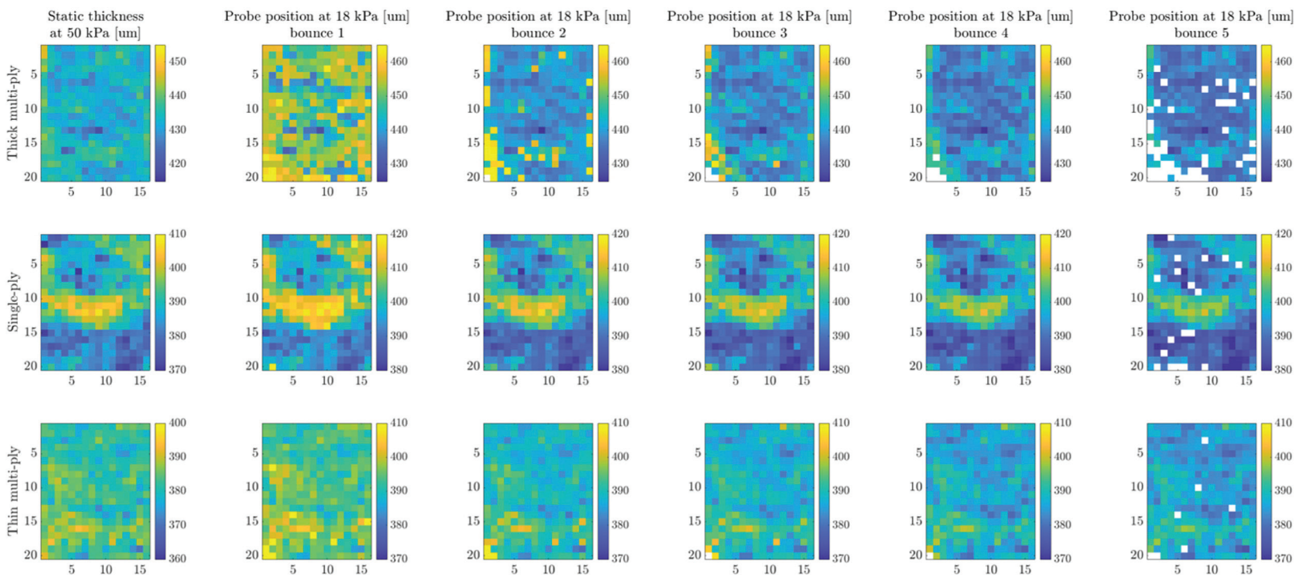

Figure 8. The colormap in the leftmost column shows the initial static thickness measurement at 50 kPa. The probe position at trigger pressure per bounce are in column 2–6. Both measurements in micrometer. White grid-points are rejected measurements set as not a number in the calculations of the mean.

