

Mechanical properties of corrugated board as studied by holographic interferometry

Kenneth Olofsson, Nils-Erik Molin, and Anders Kyosti

ABSTRACT: Pulsed holographic interferometry was used to examine the mechanical properties of paper and corrugated board. For determinations using bending wave propagation, the wave was generated by the impact of a small pendulum. The wave propagation pattern and the disturbances of the pattern were analyzed to detect anisotropy, principal directions, and local variations and defects in paper and corrugated board. Experiments show that the local dynamic behavior of the corrugated board is different from what can be expected based on static tests. It is also possible to identify mechanical defects. A box of corrugated board received impact, and the wave propagation was visualized. The support of interconnecting sides of the box acts like a pinned joint.

KEYWORDS: Anisotropy, chemical analysis, chemical tests, cross direction, holography, interferometry, machine direction, measurement, optical measurement, paper, variations.

Recently, we proposed a new method to detect anisotropy and local variations in paper (1). Holographic interferometry with a double-pulsed ruby laser as the light source (2) was used to study bending wave propagation in paper, as others have done with plates and shells (3-7). The paper behaves as a plate during and shortly after impact. Such experiments with paper and paper products are quite easy to perform, and conclusions about the mechanical properties can be drawn from the results. Here, the results are compared with those obtained through traditional methods and with the results obtained through an analytical

solution to the isotropic Kirchhoff plate equation.

Holographic interferometry and bending wave propagation

In the experiments, the bending waves are created with the impact of a small steel sphere of a ballistic pendulum, as illustrated in the first figure of our earlier paper in this journal (1). The pendulum is now equipped with a piezo electric accelerometer. As described in more detail there, a ruby laser is used to record double-exposed holograms that display contours, of equal out-of-plane displacements.

The out-of-plane deformation, w , of an isotropic plate receiving impact from an ideal Dirac pulse in space and time (the limiting special case) is a function of only the parameter β (that is, $w(\beta)$), where β is defined as (4,5):

$$\beta = \frac{r}{\sqrt{at}} \quad (1)$$

In Eq. 1, a is a plate parameter defined as

$$a = \sqrt{\frac{D}{\rho}} \quad (2)$$

where

D = plate stiffness

ρ = mass per unit area of the plate (basis weight)

t = time after start of impact

r = distance from the center of impact to the point of interest.

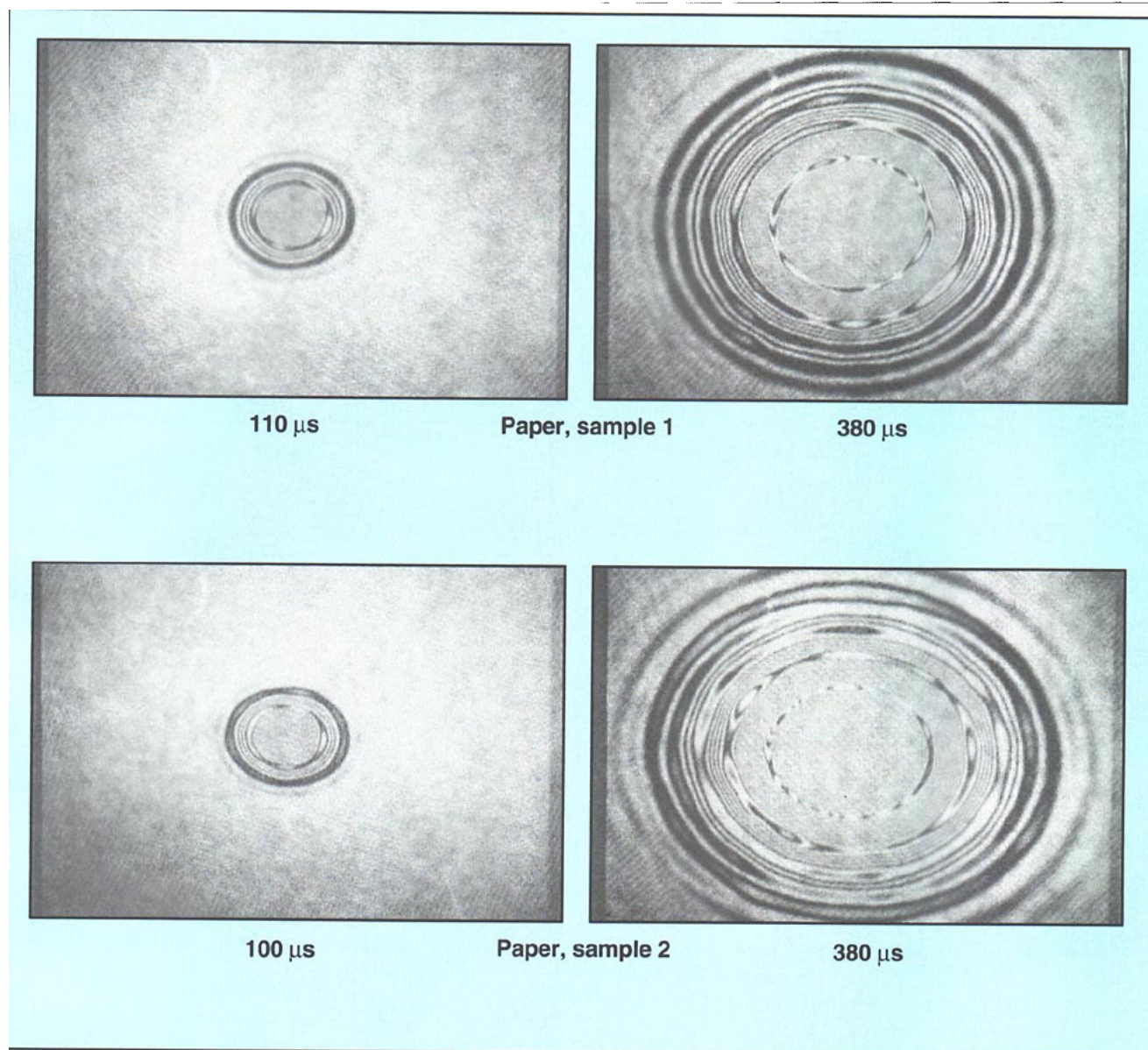
The plate parameter a is thus an important factor in describing wave propagation in plates. The value of β gets small for stiff plates (with a high modulus of elasticity and large thickness) combined with a low basis weight. The out-of-plane deformation in the ideal case of a Dirac pulse impact can therefore be of constant value (that is, a constant β) for different combinations of r and t . A more detailed description of holographic interferometry and bending wave propagation is given elsewhere (1, 2, 4, 5).

