Dynamic out-of-plane compression of paperboard — Influence of impact velocity on the surface

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ABSTRACT: Processes that convert paperboard into finished products include, for example, printing, where the paperboard is subjected to rapid Z-directional (ZD) compression in the print nip. However, measuring and evaluating the relevant properties in the thickness direction of paperboard are not necessarily straightforward or easy. Measuring at relevant, millisecond deformation rates further complicates the problem.

The aim of the present work is to elucidate some of the influences on the compressive stiffness. Both the initial material response and the overall compressibility of the paperboard is studied. In this project, the effect on the material response from the surface structure and the millisecond timescale recovery is explored.

The method utilized is a machine called the Rapid ZD-tester. The device drops a probe in freefall on the substrate and records the probe position, thus acquiring the deformation of the substrate. The probe is also allowed to bounce several times on the surface for consecutive impacts before being lifted for the next drop. To investigate the time dependent stiffness behavior, the probe is dropped several times at the same XY position on the paperboard from different heights, thus achieving different impact velocities. The material response from drops and bounces combined allows study of the short-term recovery of the material. The material in the study is commercial paperboard. The paperboard samples are compared to material where the surface has been smoothed by grinding it.

Our study shows that there is a non-permanent reduction in thickness and a stiffening per bounce of the probe, indicating a compaction that has not recovered in the millisecond timescale. Additionally, a higher impact velocity has an initial stiffening effect on the paperboard, and this is reduced by smoothing the surface.

Application: This study shows that the surface and its structure play an important role in rapid ZD compression of paperboard, which is relevant in contact printing applications.

Commercial paperboard for packages is a laminate structure often consisting of several layers of different fibers that provide different mechanical properties. The thickness of a paperboard is often no larger than around 500 µm. On top of the fiber structure is a coating layer consisting of latex and pigments that achieves a smoother surface that is better for printing. Dynamic out-of-plane compression of paperboard is important to several industry processes, such as contact printing, where the compression in the print nip will affect the ink transfer and therefore the print quality. In a printing press, the pressure pulse is in the millisecond range, but standard methods for measuring material properties in compression are slow in comparison. However, correct evaluation of the interplay between the different layers, materials, and variations enables better material design.

The compressive stiffness of different plies can also be separately evaluated to determine their relative influence on the whole structure [1,2]. Similar to the studies on separate plies, the compressive stiffness of the coating layer has been studied [3-7]. However, as Rättö shows, the conformability of the coated paperboard surface in compression is dependent on the bending stiffness of the coating rather than the compressive stiffness of the coating layer [8]. Due to the latex, the mechanical properties of the coating layer are dependent on the deformation rate, as is pointed out in Azadi's study [7], for example. The strain rates used in that study were 10 and 0.003 s^{-1}. The compressive moduli of the latex at those rates were 4.6 and 1040 MPa, respectively [7].

Out-of-plane compression measurements of the full structure have been performed in several studies [9-16], but most often under conditions much different from the situation in an industry process. Standard methods for compression testing are usually quasi-static and slow in comparison to a printing press or other converting processes, for example.

Paperboard usually has an average thickness of less than 500 µm, and in the present study, less than 400 µm. The structural and textural variations of a paperboard are a few micrometers but cannot be disregarded, especially when considering out-of-plane properties related to processes such as printing. The variations in structure and the surface roughness will also influence the shape of the Z-compression curve. The thinner the paperboard, the larger the influence of the surface roughness [17]. To measure the compression response in the Z-direction (ZD) without the influence of the surface roughness, the paperboard can be glued to the testing platens [18,19]. Measuring this way is more cumbersome, but it shows that the initial soft part of the compression curve disappears and instead a more linear response is seen. For this reason, the compression modulus EZ is sometimes taken from the return curve during offloading instead [20].

In a converting process for a finished paperboard, the combined effect of the mechanical properties of plies and coating, as well as the structure and the structural variation, will all interplay to affect the result. In a previous work by some of the authors [16], the Rapid ZD-tester was utilized as a measurement device, given the contention that material characterization relevant to rapid processes should be measured at relevant speeds when dealing with viscoelastoplastic materials such as paperboard. In that work, it was shown that the material properties of the paperboard remained unchanged between two pulses achieved by the drop of a probe on the surface. The time between one drop and the next in the Rapid ZD-tester is approximately 5 s. However, between the drops, the probe is allowed to bounce on the surface a few times before the probe is lifted for the second drop. For each bounce, the probe position was recorded at a stress of 18 kPa, referred to as "impact position" and "trigger stress," respectively. The impact position was lower for each bounce, indicating either less stiff material response with lower speed (per bounce) or insufficient time to recover between each bounce, with the recovery time here being 1.5–2 ms. The measurements in that study were insufficient to answer which mechanism was at play, delayed recovery or surface softening. A comparison to quasi-static compressive measurements indicated that the largest difference in behavior between slow and rapid measurements occurred in the initial part of the curve.

The aim of the present study is twofold. One is to explore the effect of impact velocity on commercial paperboard in rapid Z-compression. The second is to investigate the effect of the surface roughness on the paperboard's response in rapid Z-compression. In the present work, two approaches have been taken to further elucidate on the behavior of the paperboard in rapid out-of-plane compression. The first is to drop the probe in the Rapid ZD-tester from different heights, thereby being able to compare initial impact at different speeds with the bounces. The second is to grind the surface of the paperboard, smoothing out some of the unevenness.