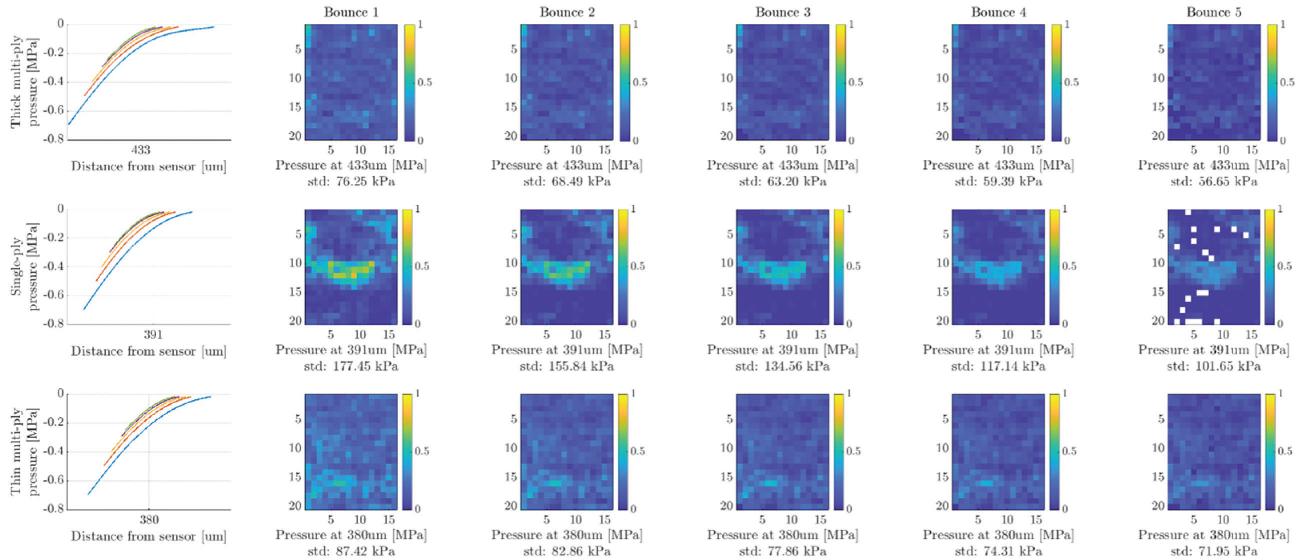

Figure 9. The line plot shows the mean pressure-displacement for the bouces, with the mean structural thickness noted in the x-axis grid line. The corresponding pressure maps at this fixed height from the sensor are shown in the subsequent columns. White grid-points are rejected measurements set as not a number in the calculations of the mean pressure.

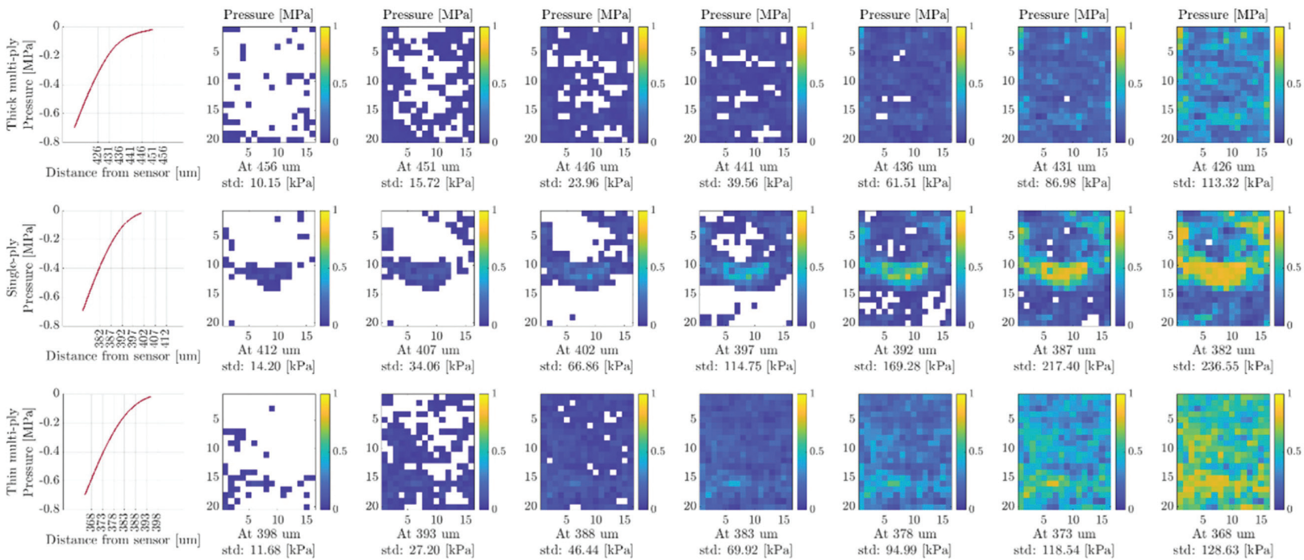

Figure 10. The heights above the sensor at 5 μm intervals are indicated as x-axis grid-lines in the mean pressure displacement line plot in the leftmost column. The pressure maps and the standard deviation in pressure are shown in subsequent columns for the indicated heights. The white, non-contact areas are calculated as zero pressure.

