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Forces and Damage involved in the Hydraulic Shearing of Wood

Krafter och skador vid hydraulisk trädklippning

by

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PREFACE

This research was conducted at the Wood Technology Department of the Forest Products Research Laboratory in Stockholm, while the author was employed as research assistant at the Department of Operational Efficiency at the College of Forestry in Garpenberg. The project was initiated by Professor Staaf of the College of Forestry and was financed mainly by his department.

Through the agency of Professor Sundberg in autumn 1962, two identical letters of enquiry were sent to Mr. Holekamp in the United States and to Mr. Silversides in Canada. These letters resulted in an exchange of information about experience obtained in cutting frozen wood with the Busch Combine. In particular the letters resulted in a contact with Mr. John S. Johnston, Forest Products Research Branch, Ottawa, Canada, who was to begin a similar project himself. Since he was going to Europe, a conference was arranged for 19 December, 1962 at the Swedish Forest Products Research Laboratory in Stockholm. At this conference an attempt was made to distribute the tasks so as to avoid unnecessary duplication of work. The contact with Mr. Johnston was very stimulating, and has had an influence on this publication.

The personnel of the Swedish Forest Products Research Laboratory have greatly assisted me throughout the project, with ideas, opinions, technical knowledge and with their constant interest, I am particularly grateful to Bertil Thunell. From the College of Forestry, I had valuable assistance through Professors Ulf Sundberg and Anders Staaf. Nils Hartler of the Central Laboratory of the Swedish Cellulose Industry and Julius Boutelje of the Forest Products Research Institute have generously assisted me with advice and help both in planning the investigation of damage and in analysing the results.

Stockholm, November 1964

Carl Kempe

PREFACE TO THE TRANSLATED SUMMARY

This translation has been made possible by the kindness of Mr. Magnus J. Larsson, now studying at the University of New Brunswick, Canada, and my colleague Mr. John S. Johnston, Acting Head of the Wood Utilisation and Anatomy Section, Forest Products Laboratory, Ottawa, Canada. The task of publication has been undertaken by Professor Anders Staaf, College of Forestry, Garpenberg, Sweden, to whom I should like to express my gratitude.

Montreal, Canada, 2 June, 1966

Carl Kempe

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NOTATIONS

α	= half the knife angle
β	= the angle between the edge of the microtome knife and the direction of movement
γ	= the angle between the fibre orientation of the sample and the direction of movement of the microtome knife
μ	= Coefficient of friction
b	= width (cm)
r	= volume weight (grams/cm³) = specific gravity
t	= thickness of knife (cm)
u	= moisture quotient (%)
E	= modulus of elasticity (kp/cm²)
E_V	= modulus of elasticity perpendicular to the grain
E_L	= modulus of elasticity, along the grain
E_T	= modulus of elasticity, tangential
E_R	= modulus of elasticity, radial
F	= friction force (kp/cm)
F_n	= force perpendicular to direction of movement (kp/cm)
F_p	= force parallel to the direction of movement (kp/cm)
K	= wedging force (kp/cm)
N	= normal force (kp/cm)
P	= specific wedging force (kp/cm²)
Q	= pressure in the direction of fibres on the edge of the knife (kp/cm²)
T	= compressive strength (across the grain) of the wood (kp/cm²)
U	= specific friction force (kp/cm²)
Z	= pressure in the direction of fibres on the surface of the knife (kp/cm²)
1 Mp	= 1 000 kp = 2,200 lbs.
1 kp/cm	= 5.6 lbs per inch
1 kp/cm²	= 14.2 psi

1. Introduction

Cross-cutting of wood by shearing is already used in some wood harvesting machines developed recently, i.e. the Busch Combine (Fig. 1), Spruce Harvester (Fig. 2); and the LRA Processor. These cross-cut roundwood, either in felling trees or in bucking them into short-wood lengths. The shear is used to provide a fast and reliable action in felling, and sometimes to act as a wedge and thus to control the direction of felling. It is used to increase the rate of bucking work.

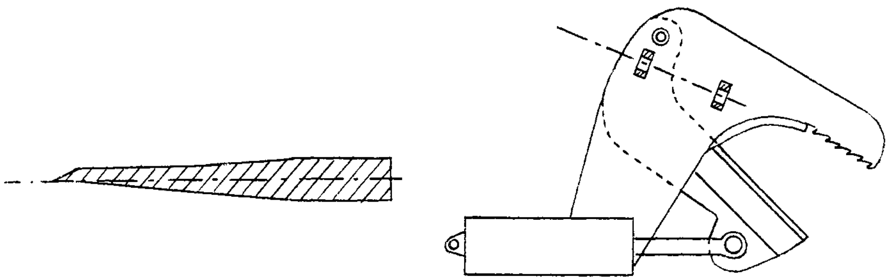

Fig. 1 Busch Combine: The Shearing Device

The shear designs on these machines have been judged not to be the best possible, the damage they cause being too great to be tolerated by Swedish foresters. This investigation was therefore begun with the intention of giving more knowledge about forces, damage and other cutting variables involved in shearing.