The hypothesis is that a higher impact velocity will have a stiffening material response that is seen in the initial part of the compression response (shown as a higher impact position at trigger stress); with increased impact velocity, the stiffer response will be seen by the probe reaching the trigger stress earlier, thereby giving a higher impact position. It is also proposed that the initial stiffening response mainly occurs at the surface or top layer of the paperboard. In a previous work by the authors [16], it was speculated whether the lowered impact position per bounce in the Rapid ZD-tester measurements was due to non-recovered compaction or an effect of the lower impact velocity of each bounce. These questions are addressed here by dropping the probe from different heights in the Rapid ZD-tester.

The present study shows that position of impact on the paperboard changes with different drop heights. A lower drop height elicits a softer initial response and registers a lower impact position. However, the decreased impact position per bounce is larger than the effect of different drop heights. The lowered impact position together with a consistent increase in tangential stiffness between bounces indicates that there is unrecovered deformation in the millisecond timescale between bounces. This effect is more pronounced in the lower density paperboard. The study also shows that by grinding away the surface, the difference in initial material response is reduced between the different drop heights, whereas the shift in impact per bounce is largely unaffected by this. We therefore conclude that there is a speed sensitivity, and it occurs mainly in the top layer.

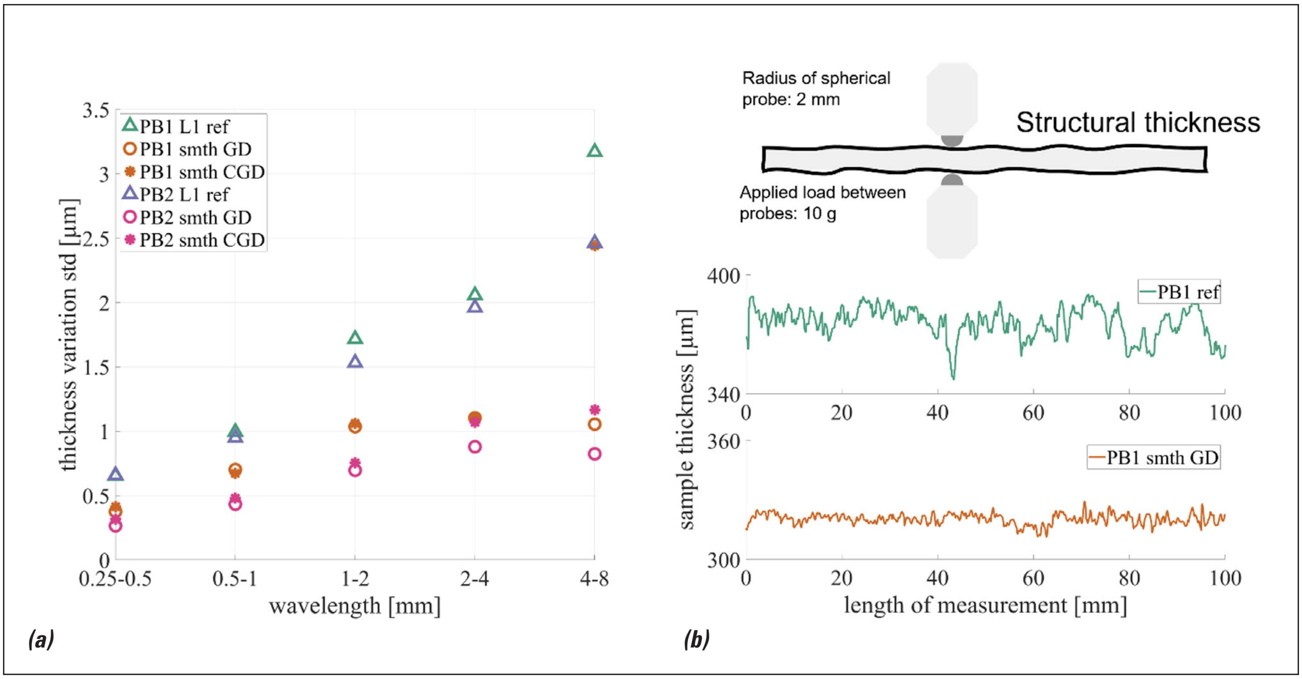
The polymeric print plate that transfers the ink in flexographic printing has a similar stiffness to paperboard when considering quasi-static compression measurements. Quasi-static measurements will, however, not account for the possible stiffening of either material due to the speed of the compression. Conformity between the print plate and the paperboard is essential to achieve good contact and is therefore important in contact printing. The study of the composite paperboard material and the relative influence of its bulk and surface texture is relevant to converting processes such as printing. The non-permanent but unrecovered deformation and stiffening of the compacted network on the millisecond scale could have an effect on consecutive, rapid compressions of print nips, for example.

MATERIAL

Two multiply liquid packaging paperboards (PB1 and PB2) that are intended for flexographic printing have been utilized in the present study. The material properties are presented in **Table I**. The paperboards are commercially produced and consist of several fiber layers, and they both have a one-sided multilayered pigment coating. The pigment coating consists of mineral pigments (e.g., clay or calcium carbonate) and latex binder.

	SCAN P88 Test Method, µm [std]	Static thickness (ZD-tester), µm [std]
PB1_ref	373.7 [8.2]	369 [4]
PB2_ref	393.2 [8.8]	324 [2]
PB1_smth	320.4 [2.7]	395 [6]
PB2_smth	369.3 [2.3]	368 [2]

I. Material properties of the two reference/untouched (ref) and the two smooth/ground (smth) paperboards (PBs) in the study.



1. (a) Thickness variations filtered by wavelength for the two reference/untouched (ref) and the two smooth/ground (smth) paperboards (PBs) in the study, with grinding direction (GD) measurement and cross grinding direction (CGD) measurement. (b) Working principle of the structural thickness measurement is shown at the top, while the bottom shows an example of unfiltered structural thickness data for one smooth and one reference sheet, respectively.