Experiments with paper

Experiments with two different papers were reported in full earlier (1). The samples were made of unbleached

Olofsson and Molin are with the Division of Experimental Mechanics, Luleå, Sweden. Kyosti is with SCA Nordliner AB, S-94187 Piteå, Sweden.

1. These interferograms show bending wave propagation in two samples of 400-g/m² paper. [In our earlier article (1), the fifth figure shows the same photographs with additional photos at 250 μ s and 265 μ s.]



linerboard with a basis weight of 400 g/m² produced on a fourdrinier machine.

Figure 1 shows two interferograms of each paper from the earlier work (1). In the upper part are two interferograms of the first sample taken at 110 μ s and 380 μ s after the start of impact. In the lower part are pictures of the second sample in which the times elapsed after the start of impact are 100 μ s and 380 μ s.

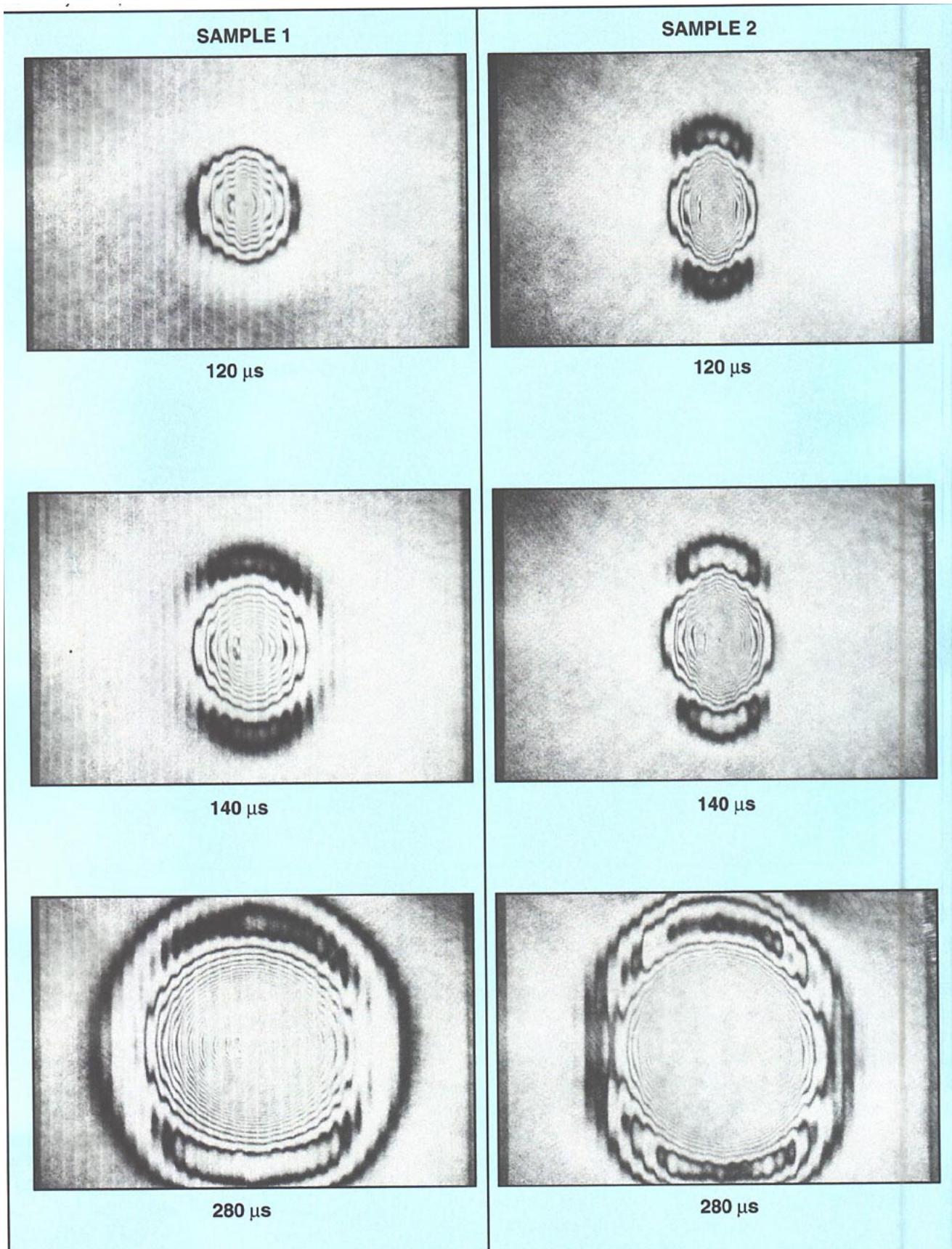
Impact times in both experiments are about 1.5 ms—that is, all interferograms are recorded while the impact is still going on. The wave is already being

propagated as the pendulum is in contact with the paper, still transferring energy to the paper. The central peak is thus growing in amplitude, while the outermost fringes are more the result of the early part of impact.

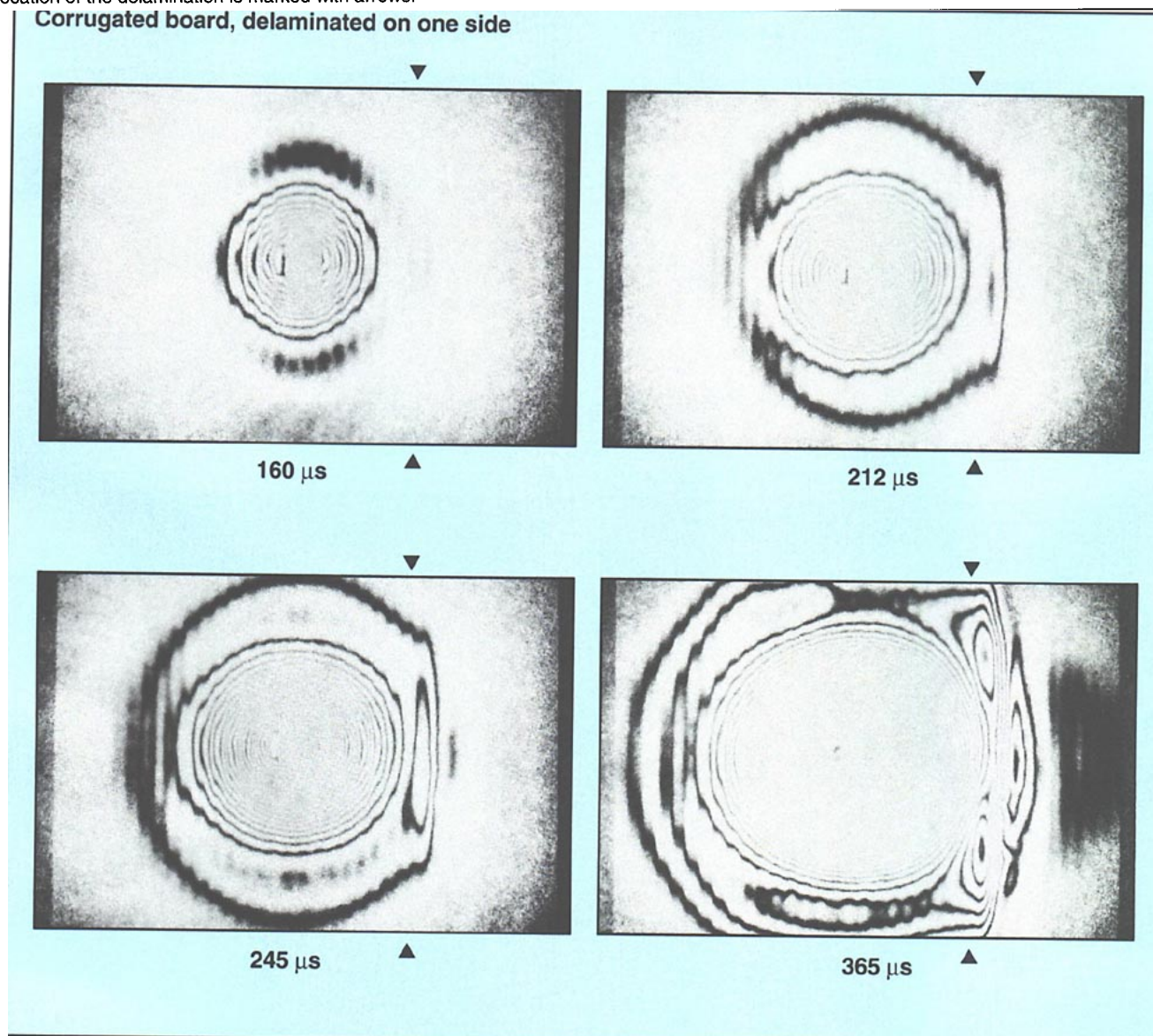
More ripples around the central peak are developing with time. The fringes near the center are so closely spaced that it is not possible to resolve them. The fringe patterns in both papers are nearly elliptical—that is, the wave pattern has different speeds in different directions, indicating anisotropy in the paper.