Originally, the author hoped to derive clear formulae for the relation between different variables, but it was very difficult to measure and to express these variables numerically. Thus the investigation was confined to explaining what happens in the wood during cross-cutting by shearing and to discovering some fundamental relations.

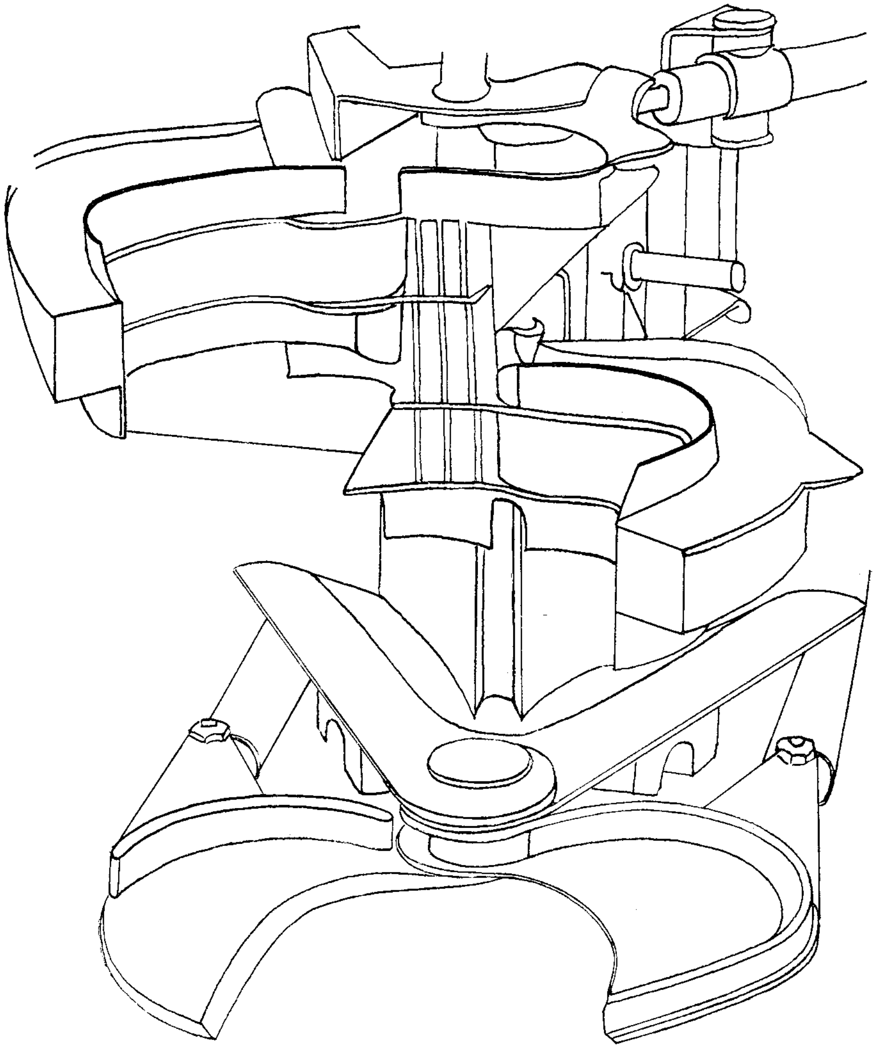

Fig. 2 Spruce Harvester: The shearing & Delimbing Device

2. Equipment and procedure

The tests were carried out on five different occasions. The first, in March 1963, used a general purpose testing machine, a knife-holder and knives, and was intended to give a general idea of the forces involved.