Surface grinding

To assess the material properties while reducing the influence of the surface structure, the surface of the paperboard has been ground down on both sides for a total of approximately 30–40 µm. The grinding was performed by fastening the sheet to an XY table that moves back and forth while a fine-grained, circular, and spinning grinding wheel is lowered onto the surface. The paperboards were smoothed in the grinding machine after the first measurements, and the Rapid ZD-tester results are therefore from the same sheets measured twice. Before the sheets were re-tested, they were reconditioned for at least 24 h. The untouched paperboards will be referred to as "reference" (ref) and the ground samples will be referred to as "smooth" (smth). The PB2 paperboard is much thicker than PB1, which results in PB1_ref and PB2_smth have comparable thicknesses, as can be seen in Table I.

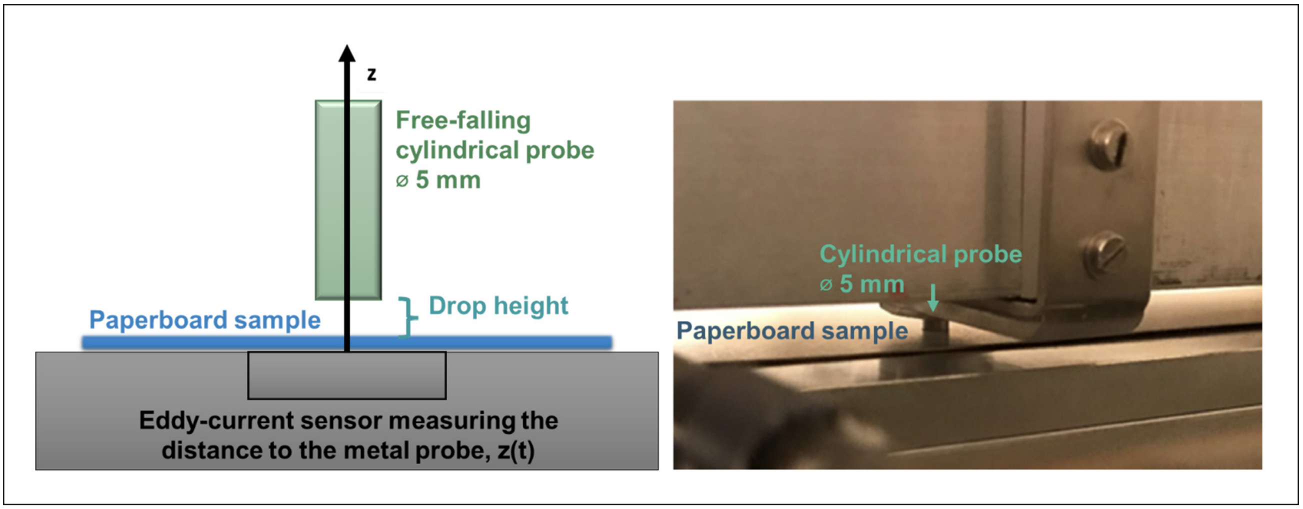
The structural thickness is measured according to SCAN Standard P88 "Structural thickness and structural density" using a mechanical probe traversing both sides at once in a line on the sheet as shown in Fig. 1. The resolution of the measurement is 0.1 mm, and examples of 100 mm measured paperboard, one reference and one smooth, are shown in Fig. 1. The length of the total measurements is approximately 200 mm, and eight different locations were measured on each sheet. The variations in structural thickness are filtered by wavelength, as presented in Fig. 1. The figure shows that the grinding not only evened out the larger scale texture, but the sheets are smoother all the way down to a wavelength of 0.25–0.5 mm.

METHOD

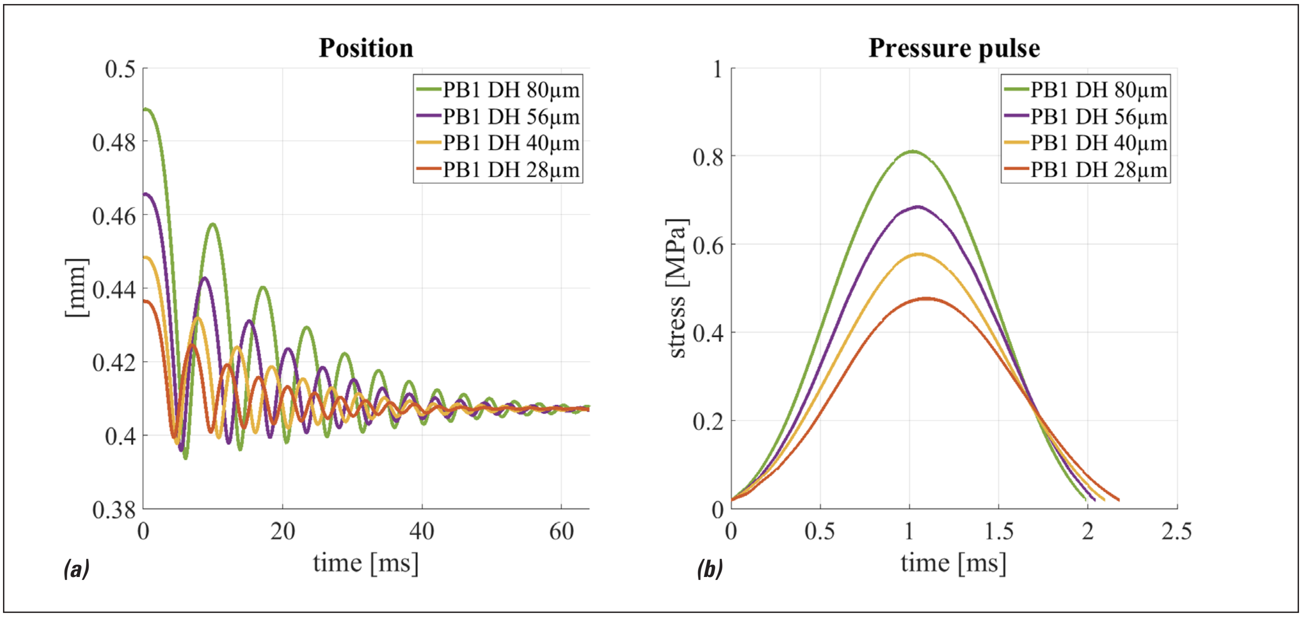
To investigate the effect of impact velocity on paperboard, the Rapid ZD-tester [21,22] has been used to perform compressive measurements. To further assess the origins of the paperboard behavior, the sheets in this study were ground to reduce the texture and structural variations. All measurements were performed in standard climate (23°C, 50% relative humidity [RH]) after sample conditioning of at least 24 h.