The interferograms also show that there are minor local variations in the developing wave patterns. These variations result from local variations in the parameter α , which accounts for local parameters of the paper such as density, thickness, modulus of elasticity, and the Poisson ratio—all factors that change the wave impedance of the paper. Some of the local variations seem to be repetitive, indicating that there is some kind of ordered structure in the paper.

2. These interferograms show bending wave propagation in two samples of corrugated board. Sample 1 is of standard quality, and Sample 2 had a tendency to warp.



3. Bending wave propagation in corrugated board is shown in these interferograms. The sample is delaminated along one rib of the fluting. The location of the delamination is marked with arrows.



Experiments with corrugated board

Corrugated board

In the first experiment, we studied two rectangular samples of corrugated board. **Table I** presents the physical parameters. One sample was considered to be of "good" quality. In the second sample the corners had a tendency to lift, instead of the sample staying flat when placed on a desk. For both, the contour was B-flute.

Figure 2 shows three interfero-

grams for each corrugated board sample. The times after the start of impact were 120, 140, and 280 μ s. The impact time can be as long as 1 ms, which means that the impact is still going on, delivering energy and momentum to the board.

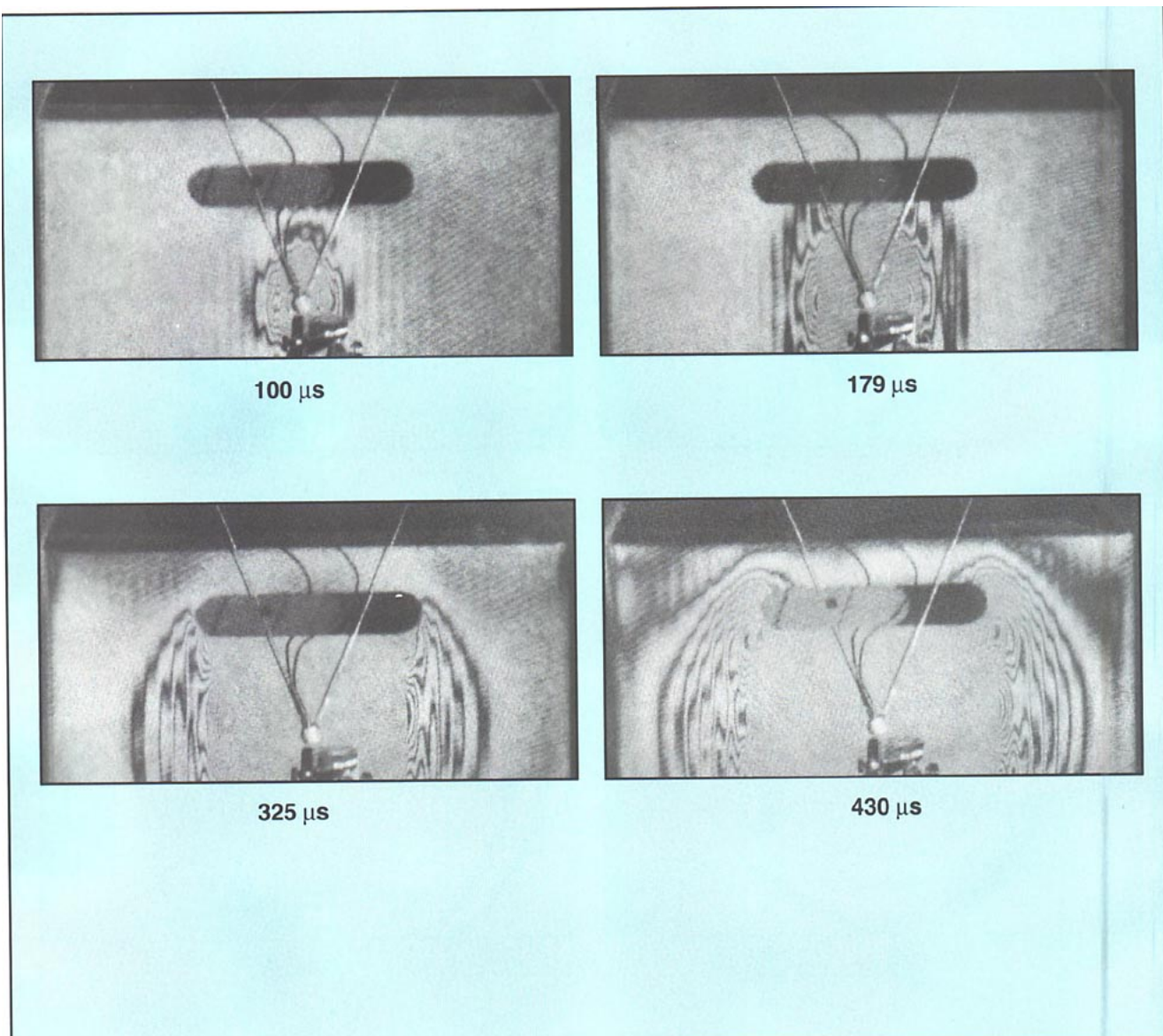
The wave pattern of the standard sample, Sample 1, is more circular than for Sample 2. The valleys in the cross direction in Sample 2 are more concentrated and deeper than in Sample 1.

