Compression phenomena in the Z-direction of board or paper

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Introduction

The reason for the investigation of the compression properties of board or paper was the need to develop a simulation program for the AIF-Project number 13951 about cutting with circular knifes. Such a program should show the deformation and the forces that occur during the cutting process. That means that the model must be able to handle different materials (paper or board) with different material thicknesses.
The first compression experiments were made on 3mm solid board, with different die dimensions. It turned out that the compression properties were depending on the dimensions of the die.
Then experiments on paper were made. But I did not get the information I needed for my simulation model. The PTS-engineer Mr. Saarbach came up with the idea to use a thin die, 0.71 mm thick. With this die experiments were made on different numbers of layers of sheets; then it was possible to define the dependency of the compression I was looking for.

The compression property in this model consists of:

- pure compression, independent on the thickness of the product
- edge load, fully dependent on the thickness of the product.

When I was looking for a description of the forces at sharp knifes, I did not take into account the dimension of the die. But this may be necessary for printing as well as for roughness/smoothness measurements by means of air leakage-methods. (Reference 2)

An attempt to link all information failed. With the help of the theory of prof. Timoshenko, valid for isotropic material in the elastic area only, we can understand the relationship better. The most important element of this theory is that it explains the pressure distribution under the die. That might explain the white (lighter) lines, due to the high pressure, next to the dark lines (overflow of ink) in flexo print and letterpress. See figure 1.

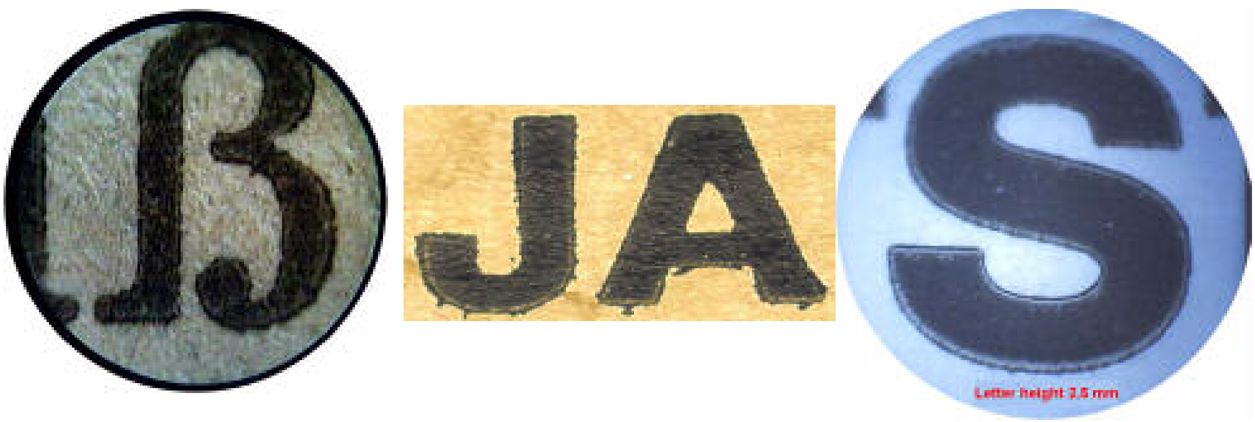


Figure 1: Letterpress | Flexo-print on corrugated board. Letter height 7.5 mm | Flexo-print on high quality coated paper

The width of the white line in the right picture is varying from 0.030 to 0.060 mm.

Compression in general

The test rig for the compression of board is shown in figure 2. The die and the impressions in the board are shown in figure 3.

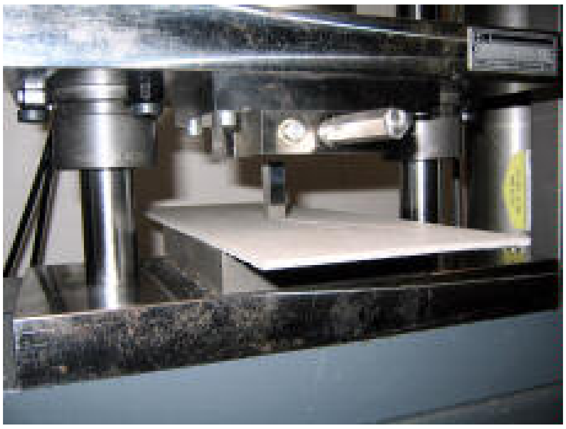


Figure 2: test rig

Figure 3: impression in board

What we see is that the deformation as a whole is larger than the die dimensions. Doing the same experiment on one sheet of paper and on a pile of 30 sheets, shows that the total deformation area is not equal, not even if the paper in both trials is the same. Not only the deformation area is not identical, but also the forces required for the same relative deformation under the die are not identical.