The Rapid ZD-tester

The Rapid ZD-tester was patented by Anttila in 2005 [21,22], and it was further developed and described in a previous work by the authors [16]. The purpose of the device is to perform rapid pressure pulses on a substrate on the millisecond scale and with a probe diameter similar to the length of a nip in a printing press. The working principle of the Rapid ZD-tester is to drop a weighted probe in freefall on a substrate. An eddy current sensor underneath the substrate records the position of the probe as it falls, impacts on the paperboard, and bounces. The setup is illustrated in **Fig. 2**. From the recorded position, as shown in **Fig. 3**, the derivatives, velocity, and acceleration are obtained by numerical differentiation. From the acceleration a, the force F and stress σ exerted by the probe on the paperboard are calculated as:



2. The Rapid ZD-tester setup.

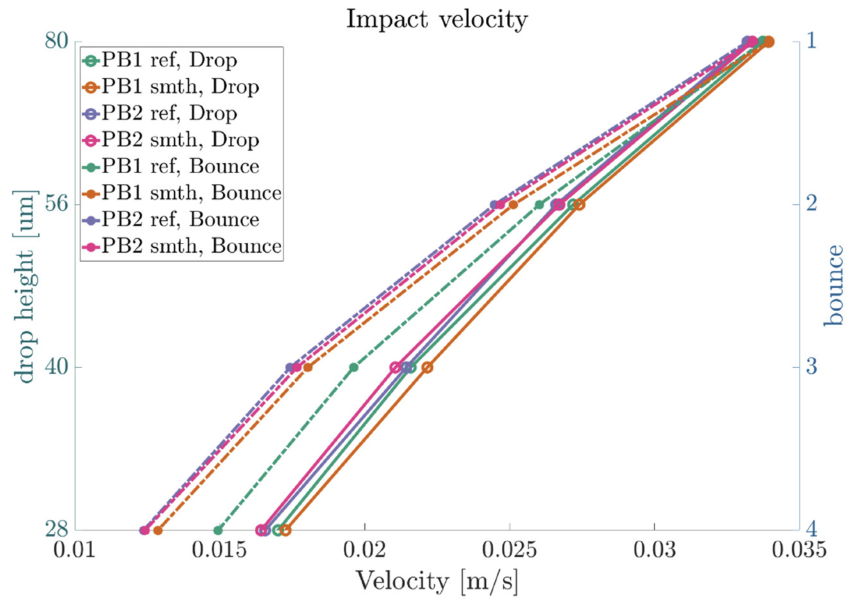


3. (a) Probe position over time from the 4 drop heights (DH), and (b) timescale of the pulse duration and maximum stress for the first bounce of the 4 drops.

$$F = m(a_{\text{gravitation}} - a_{\text{measured}}) \quad (1)$$

$$\sigma = \frac{F}{A} \quad (2)$$

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 is 5 mm (±1 µm) in diameter. The surface of the probe is polished steel. Theoretically, the impact of the probe on the surface is seen as a change in the constant acceleration of a freefalling object; i.e., the stress in the paperboard is initiated when the acceleration deviates from the gravitational acceleration, and the end of the pulse is when the probe returns to constant acceleration. Between those timestamps in the data, the probe is in contact with the substrate, slowing its fall and bouncing back up. We refer to these two points, or timestamps, in the data as trigger stress. In the present work we do not consider the return of the probe, only the part between impact and a maximum stress. Therefore, the trigger stress only refers to the impact of the probe on the substrate. The position and the velocity of the probe at the initial trigger stress are referred to as "impact position" and "impact velocity," respectively. Due to data quality and artefacts introduced by numerical differentiation, the trigger stress is set to 18 kPa instead of 0 kPa. Since the interest in this work is to explore the initial behavior of the paperboard in rapid compression, the trigger stress indicating where the probe meets the surface is set as low as possible. The resulting pulse is approximately 2 ms, as can be seen in Fig. 3.