Corrugated board delaminated on one side

In the second experiment, a corrugated board cut from the same sheet as Sample 1 was deliberately delaminated along one rib of the medium to simulate a defect. No damage can be seen on the surface of the sample.

In **Fig. 3**, four interferograms of the board are shown. The times after the start of impact were 160, 212, 245, and 365 μ s. The location of the defect is marked with arrows. When the wave reaches the delamination, one part of it

4. With the pendulum and sphere in the foreground, these photographs show bending wave propagation on one side of a box of corrugated board with a handle.



is reflected and one part is transmitted. On this side, the wave pattern is disturbed compared with the undisturbed wave pattern on the left side of the sample.

Corrugated board box

Third, we examined a box of corrugated board. The geometry of the box was 255 x 150 x 255 mm. A handle was cut out at the top of the box. The handle had a length of 95 mm and a width of 20 mm with circular ends.

Figure 4 shows four interferograms of the impacted box. The times after

the start of impact were 100, 179, 325, and 430 μs. The pendulum arrangement can be seen in front of the box. The interferograms in Fig. 4 show that the bending wave travels slowly around the handle.

Actually, two sides of the box were studied simultaneously. Only the front side is shown in Fig. 4. In Fig. 5, a mirror is used to illuminate and observe the left side of the box (at right angle to the one seen in the interferograms in Fig. 4).

In the mirror view, we see that only a very small part of the bending wave

is transferred around the 90° corner, meaning that the corner acts like a pinned joint.