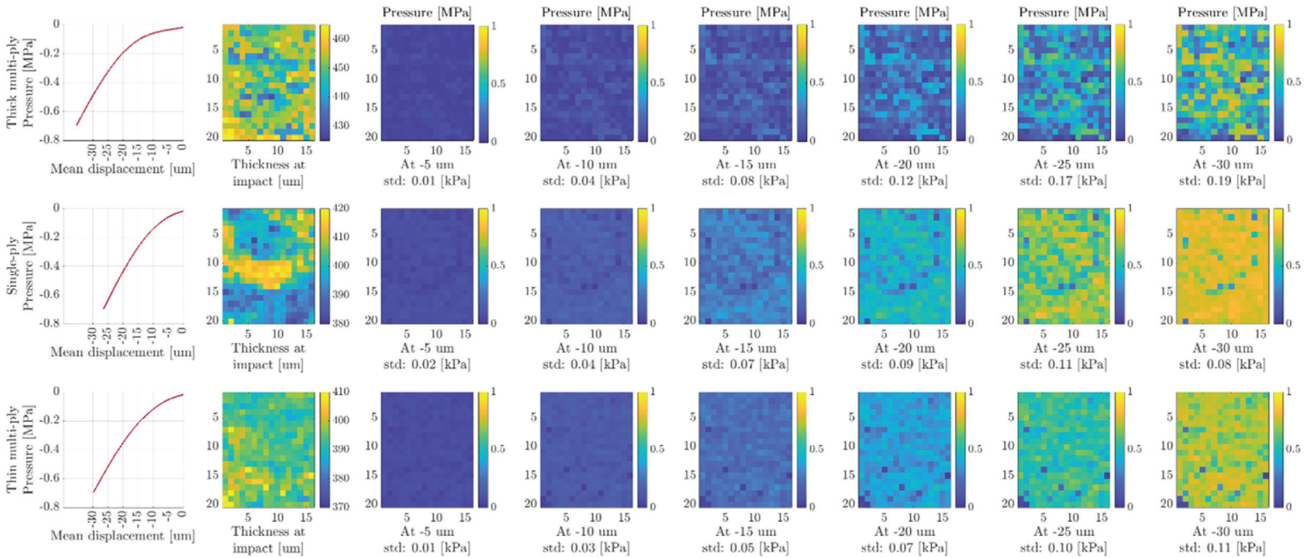

Figure 11. The 5 µm intervals from 0 at the local heights above the sensor are indicated as grid-lines in the mean pressure displacement line plot in the leftmost column. The pressure maps at the corresponding displacements and the standard deviation are shown in columns 3–8. In the second column the local thickness in micrometres at first impact is presented for reference.

for the thick multi-ply paperboard. The large influence of the local thickness indicated in Figure 9 is supported by the results in Figure 11.

CONCLUSIONS

The three different commercial liquid packaging paperboards behaved similarly when tested in slow compression. When compressed in the rapid ZD-tester, all the tested paperboards showed complete recovery within 5 s, while the slower UTM-compression to the same pressure left a deformation that remained after 5 s. The stiffness response of the board (in terms of total deformation achieved between 18 kPa–0.7 MPa) did not consistently increase or decrease between slow or rapid compressions but differed between the paperboards. The sensitivity to rapid compression appeared larger for the low-density paperboard in the study. The low-density board also exhibited the largest difference in height at 18 kPa between the first and second bounce of the rapid ZD-tester probe on the surface.

The rapid ZD-tester provides out-of-plane results in a speed range that is far from common measurement methods and provides a convenient way of mapping the lateral variations of the out-of-plane compressibility, which could be linked to printing quality metrics or be used in modelling. The adjacent measurements over the surface enable the study of lateral variations in the pressure response at fixed heights from the sensor, or to consider how pressure is built up across the sheet. When studying compressibility from a printing perspective, this is a feature of interest, and the colour maps illustrate how the different boards respond and the variation in pressure build-up between them.

The possible delayed recovery of the compressed material in the millisecond scale between bounces are also of interest in processes with consecutive nips and high speed, e.g. printing. Assuming that the “lowering of the surface” between bounces is at least partly due to delayed recovery, a paperboard that makes a good packaging material (low density bulk for high bending stiffness) might require more changes in settings between consecutive nips than a denser material.

ACKNOWLEDGEMENTS

A special thank you to Lars Granlöf (RISE) for his work on the rapid ZD-tester. This work has been granted by STFIs Intressentförening (STFIs Association of Interested Parties) and strategic competence-funds from RISE Research Institutes of Sweden.