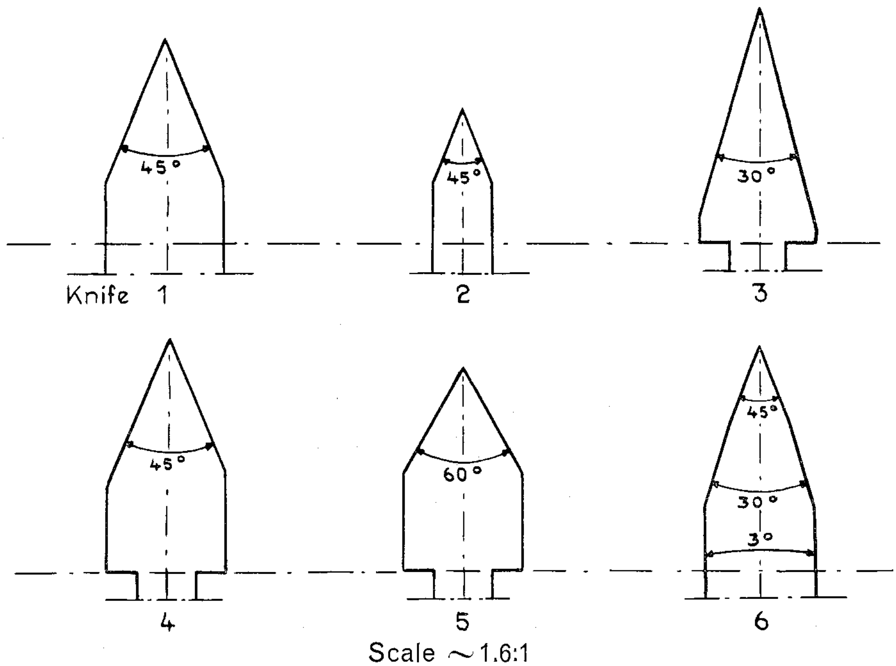

Fig. 3 The final configuration of the knife edges

A machine was then built to withstand the forces as estimated from this first test, and is best described by Figure 4.

The main tests were carried out in November 1963, at about 0°C, with knives like these in Fig. 3, all knives being 100 mm wide. All tests were on square logs, with one knife against an anvil 75 mm (3 inches) wide. Only spruce were cut and all the cuts were at right angles to the grain. The logs were cut the same week they were felled and the same day they were squared. The dimensions ranged from seven to 18 cm wide and from seven to 14 cm high, and the cutting speed from five to

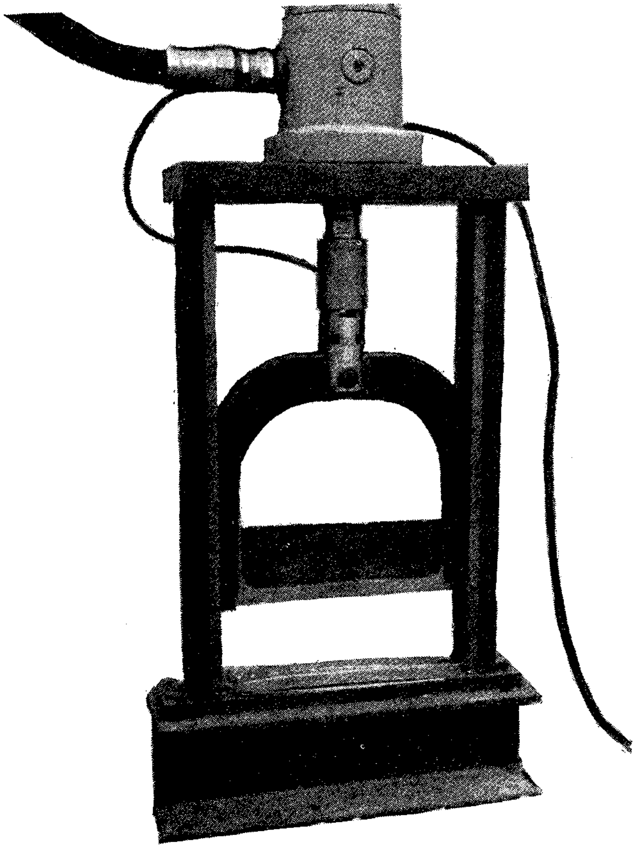

Fig. 4 »The Giljotin»

20 cm/second. The recorder used produced recordings of the same type as those in Fig. 10.

On 13 March, 1964 a tree was brought in to the Forest Products Research Institute and cut into pieces within six hours of felling. The wood temperature was $-5°C$ to $-10°C$ (15 to 25°F) after a night temperature of minimum $-10.4°C$ (12°F). Some of the pieces were put into a freezing box for one or two days and the others were stored indoors for one day, until temperatures of $-17°C$ and $+17°C$ respectively ($+1°F$ and $+63°F$) were reached. To keep them fresh they were wrapped in plastic until they were cut. One log was ripsawed into two square pieces about 6×6 cm and one piece 10×18 cm: the two small pieces were used in tests of radial and tangential cross-cutting.