Comparison with an analytical solution to the Kirchhoff plate equation

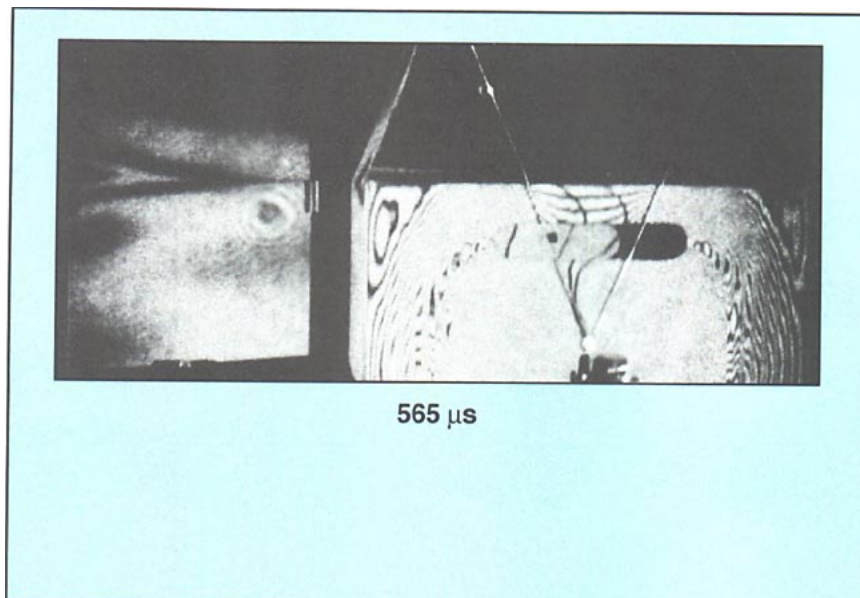
Figure 6 shows a typical signal from the accelerometer of the impacting sphere plotted against time, from the same experiment as in Fig. 2. The impulse lasts for about 1 ms. The interferograms shown in Fig. 2 have a maximum wave propagation time of

I. Parameters for the two samples of corrugated board

	Sample	
	1	2
Dimensions, mm		
MD	239	239
CD	189	189
Thickness, ^a mm	2.99	3.06
Bending stiffness, Nm		
MD	6.75	8.72
CD	2.98	...
Edgewise crush test, ^b kN/m	7.95	8.29
Basis wt., g/m ²		
Linerboard	179.4	195.0
Linerboard	179.4	195.6
Medium	108.4	115.0
Total	467.2	505.6
Density, kg/m ³	156.25	165.23

^a Average of 5.
^b Average of 4.

5. Two sides of the same box of corrugated board as in Fig. 4 are shown simultaneously in this mirror image. The small dark circle in the top right corner is caused by an imperfection in the illumination.



$$w(r,t) = \frac{Aa}{2\pi D} \int_0^\infty \frac{J_0(x)}{x} \frac{\frac{\pi}{T} \sin \frac{\alpha^2}{r^2} t - \frac{\alpha^2}{r^2} \sin \frac{\pi t}{T}}{\left(\frac{\pi}{T}\right)^2 - \left(\frac{\alpha^2}{r^2}\right)^2} dx \quad (4)$$

280 μ s, so the impact is still transferring momentum to the plate as the wave propagates.

Fallstrom *et al.* (4) have given an analytical solution for the impact of isotropic plates, where the impact time T is larger than the wave propagation time t . The force during contact is assumed to be as given in Eq. 3:

$$\begin{aligned} F(t) &= A \sin \frac{\pi t}{T} \text{ for } 0 \leq t \leq T \\ F(t) &= 0 \text{ for } T \leq t \end{aligned} \quad (3)$$

The out-of-plane displacement $w(r, t)$ can then be described by Eq. 4, where

r = distance from the point of impact to the point of interest

a = plate parameter, from Eq. 2

J_0 = zero-order Bessel function

D = bending stiffness of the plate.

We adjusted a sine curve to fit the impact presented in Fig. 6. The mass of the pendulum is 5 g, which gives, together with the acceleration in Fig. 6, the force acting on the board. The out-of-plane displacement $w(r, t)$ was calculated from Eq. 4 for Sample 1 at $t = 120 \mu$ s in the machine direction (MD) and cross-machine direction (CD), where the bending stiffness D in Eq. 4 was substituted by D_{MD} and D_{CD} (Table I). In other words, as a simple approximation, we assume that the plate can be described as if it is isotropic along both main axes of the anisotropy (5).

Since we do not have an analytical solution for the anisotropic case, Fig. 7 shows the displacement $w(r)$ plotted against distance r , comparing experimental data with data from Eq. 4. The

experimental data in Fig. 7 are taken from Sample 1 in Fig. 2 at 120 μ s.