NOTES

1 A hydraulic machine with a 100 N load cell.
2 The structural thickness is measured in accordance with SCAN P88:01 which provides a value slightly lower than calliper thickness, thus resulting in a starting point 200 μm above the structural thickness rather than the intuitive 150 μm to get a delay of 5 s with a piston speed of 60 μm/s.
3 Using MATLAB's built-in function diff.
4 Same pressure as in Thickness (Calliper) of Paper, Paperboard, and Combined Board T 411 Om-97, Tappi Test Methods. Tappi Press, 2001, but with a calliper (probe) size a third of the diameter than the one in the standard.

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MECHANICAL RESPONSE OF PAPERBOARD IN RAPID COMPRESSION – THE RAPID ZD-TESTER, A MEASUREMENT TECHNIQUE

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Joel Pawlack North Carolina State University

A couple of questions for you. You mentioned tangential stiffness? Did you calculate any values?

Cecilia Rydefalk

Yes, I did. I don't have them in my head, but they are in the manuscripts.

Joel Pawlack

And then the second question I have related to that is, it looks like you're calculating it during the compression phase as tangential values. Traditionally, you don't do that because there's plastic deformation that's involved in this that skews those numbers. Why did you do it during the compression phase and not during the decompression phase?

Discussion

Cecilia Rydefalk

The reason we always look at the compression phase is that we are concerned with printing, and what happens during that process. And in that context the compression phase is more important. Considering the question, and other discussions during the past two days, I have seen other metrics being extracted that would also be interesting to consider.

Joel Pawlak

I would suggest you gain some insight by looking at the decompression phase. And also, maybe you could comment on how the slow tangential stiffness from the slow compression versus the fast compression differs.

Cecilia Rydefalk

There is very little difference. I think the only noticeable difference was in the single ply, but they are very close.

Karin Zojer Graz University of Technology

As you see, I'm perfectly unfamiliar with the concept of eddy current sensors. Could you explain me in short words, how the eddy current is translated into a voltage?

Cecilia Rydefalk

The probe is made of metal, that gives a signal when it comes within the magnetic field of the eddy current sensor. It is output in voltage that is then translated to a distance between the sensor and the metal probe. Which is why we have to figure out where the probe actually comes in contact with the paperboard, because we don't really measure the paperboard but the probe position. Did that make sense?

Karin Zojer

Okay. Perfectly. I was confused whether you're referring to electrical current or to the current induced by the flux, which could also be an interesting information. Yes, but it's the metal probe.

Robert Pelton McMaster University

I was just curious; do you ever try painting a layer of ink on your probe and dropping it and seeing if that affected the result?

Cecilia Rydefalk

I want to do that. But the distance is only around 80 microns, which is very short. You would have to figure out the application and drying of the ink, among other things.

Joel Panek

What should we expect? I mean, why would you want to look at ink?

Cecilia Rydefalk

I guess it could say something about the contact, depending on how much or what kind of ink is put on the probe, of course. Since the probe won't deform (unlike a print form). As to whether or not it would affect the mechanical properties, that's a different question.

Ulrich Hirn Graz University of Technology

It is very curious that you get the same modulus for fast and slow compression, right? For fibres we always see viscoelasticity (rate dependency) in stiffness, also when we compress fibres in cross direction. What is your take on this, that you do not see any rate effect?

Cecilia Rydefalk

No, at least not here.

Ulrich Hirn

At least not in your data, yes. Probably you discussed it a lot, right, because it is really unexpected. I have no explanation for that.

Discussion

Cecilia Rydefalk

We've talked about it, and we were also a bit surprised that the materials didn't arrange themselves the way we expected. We get a different total deformation, but the same tangential stiffness. So, there is more to try to figure out. I am happy to get some feedback and talk about it because I do not really have any answers here.

Anton Hagman RISE Research Institutes of Sweden

When we set out to do this, a consistent shift was what we expected to see. I have an additional comment to the earlier question regarding plasticity. Since these curves generally recover completely, is there any plasticity going on?

Peter de Clerck PaperTec Solutions Pte Ltd

Multiply sheets have different formations, different fibre structures within them, and often different furnish materials. These will have different energy absorptions and different coefficients of restitution, which will affect the bounce and the distribution of stress as you penetrate deeper into the layers. Have you considered this at all in your work?

Cecilia Rydefalk

Not in the sense that we go into the mechanisms, but because it is as you say, the materials were selected to have these differences. The study included both single- and multiply material of different densities for this reason.