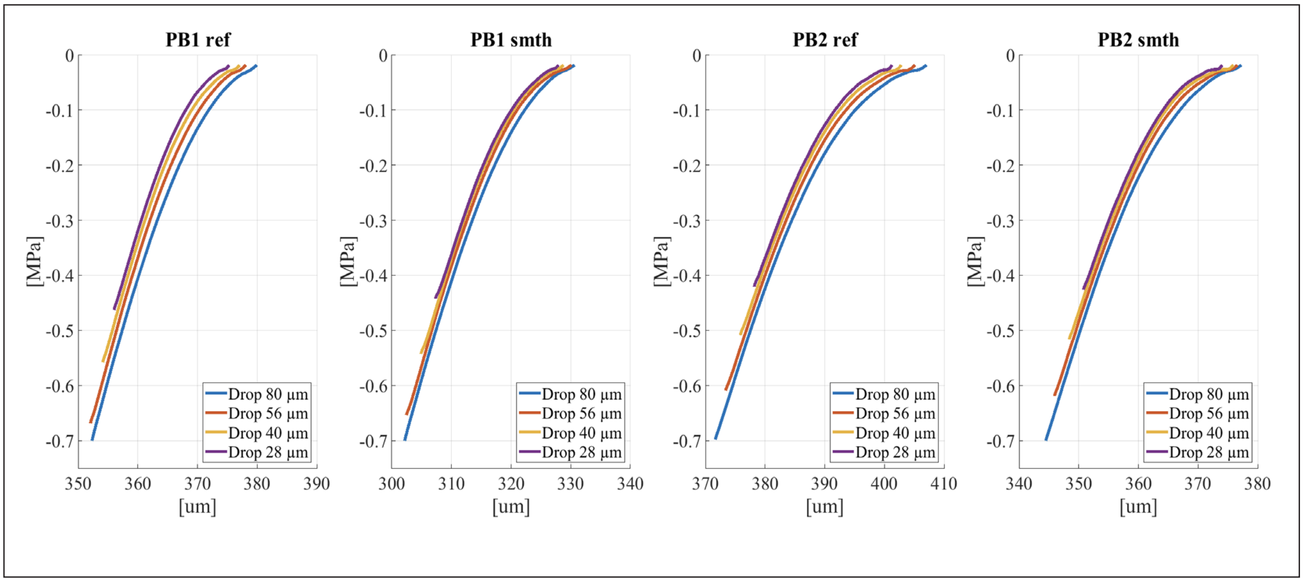
4. Impact velocity, i.e., the velocity of the probe at trigger stress, for the drop heights (solid lines) compared to the bounces (dashed lines) in m/s.

In the Rapid ZD-tester, the paperboard is mounted in a frame on an XY table, allowing measurements to be performed in a grid. In the present study, 16 x 16 grid points are used, providing measurement data in 256 adjacent points, thereby covering an area of 8 cm x 8 cm. In each point of the grid, the procedure is as follows: an initial static thickness measurement is performed by slowly lowering the probe to rest on the surface with a pressure of 50 kPa. The Z-position at 50 kPa is then recorded and used as a reference position. The probe is then raised from this reference position to the set drop height and released in freefall. After the probe has impacted on the substrate, it is allowed to bounce a few times before it is lifted for the next drop. In the present study, the probe is dropped 4 times from increasing heights. After this has been performed in one grid-point, the XY table shifts to perform the same sequence (from static thickness measurement to the last drop height) in the next adjacent point. When comparing the compression behavior in consecutive bounces, the data is always taken from the last and highest drop height (80 µm).

The probe position over time for the different drop heights is shown in Fig. 3 as well as the first pressure pulse over time. The time between drops is approximately 5 s. The drop heights utilized here are (in the following order) 28, 40, 56, and 80 µm. The registered position for each drop in one point on the paperboard PB1 is shown in Fig. 3. The calculated pressure pulse from each drop in one measurement point is shown in Fig. 3, where it can be noted that it reaches a maximum of 0.8 MPa with the highest drop height, and that the pulse duration is approximately 2 ms for all the pulses. A previous study [16] showed that two consecutive drops from 80 µm induced no permanent deformation, and the material recovered in the time it took to raise the probe. Therefore, it is assumed that the deformation is non-permanent and the recovery is complete between drops for the heights used in this study.

Impact velocity

The impact velocity is a direct result of the height from which the probe falls unto the paperboard. In the present work, it is obtained at the trigger stress from the first derivative of the probe position data. The difference between the impact velocity for the drops compared to the bounces can be seen in **Fig. 4**. The left *y*-axis shows the drop heights, and the right *y*-axis shows four bounces from the highest drop height (80 µm) for comparison of the velocity decrease for the respective procedure. The highest point in Fig. 4 is the first bounce from the highest drop height, and thus drop height and bounce coincide. The impact velocity naturally decreases with each bounce, as well as with lower drop height. It should be noted that the velocity decrease for each drop height is a little bit lower than the loss of velocity, due to the repeated impact on the substrate. Additionally, regardless of the paperboard, the probe hits the substrates with the same velocity when the probe bounces, except for the reference sheet of PB1. Since the impact velocity is a result of the height from which the probe freefalls, it means that the arch the probe makes between impacts is slightly higher for this material, which is an indication that the material has a lower damping than the other samples. However, since the trend in velocity decrease per bounce or drop is similar between both of the different paperboards and the drop vs. bounce, the trends in material response will be plotted for the respective drop or bounce and not the velocity.



5. Stress-position curves for each paperboard and drop height.

RESULTS AND DISCUSSION

The present study utilizes the compression performed by the Rapid ZD-tester to investigate the speed dependence of paperboard at high compression rates. The different drop heights mean different impact velocities on the paperboard. To investigate the origin of the observed behavior, the reference paperboards are compared to the smoothed samples where the surface has been ground away and smoothed.