The deformation underneath the die is a very complex phenomenon. If the compression is high enough, flow phenomena will occur. When you are looking at the cross section of a 3 mm solid board pressed by a cylindrical die, the pressure distribution underneath the die is not uniform. Figure 4 shows the edge of a cylindrical impression. Right at the corner a crack starts. Note that the picture was made after the load had been taken away.
That strange phenomena may occur is shown figure 5, showing a sponge under compression. Strange deformations take place around the corners of the ruler.

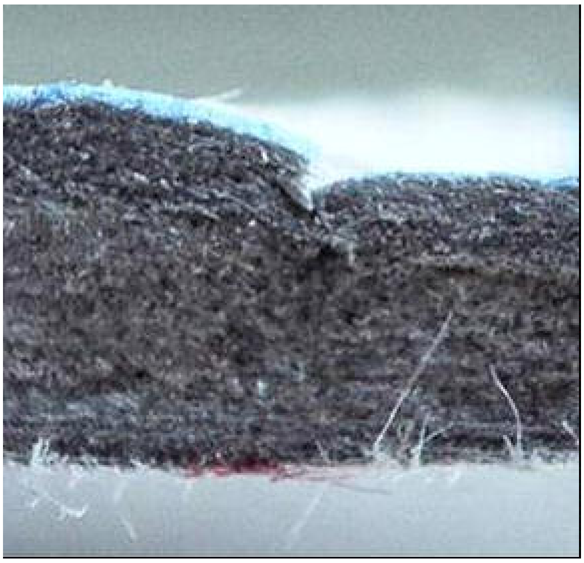


Figure 4: cross section of 3 mm board

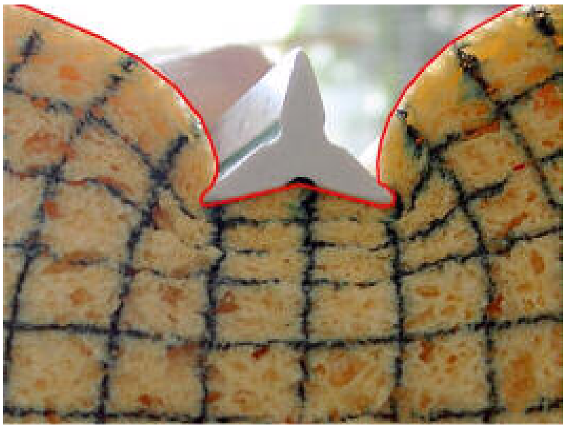


Figure 5: sponge compression

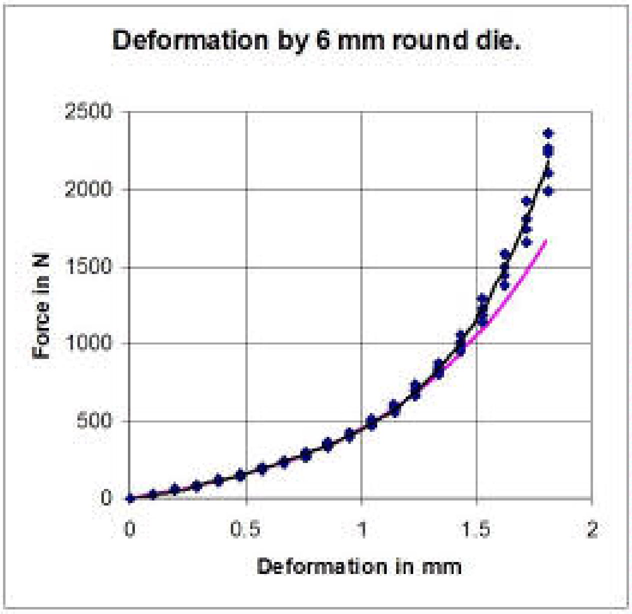


Figure 6: deformation by 6 mm round die

When we made experiments with 6 mm and 8 mm round dies on 3 mm solid board, it was difficult to remove the 6 mm die. The force measurements for the 6 mm die show an increasing force at about 1.3 mm, as you can see in figure 6. For the 8 mm die, using the same load, this increase was not found. Due to load limitations we could not investigate this phenomenon in detail. But it seemed to be obvious that this phenomenon is depending on the pressure underneath the die. If this results in a side pressure on the die, due to the phenomena shown in figure 5, there will be resulting friction forces as well.
This could explain the increase in force as shown in figure 6.

Let's take into our mind the deformation of one sheet in the Z-direction, caused by a die. Let's assume that there is no stiffness in the sheet. If we then make a pile of 3 sheets, with the identical deformation, on a flat table, the total deformation will look as shown in figure 7.