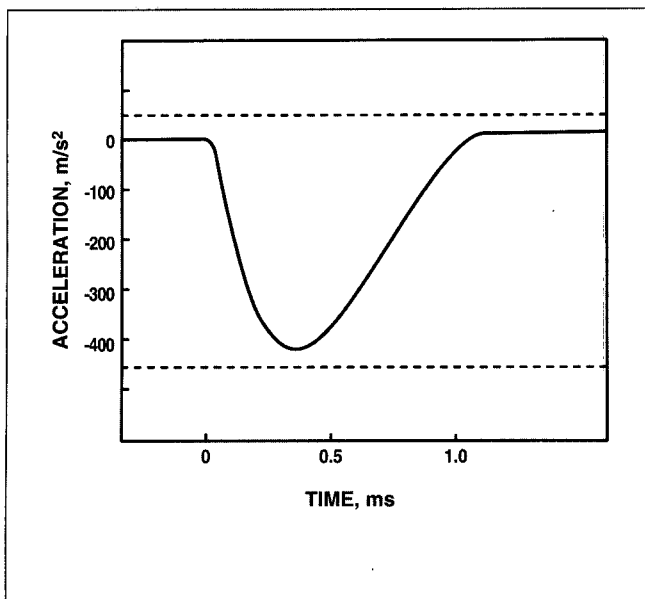
The calculated curves were scaled to fit the experimental amplitude at $r = 0$. The calculated wave pattern is propagating slightly faster in the machine direction than in the cross direction. However, this is not what we observed in the experiments. Instead, it is the wave propagating in the cross-machine direction that is moving slightly faster. Thus, the material responds differently to an overall static load than to a local dynamic load.

Static vs. dynamic tests

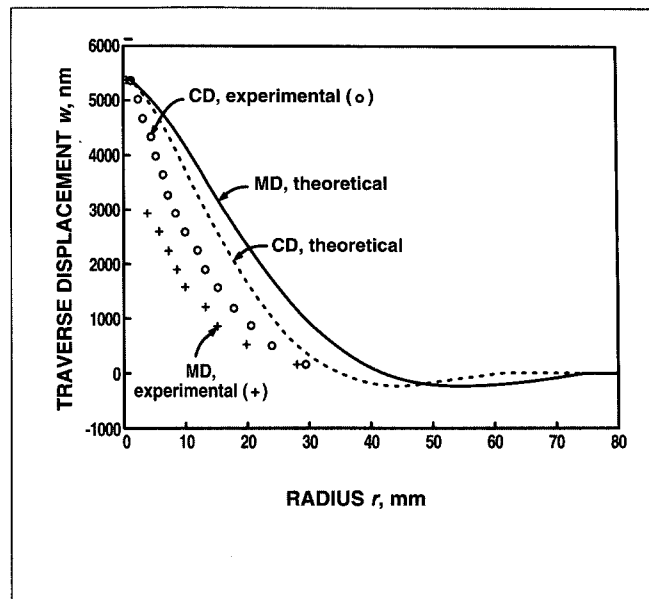
Measures of bending stiffness obtained in a static four-point bending test do not lead us to expect the behavior we observe in the impacted corrugated board—that is, in a highly dynamic situation. In the static test, the plate stiffness is about twice as high in the machine direction as across the board. If this were true in the dynamic test, we would expect elliptical fringes with a major axis in the machine direction—that is, the wave should travel at higher speed in the direction with a higher modulus of elasticity.

Instead, we see a more or less circu-

6. The acceleration of the 5-g pendulum plotted against time. The impact duration is 1 ms.



7. The out-of-plane displacement w in Sample 1 at 120 μ s after the start of impact



lar fringe pattern. There are also small deviations in the wave pattern between the ridges of a mainly circular fringe, as if the wave traveling in the space between the ridges is delayed as compared to its speed at the ridges. The dynamic stiffness seems to be about equal in both main directions since the wave pattern is close to circular.

How can this deviation be explained?

To begin with, the out-of-plane displacements of a plate are related to the transverse forces (shear forces) traveling in the plate. Along and across the ridges, we have two different situations. Any section taken *across* the ridges of the plate shows the same situation. However, *along* the ridges, the situation is different. At different places between two ridges, the rib of the corrugated board appears at different heights. Shear forces must be transferred from the top paper sheet to the bottom paper sheet and back again via the rib. The rib is in contact with the top and bottom sheets only at those places where it is glued to one or the other. The length of a rib measured along the curved rib is about 1.45 times the distance between the ridges measured along the flat top sheet.

This means that a shear wave trav-

eling along the rib will be delayed, in comparison to the same signal in the top paper sheet. The stiffness of an individual paper sheet is also less than that of the total corrugated board. The thickness of the corrugated board between the ridges also can get smaller than the nominal thickness—that is, its bending stiffness can be less. Thus, it is to be expected that transient waves traveling across the ridges will be delayed and that there should be a difference in the bending stiffness results between the static and dynamic tests.