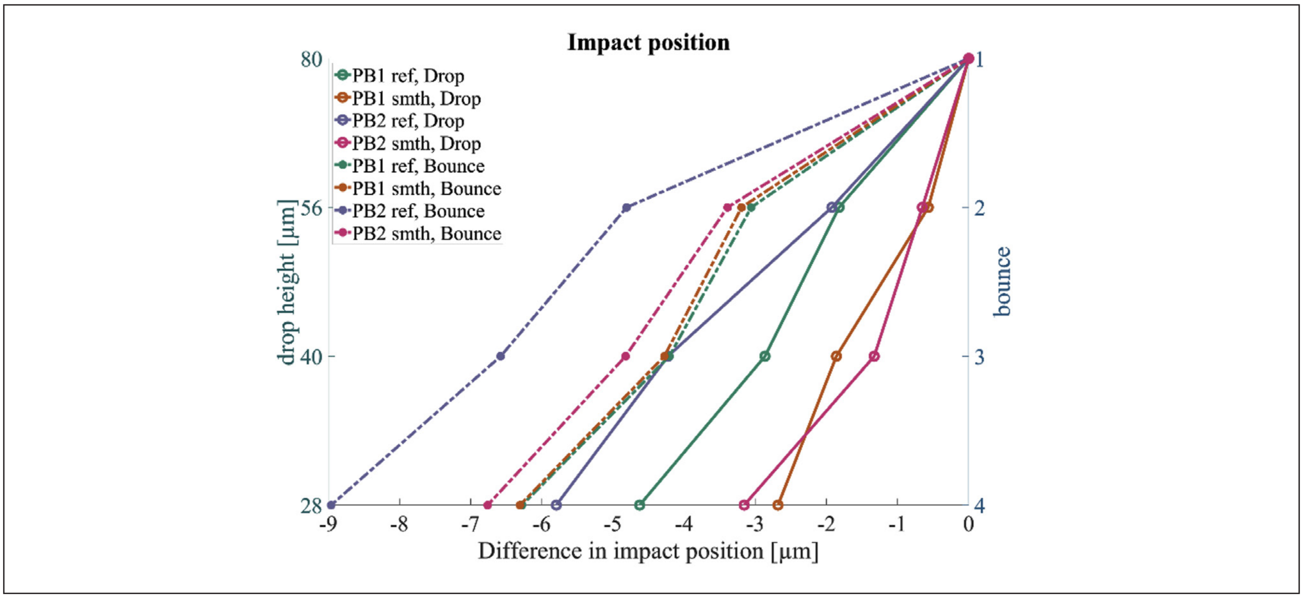
Initial stiffening response to higher impact velocities

The proposition that there is a stiffening due to the impact velocity was tested by dropping the probe in the Rapid ZD-tester from different heights. In **Fig. 5**, the stress-position curves from the different drop heights for the paperboard samples are presented. It should be noted that the drop from the lowest drop height is performed first. The *x*-axis shows the distance from the sensor underneath the paperboard. The impact position, the start of the curve, shifts up with higher drop heights. A previous study utilizing the Rapid ZD-tester [16] showed complete recovery of the material in the time it took to lift the probe and drop it again (approximately 5 s) from 80 µm, which is the highest drop height utilized here. It can therefore be assumed that the behavior shown in Fig. 5 is not affected by any delayed recovery between the drops. Secondly, the same study showed the complete recovery behavior for two consecutive drops from the highest drop height utilized here (80 µm), and it can therefore be assumed that the lower pressures would not induce any permanent deformation. Thirdly, the drops are performed from low-to-high drop height to ascertain that the highest pressure is performed last, again to ensure non-permanent deformation. The higher impact position at the highest drop height could therefore be attributed to an initial stiffening due to a higher impact velocity.

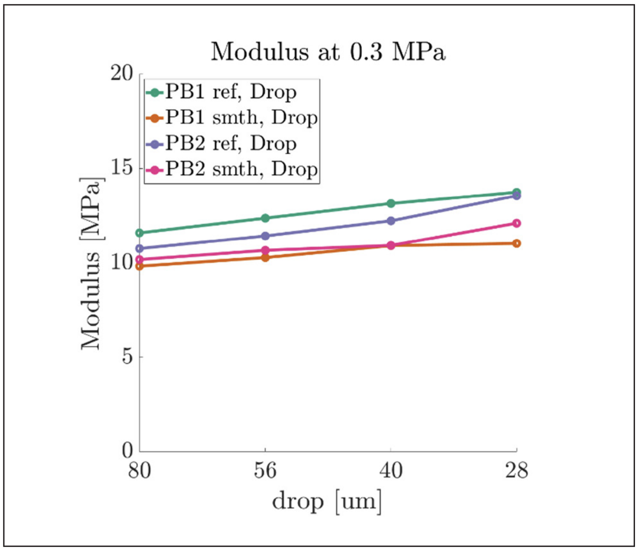
Influence of surface structure

To further investigate the source of the stiffening behavior, the paperboard samples had their surfaces ground down and smoothed. After reconditioning, they were tested in the Rapid ZD-tester again. When comparing the shift of impact position on the smoothed paperboards with the reference boards in Fig. 5, the shift is smaller for the smooth paperboard. The difference in mean impact positions is also presented in **Fig. 6**, where the solid lines denote the different drops. The difference between the first and last point of the smoothed samples is smaller than for the two reference samples (about half for PB2 between smooth and reference). The change in impact velocity shows a much smaller influence on the ground sheets, which leads to the assumption that that the surface and its structure is the most impact velocity-sensitive part. It is well documented that the surface roughness plays an important part of the initial behavior of the compression curve [18,23,24] and that the resulting curve would have a steeper shape. It is not unreasonable that the impact velocity might have an effect on the registered impact position when changing the surface structure, considering the stiffness increase of the latex at rapid compression [7].