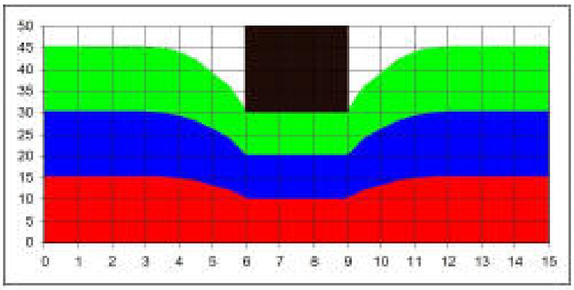


Figure 7: compression of 3 layers

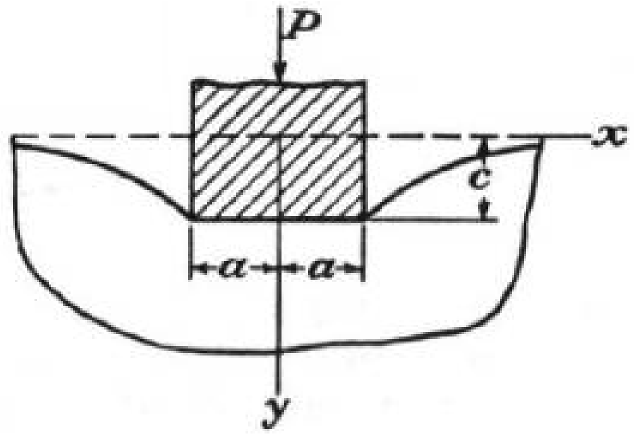
What catches the eye immediately is the fact that:

- the horizontal line-length at the top of each sheet becomes longer on each following sheet. That is only possible if there are tension forces in the sheets
- the angle of the web next to the die is depending on the number of sheets
- the resulting vertical force at the edge of the die therefore is depending on the thickness of the product.

In this way we can make it plausible that the force required to create a deformation, at the same relative deformation, is depending on the thickness of the material.

Now there is the question: how does the pressure distribution at the bottom of the die look like?
As we know, paper nor board is an isotropic material. By far not! So we have to investigate these phenomena in detail. For isotropic material under elastic conditions these phenomena already have been studied.

Prof. Timoshenko (reference 1) proved that the formula for the pressure distributions underneath a die (support) is as shown in figure 8.

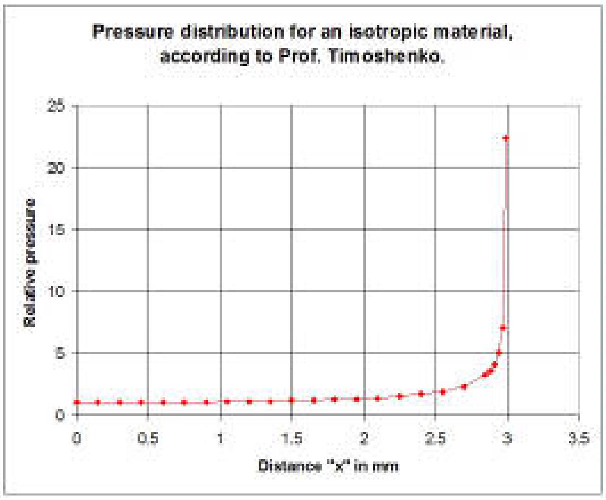


$$q = \frac{P}{\pi\sqrt{a^2 - x^2}}$$

q = pressure
P = load

Figure 8: pressure distribution according to Prof. Timoshenko

As we can see from this formula, the highest pressure always is at the corner of the die! This corresponds with the explanation given to figure 7. An example of such a compression distribution is shown in the adjoining figure.