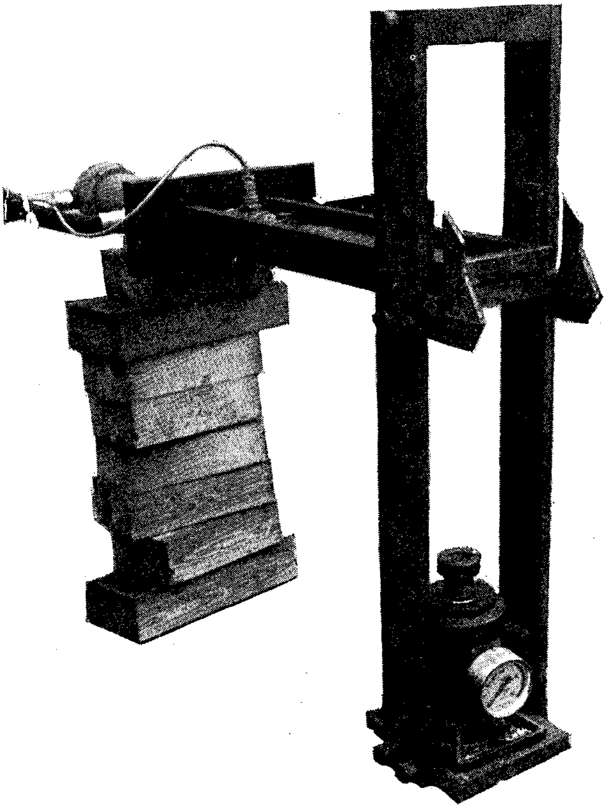

Fig. 5 The friction test equipment

On 24 March, 1964 a tree was brought in the same way and at about the same temperature. It was used primarily for friction studies with a testing apparatus like that in Fig. 5. The log was first cut, an axial pressure was applied and then the rest of the knife was forced through the wood. The knife was 18 inches long and $^3/_8$ inch thick and passed through a slot in the anvil. The cutting angle was 45° and the knife six inches wide. The sides of the knife were ground before hardening and tempering. The wood pieces were about 70 cm (28 inches) long before and 35 cm long after the cut.

3. Primary results

3.1. Influence of the Knife

The forces required are related to each other in the following way (knife 2 = 100):

Knife number	1	2	3	4	5	6
Relative force req'd	150	100	125	122	160	115
Cutting angle	45	45	30	45	60	45/30
Thickness	10	5	10/5	10/5	10/5	9/4

The knives resembled those in Fig. 3.

The speed did not seem to have a significant influence on the force required.

3.2. Influence of the Wood

1. The width of the wood influenced the forces directly, as all cuts were made on square logs. To compare different cuts with each other, the forces were divided by the width of cut to form a unit "kp/cm".

2. Length of cut also influenced forces owing to friction. This will be analysed later.

3. Knots increased the force required by up to 50 per cent.

4. The specific gravity had an influence, but the investigation was not large enough to give any definite relations. The increase in force required may be only a few per cent for every change of one per cent in the S.G.

5. The moisture content was about the same in all round logs, because all were from the same stand and were freshly cut. The only major difference, therefore, was that between heartwood and sapwood, the heartwood having about 30 per cent MC and the sapwood about 100 per cent MC. They differed in their force requirements mainly when they were frozen. Under warm conditions the sapwood required about 15 per cent greater force than the heartwood, which may depend on the greater number of annual rings per centimetre in the sapwood than in the heartwood.

6. The influence of temperature was investigated for three different temperatures: frozen wood (about – 17°C), fresh wood (about – 5°C)

and warm wood (about + 17°C). The results are shown in the following table:

Heartwood	at	—17°C	required	about	20	per	cent	greater	force	than	at	+17°C
	»	—5°C	»	»	15	»	»	»	»	»	»	»
Sapwood	»	—17°C	»	»	50	»	»	»	»	»	»	»
	»	—5°C	»	»	20	»	»	»	»	»	»	»

7. Tangential cutting (cutting direction parallel to the annual rings) required 20 to 30 per cent greater force than radial cutting (cutting direction perpendicular to the annual rings).