The measurements were normalized with the impact position of the highest drop height to account for the differences in thickness. For further comparison of compression stiffness between the drops and bounces, a stress level of 0.3 MPa was chosen. For each bounce or for each lower drop height, the maximum stress that is reached is decreased. This stress level was selected because 0.3 MPa was the highest stress achieved in all the drops and



6. Decrease in impact position for each drop height (solid lines) and bounce (dashed lines).



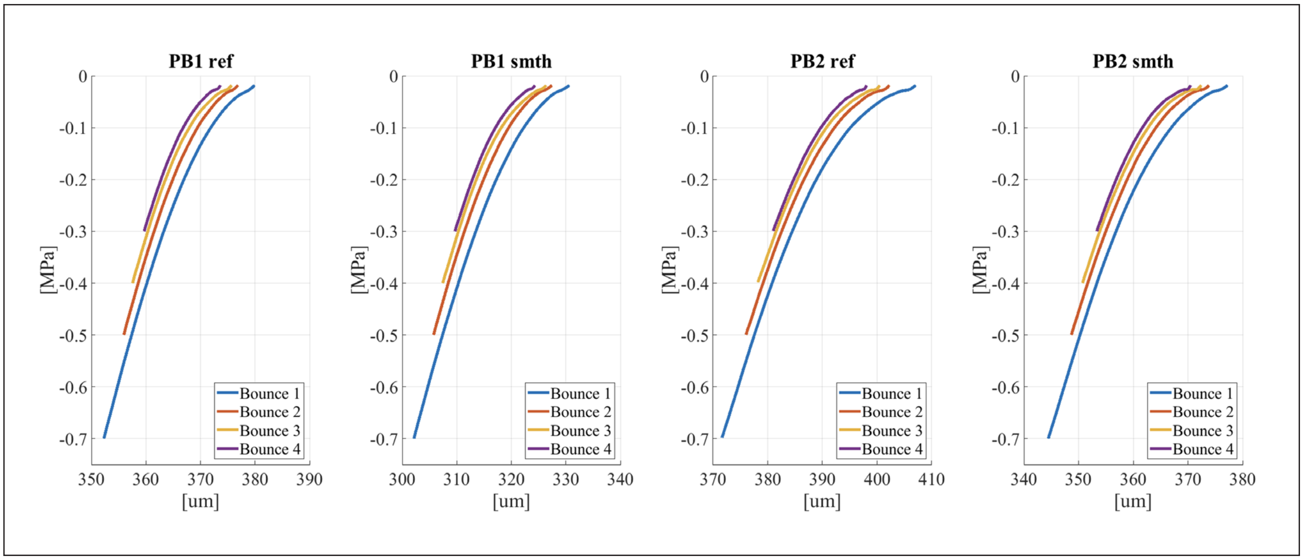
7. Modulus at 0.3 MPa for the reference and smooth paperboard samples per drop height.

bounces. A closer look at the modulus at 0.3 MPa is shown in **Fig. 7** in MPa per drop height. The samples show a small tendency of grouping per quality. Regardless, the difference in modulus between the reference measurement and the smoothed sample is small. Additionally, the difference between the different drop heights is also small. At the stress level of 0.3 MPa, the contact between the probe and substrate has been established, and the deformation should take place in the fiber network. That the difference between the different drop heights is small at this stress level further indicates that the largest effect of rapid compression is initial and at the surface. A previous study showed that the tangential stiffness of the paperboards was almost the same when comparing the Rapid ZD-tester measurements with the almost 1000 times slower measurements from a universal testing machine [16].

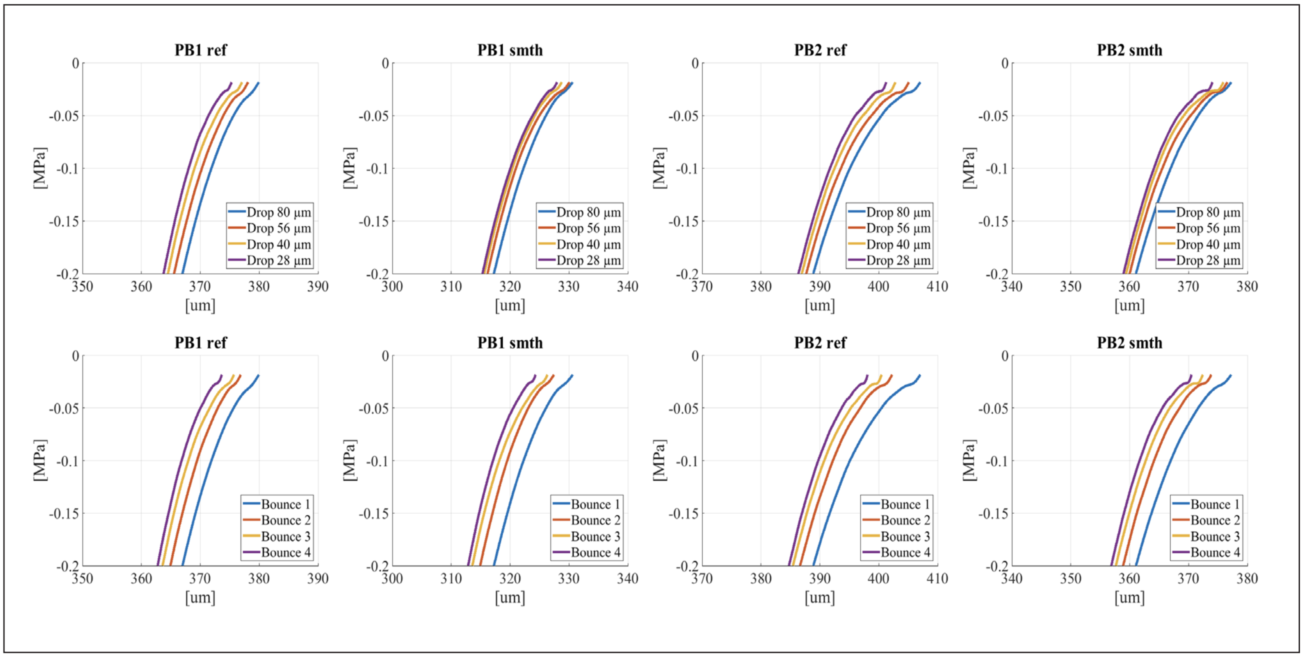
Unrecovered thickness on the millisecond scale