For my cutting simulation program I did split up the compression force into:

- an equal load under the die
- an edge load next to the die.

The forces resulting from deformation next to the die, in this article, I called edge load.

The formula of Timoshenko shows the pressure distribution at a certain deformation depth. For a certain deformation depth and die dimension a certain force is necessary. As the formula shows, the relative pressure distribution over the die/support surface is independent on the die/support width.

The results of the experiments

We started the experiments with a die of 9 x 10 mm, as shown in figures 2 and 3. By this experiment we got the compression properties, inclusive edge load. Then we made experiments with a sample that was smaller than the die. See figure 9. In that case we got the information about the compression properties without edge load. After this test the sample was just slightly bigger in dimensions, related to the dimensions before the test.

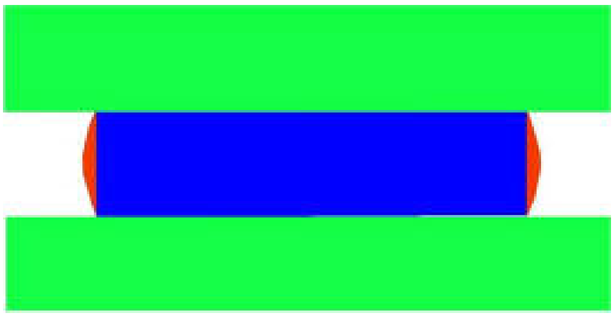


Figure 9: compression without edge load

If you subtract the curve without edge load from the curve with edge load, then you will get the figure of the edge load itself. We do know the length of the outline of the die, so we can calculate the specific edge load. See figures 10 and 11.

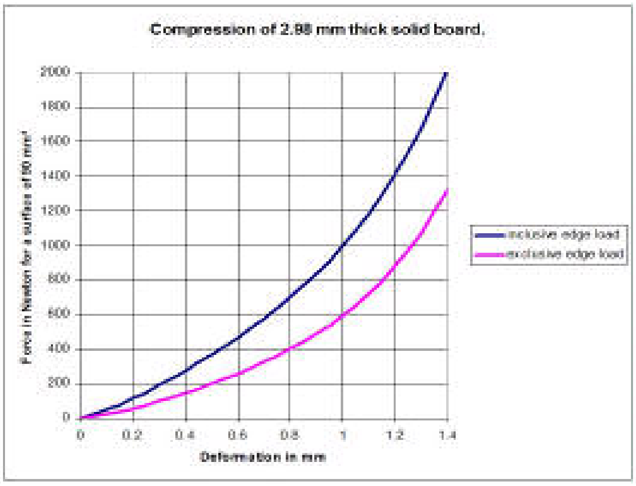


Figure 10: compression curves

Figure 11: specific edge load

I got the feeling that something was wrong in this approach, and therefore I asked for an experiment with round dies of 8 mm and 6 mm. The advantage of the round die was that the results were independent on the running direction of the product. Then I compared the average pressure under the dies of all tests. See figure 12. It showed clearly that the smaller the die, the higher was the average pressure.