3.3. The Friction Coefficient

The following table shows variations in the friction coefficient:

+ —	warm wood	H —	a cutting speed of 20 cm/sec.
— —	frozen wood	L —	7 cm/sec.
F —	fresh wood		

PIECE	*DIMENSIONS*	*HEART OR SAPWOOD*	*+H*	*+L*	*—H*	*—L*	*FH*	*FL*
2	10×14	both	18	18			21	24
3	10×10	both	15	16			19	16
4	10×10	more sapwood	15	(16)	14	19		
5	7×7	most sapwood	14	14	10	18		
Cl	7×7	Heartwood	(18)	14	21	18		
A1T	7×7	both		19				18
B1T	Tangential	both		17				18
A1R	7×7	both		11				15
B1R	Radial	both		10				(21)

Every figure represents one attempt. Samples containing knots are shown in parentheses. The figures are obtained by dividing the cutting force by twice the axial load.

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4. Analysis of the results

4.1. Theory

The cutting force was assumed to consist of three parts: edge force—caused by the edges not being ideally sharp; wedging force—caused by increasing knife thickness, and frictional force—caused by friction between the wood and the sides of the knife (friction on the edge part of the knife is included in the wedging force). This assumption was later revised slightly.

4.1.1. Edge Force

This is caused by the fibres' bending away before being cut through, which requires force both for bending and stretching. McKenzie (1961) has presented a hypothesis to explain what happens when the edge goes into the wood perpendicular to the grain, based on an incision stage as shown in Fig. 6 and has calculated the forces to a few kp/cm for the bending action alone. The stretching action can be calculated not to exceed 4 kp/cm. Samset (1962) gives some figures for the shear of the Busch Combine, in which the cutting force is given as 65 MP on a 19 inch tree, 95 per cent of this force being friction. Thus the edge forces will be about 70 kp/cm. Hartler (1963 a) measured the total cutting force used while chipping and gives a figure of ca. 20 kp/cm. To find what is true we shall further examine McKenzie's hypothesis in Chapter 6.

4.1.2. The Wedging Force

The pressure on three different knives is assumed to be as that shown in Fig. 7. Whether the pressure on the edge part of the straight knife is the same as the pressure on the sides of the knife is not clear, but these are denoted Q and Z respectively. The influence from Q on the edge can be obtained from Fig. 8, which gives a value of:

$$P = 2Q \ (\mathrm{tg}\ \alpha + \mu)$$

P is the specific wedging force in kp/cm^2 surface of the edge, i.e. if the width of the wood is b cm and the edge part of the knife is a cm