These results are in correspondence with results from McKee *et al.* (8), who compared the three-point and four-point measurements of the bending stiffness of board. The three-point bending stiffness measured with a short span tends to be stronger in the cross direction than in the machine direction.

For the ability of the corrugated board to resist impact from small size objects, we can therefore conclude that shear forces are important. Furthermore, one has to be careful when comparing the static behavior and the dynamic behavior of corrugated board.

The interferograms of the impacted board shows the dynamic behavior and

could be a valuable tool in comparing different boards with respect to impact strength.

Discussion

Interferograms of propagating bending waves in paper show different propagation speeds in different directions. This difference is caused by the anisotropy of the paper. The interferograms also show disturbances in the wave pattern, revealing local deviation in either material or geometry, or both. The results show good correspondence with other methods, such as ultrasonic testing, in determining the anisotropy of the paper.

The same type of experiments applied to samples of corrugated board show some rather interesting results. We observed a difference in the wave patterns for the samples. One of these samples represented a normal, or "good," piece of board, and the other board had a tendency to warp around the diagonal of the sample. The sample of normal quality showed a more even wave pattern in both the machine and cross-machine directions than did the second sample. For the second sample, the wave travels faster in the cross

direction and creates a strange wave pattern. The out-of-plane deformations show a picture in which the leading edge in the cross-machine direction is out of phase with the leading edge in the machine direction.

It is also interesting to compare the anisotropy predicted by studying the out-of-plane deformation with the results of a four-point bending stiffness test. The correspondence is poor, which can be explained by the fact that shear deformation is important for impacts that take place over areas that are the same size or smaller than the wavelength of the corrugated media. A pure bending model will not explain the deformation pattern, and shear deformation must be included.

When a sample of corrugated board has a defect, such as a missing glue joint, the wave pattern in the interferograms is disturbed and is possible to localize by a simple visual inspection.

Impact testing applied to a side of a box of corrugated board revealed that the sides of the box are connected to each other like pinned joints. Bending moment is transferred around the corner only in very small amounts. [This edge condition was used by McKee *et al.* (9).] Furthermore, the deformation gets very high at the free edge of a handle. The wave has a high amplitude and is clearly delayed around the handle, compared with the wave propagating in undisturbed areas.

From the different experiments performed with this holographic method, our conclusion is that this technique is a valuable tool for studies of mechanical material parameters and geometries in optimizing the usage of the material. It may also be useful when personnel in quality control are looking for defects.

A development of the impact method is also in progress in our laboratory. In this work, the mechanical impact device is being replaced by a focused pulsed laser, which produces a purely optical impact (10). ■

Literature cited

1. Olofsson, K., Molin, N.-E., and Kyosti, A., *Tappi J.* 74(3): 195(1991).
2. Vest, C. M., *Holographic Interferometry*, Wiley, New York, 1979.
3. Aprahamian, R., Evenson, D. A., Mixson, J. S., *et al.*, *Experimental Mechanics* 11(8): 357(1971).
4. Fallstrom, K. E., Gustavsson, H., Molin, N.-E., *et al.*, *Experimental Mechanics* 29(4): 378(1989).
5. Fallstrom, K. E., Lindgren, L.-E., Molin, N.-E., *et al.*, *Experimental Mechanics* 29(4): 409(1989).
6. Molin, N.-E., Wahlin, A. O., and Jansson, E. V., *J. Acoust. Soc. Am.* 88(5): 2479(1990).
7. Molin, N.-E., Wahlin, A. O., and Jansson, E. V., *J. Acoust. Soc. Am.* 90(4): 2192(1991).
8. McKee, R. C., Gander, J. W., and Wachuta, J. R., *Paperboard Packaging* 47(12): 111(1962).
9. McKee, R. C., Gander, J. W., and Wachuta, J. R., *Paperboard Packaging* 48(8): 149(1963).
10. Fallstrom, K. E., Olofsson, K., Sarady, I., *et al.*, Generating and recording transient bending waves in plates by pulsed lasers, submitted for publication to *Experimental Mechanics*.

We are grateful to Anders Wåhlin at the division of Experimental Mechanics, Luleå University of Technology, for help with the measurements. Help by the *Tappi Journal* reviewers is appreciated. This investigation was supported by the Engineering Research Council of the Swedish Board for Technical Development.

Received for review Jan. 20, 1992.

Accepted March 16, 1992.