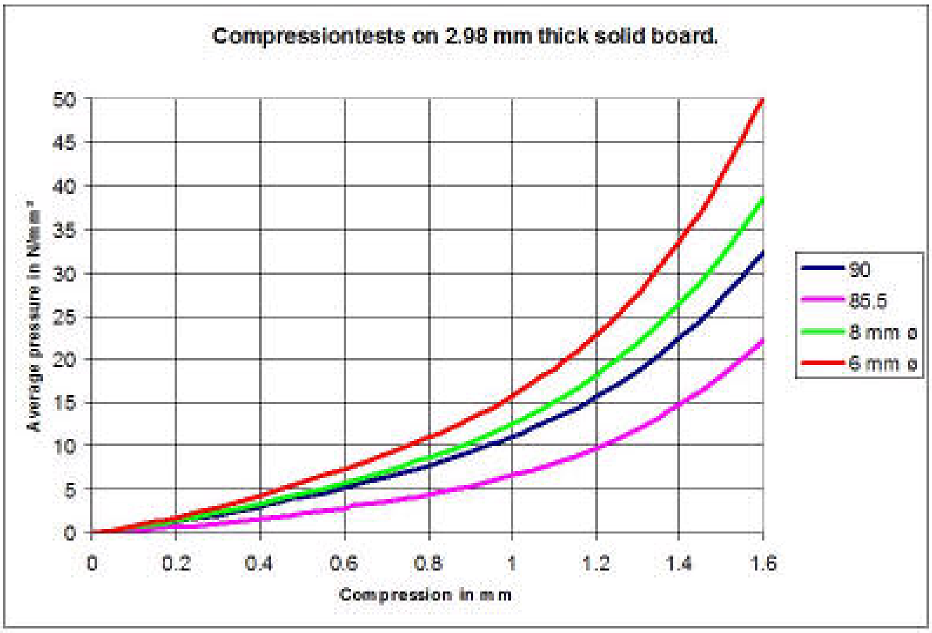


Figure 12: survey of average pressures

The figures in the legend mean:

- 90 mm² = die 9 x 10 mm, inclusive edge load
- 85.5 mm² is sample without edge load.

Following the same calculation principle as described in figures 10 and 11, the survey of the edge loads is as shown in figure 13. So, the edge loads also are depending on the dimension of the die.

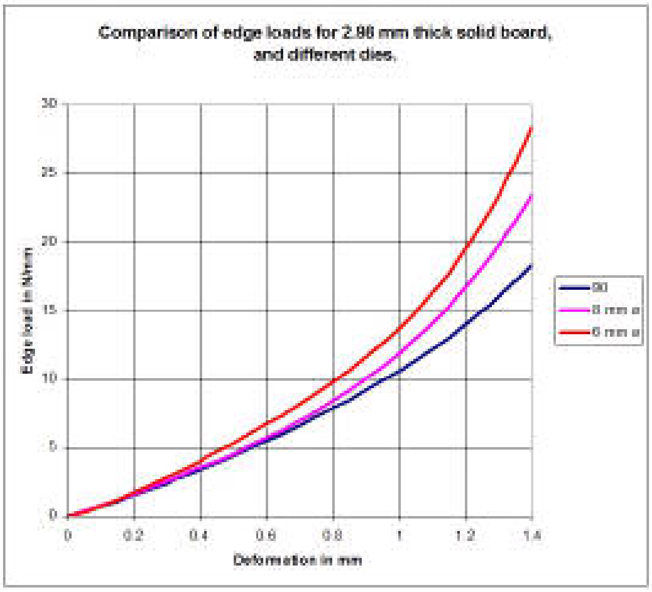


Figure 13: survey of edge loads

The consequence was that I could not use these figures for my knife simulation program, because the relation between edge length and surface of the die was not applicable to a knife.

Furthermore I like to draw your attention to the fact that these experiments were made beyond the elastic deformation limit in the plastic deformation area, which is necessary for cutting a paper or board.

About one year later, when we made experiments on paper, a new idea came up by Mr. Saarbach from the PTS to continue the experiments with a die dimension of 0.71 x 50 mm, which was much more realistic for the cutting program. Now the edge length was 101.4 mm and the surface was 35.5 mm², compared to 38 mm edge length and a surface of 90 mm² in the first experiment.

As you know, the knife load (G/m²) is an important figure in the knife technology. The max. allowed knife load of the cross knife determines the capacity of a cross cutter. If the max. allowed knife load of the cross knife is higher than the one of the longitudinal knifes, then the longitudinal knifes determine the capacity of the cutter. The consequence may be that an extra longitudinal knife section has to be installed (Dual knife section).

Therefore we investigated the influence of the number of sheets under the die, to simulate the influence of the knife load on the cutting force. The results are shown in figures14 and 15.