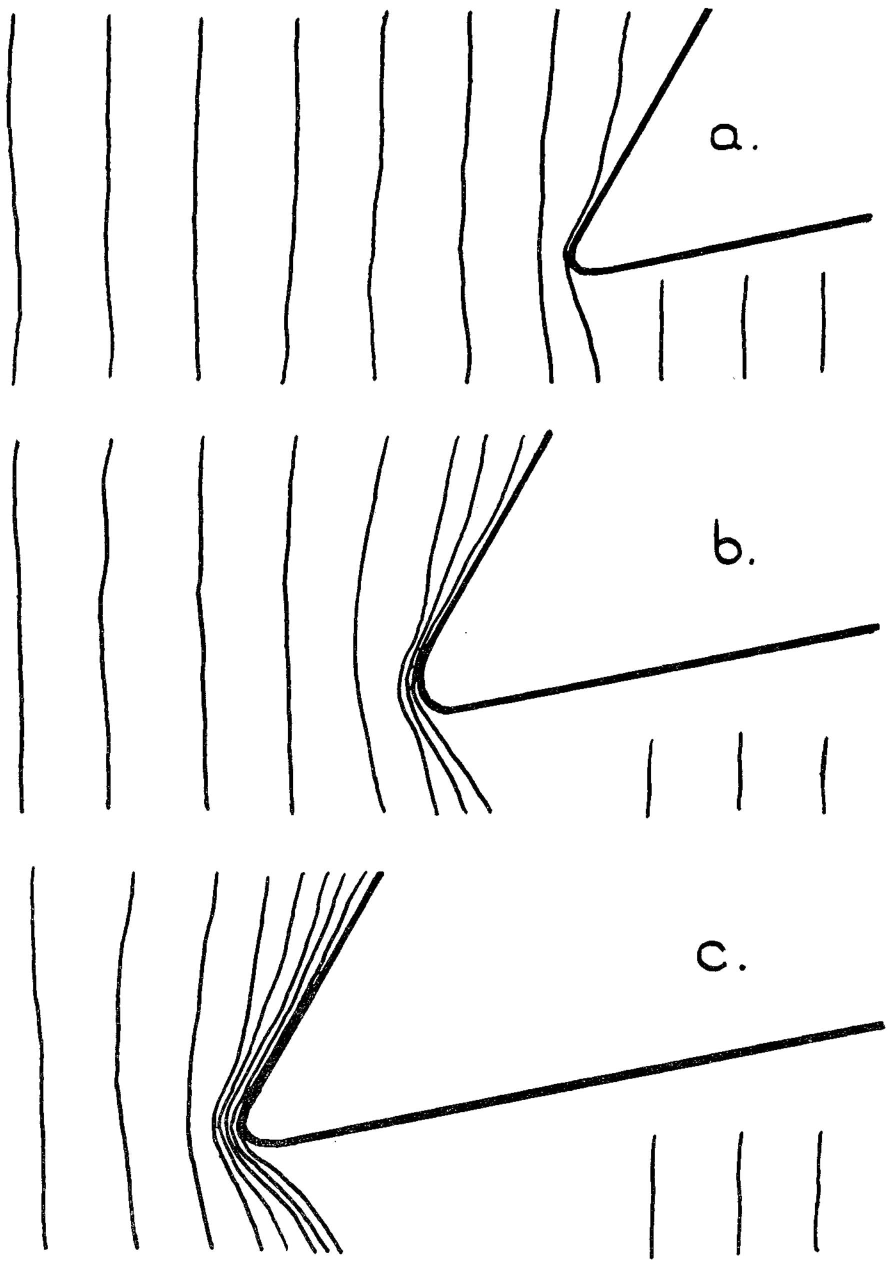


Fig. 6 The initial penetrating stage according to McKenzie (1961)

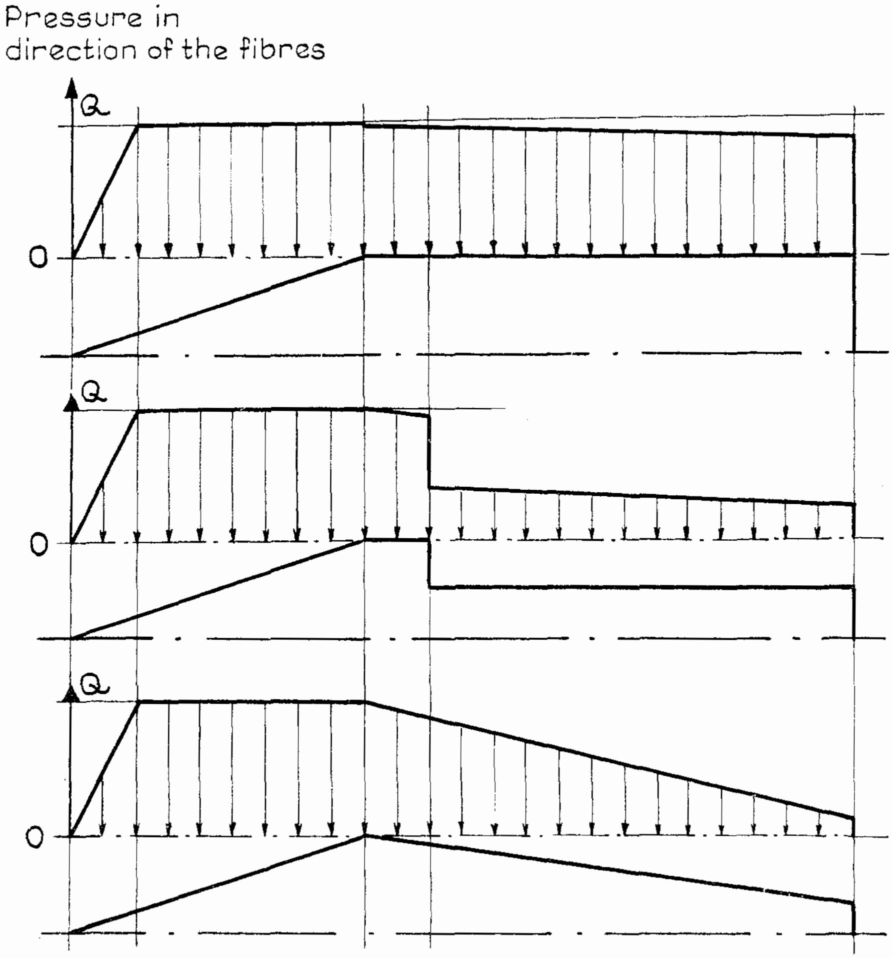


Fig. 7 Assumed distribution of pressure along the knives

long ($t/2a = \mathrm{tg}\ \alpha$) where t is the thickness of the knife, so $2a \times b$ is the surface of the edge (both sides of the knife). To obtain the total wedging force K in kp/cm the following formula may be used:

$$K = Qt\ (1 + \mu/\mathrm{tg}\ \alpha)$$

Compared to the measured forces (shown in the table on p. 4), the formula shows that this way of looking at the forces does not explain everything. The forces increase with the cutting angle. A better explanation is discussed in Chapter 6.