The probe in the Rapid ZD-tester is dropped and allowed to bounce on the substrate a few times before it is lifted for the next drop. In **Fig. 8**, it is shown how the impact position shifts down with each consecutive bounce of the probe on the paperboard. This behavior was noted in a previous study [16], where it was speculated to be either an effect of unrecovered material on the millisecond scale or an effect of decreased impact velocity per bounce. The size of the shift between first and last bounce is similar between the untouched paperboard and the one with the ground surface. The observation that the size of the shift of impact position is similar between ground and untouched paperboard when the probe bounces suggests that the effect originates in the network structure of the material and not in the interaction with the surface; i.e., it confirms the theory of unrecovered compaction between bounces.

When comparing closeups of the first part of the compression curves in **Fig. 9**, the shift of impact position is seen to be present in all cases. As previously noted, the shift between drops on the smoothed paperboards is less pronounced than on the reference measurements. When comparing with the shift in impact position between bounces for each paperboard, it can be noted that the difference in how much the position shifts between reference and smoothed is markedly less than between drops. Additionally, the shift in impact position on the reference measurements is larger between bounces than between different drop heights. The absolute difference from the first bounce and highest drop height is also presented in Fig. 6.



8. Stress-position curves for each paperboard and bounce.



9. Close-up of the stress-position per drop height on the top row, and per bounce of the highest drop height on the bottom row.

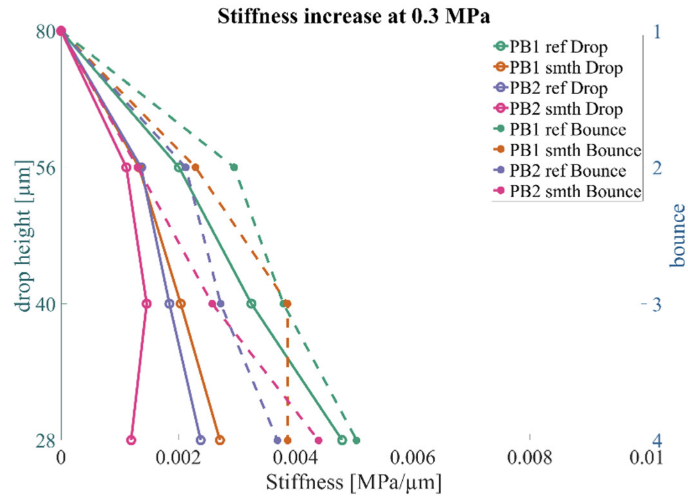
The smaller difference between drop heights than between bounces also strengthens the argument that the lowered surface of each bounce in Fig. 8 is instead mainly a result of delayed recovery.

The ZD compression curve of paperboard shows progressive stiffness as the material is compacted under compression. By looking at the difference in tangential stiffness at a specific stress, we can compare how it changes with drop heights or bounces. The difference in tangential stiffness of the paperboards at 0.3 MPa compression is presented in **Fig. 10**. The increase in stiffness per bounce is consistently larger than per drop. The larger increase per bounce should be due to unrecovered compaction of the network, leading to a slightly higher stiffness each time the probe bounces.

CONCLUSIONS

The impact position at different drop heights shows that there is an initial stiffening response with higher impact velocity not seen in slower compressive measurements. Also, the stiffening response is concentrated in the surface layer, and smoothing the paperboard reduces the effect of the impact velocity.

The shift in/of impact position between bounces is larger than the shift seen when comparing drop heights. Additionally, the shift between bounces is similar within the



10. Difference in the tangent of the stress-position curve at 0.3 MPa for the drops (solid lines) and bounces (dashed lines).

same paperboard quality, regardless of whether it has been smoothed or not. These results are indicative that there is a non-permanent deformation not yet recovered between bounces.

A small but consistent difference in tangential stiffness between consecutive bounces compared to decreasing drop height is noted. The observation of the stiffness behavior, together with the lowered impact position for both ground and untouched paperboards at each bounce, further indicates that this is an effect of delayed recovery in the network in the millisecond timescale. In contact printing, the contact between substrate and print form is essential for good ink transfer. The understanding of the interplay between surface deformation and paperboard compression and their respective response to increased velocity is important when there is a desire to increase the print speed. **TJ**

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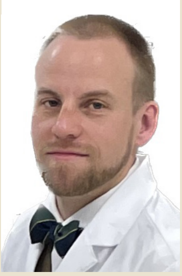

Hagman

Granlöf

Rapid Z-direction (ZD) compression is an important aspect of what occurs in contact printing. The Rapid ZD-tester in this study provides data at rates similar to those of a commercial flexographic printing press. This particular study also confirmed a hypothesis about the recovery that was posed in a previous paper by the authors.

The most difficult aspect of this work was leading up to the study. All experiments were performed close in time to a previous study that showed we had complete recovery on the second timescale, but some other phenomena were occurring on the millisecond timescale. Addressing this and thereby building the present study, as well as considering the implications to printing, were challenging. We addressed these issues by grinding the paperboard and changing the pulses of the Rapid ZD-tester.

The information presented here can help mills provide better suggestions and instructions to the converters on how their paperboards behave, as they will know the properties that are affected by rapid processes.

As a next step, we are continuing with simulations to study the interaction between the textured paperboard and the printing plate.

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