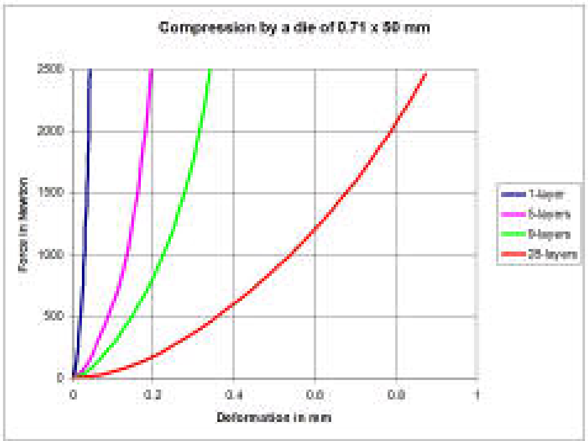


Figure 14: diagram of forces

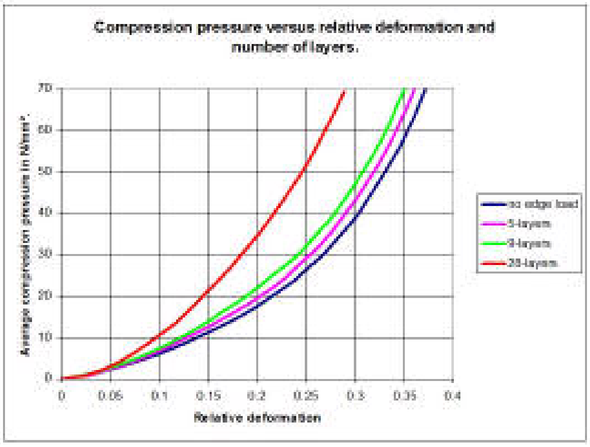


Figure 15: relative deformation

It was not possible to extend the tests to a higher loading, due to the limitation of the equipment.

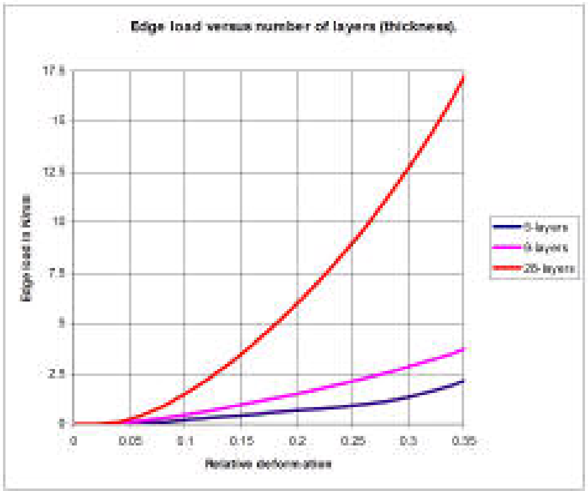


Figure 16: edge load versus number of layers

According to the same principle as described before, it is possible to split up these figures into a uniform load and an edge load. See figure 16. Then it turned out that it was possible to find a general formula that describes the edge load as a function of the thickness (number of layers) of the product that has to be cutted. This was very important for the simulation model.

It also is clear that the knife forces are not linear with the number of sheets or with the thickness of the product. This is a very important knowledge.

The paper used for this experiment was an offset paper.

Summary

The experiments show clearly that the compression force, at the same relative deformation, is depending on:

- the dimension of the die
- the thickness of the product.

The question rises: how do we describe the compression properties of a product, to enable the printing industry to select products for certain purposes? Are we doing that as a function of:

- grammage
- specific weight
- or thickness of the product.

Much more investigations are needed to explain these phenomena and to get a proper theory which may be applied to a variety of subjects, for example:

- roughness/smoothness measurements by means of air leakage methods
- limitations on cutting devices (knife loads)
- printing of flexo print and letterpress
- supports for buildings.

The effect of the number of sheets of a certain product on the knife forces is not linear, the edge forces are increasing more and more with the number of sheets.

Acknowledgment

I like to thank the PTS-Munich for supporting me by making the non standard experiments, in an attempt to get nearer to the reality of cutting phenomena.

References:

1. Pages 91 till 96 from the book: „Theory of Elasticity“ by Prof. S. Tomishenko and Goodier. „International Student Edition; second edition 1951”.
2. Cost E11\calendering: “The need to develop surface-measuring equipment”, by Ing. P.Veenstra.