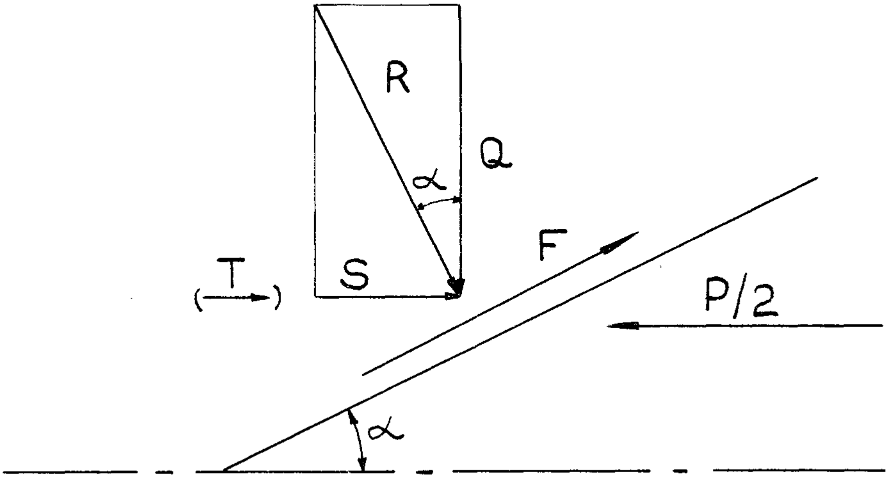


Fig. 8 Calculation of the wedging force

4.1.3. The Frictional Force

This is described by the formula:

$U = 2Z\ (\mu - \mathrm{tg}\ \alpha)$

derived in the same way as *P*, where *U* is the specific frictional force in kp/cm² of the sides of the knife, *Z* is the pressure on the sides of the knife, μ is the friction coefficient and α is the relief angle (the same on both sides of the knife). For a straight knife,

$U = 2Z\ \mu$

In cutting square logs, the force diagram under these assumptions may look like Fig. 9 as the knife proceeds through the wood. However, the changes between the different parts of the curve may look different. The three knives are the same as in Fig. 7.

4.2. Analysis of the received curves

Some of the force-time diagrams from experimental data have been brought together in Fig. 10. The main difference apparents relative to the theoretical curves, is the decrease of the force at the end of the cut. This is because the anvil was narrow and permitted the wood to bend away under the wedging action of the knife.

These force-time diagrams have been studied to obtain the assumed three parts: The edge force, the wedging force and the frictional force.

1. The edge force must be a part of the first sharp increase in the

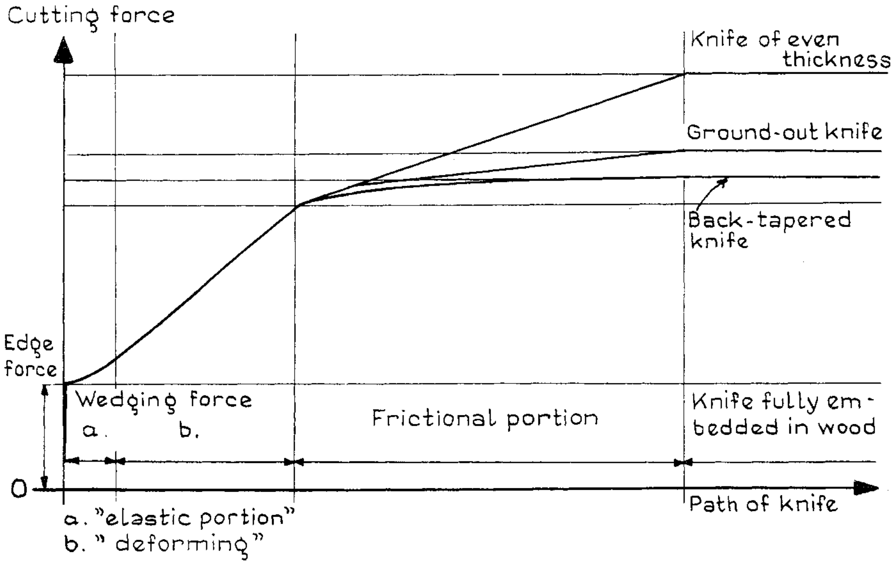
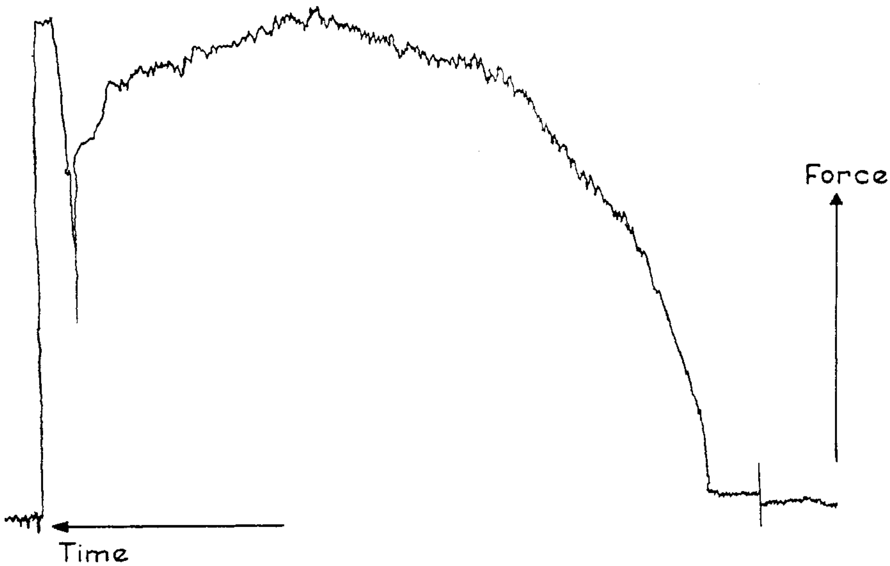


Fig. 9 Hypothetical shearing force diagram

cutting force, or must represent the increase itself. The actual value of this can only be guessed at, but it seems to be between 30 and 80 kp/cm, the larger values being for radial cutting and the smaller for tangential. As the edge force cannot be so large, these values must contain something more than the edge force.

2. The slope of the curve for the point at which the edge part of the knife starts to penetrate the wood represents the specific wedging force *P*. This has been difficult to measure, first, because of variations in cutting speed, which make it hard to ascertain the speed at the point of measurement, and which causes the graphed line to be curved instead of straight, and secondly, because of the difference between radial and tangential cutting. At the beginning of a cut in a square log, the cutting direction is more or less radial, while at maximum force it is mainly tangential. The slope is measured at the beginning of the cut, and thus special arrangements have to be made for estimating the tangential specific wedging force. The following results were obtained by measuring the slope:

(a) Increasing knife thickness seems to give increasing specific wedging force, although the knife thickness should have no influence in this case. The slope was difficult to measure on the thin knife, which may explain the slight difference.



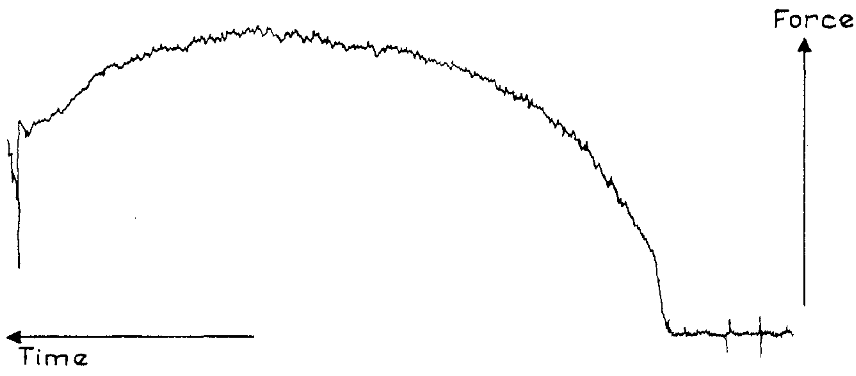


Fig. 10 A few obtained shearing force diagrams

(b) The influence of the cutting angle was studied carefully, and it has been proved that the theoretical formula does not explain the situation satisfactorily. The compression strength of the wood is in the fibre direction in warm wood 200 to 250 kp/cm², but values on *P* of 100—150 kp/cm² gives values on *Q* of about 100 kp/cm². *Q* ought to be about the same as the compression strength, so the theory has to be modified.

The specific wedging force was 20—30 per cent higher for a 60° than for a 45° cutting angle. For a 45°, as compared with a 30° cutting angle, the specific wedging force is equally high. This shows that the cutting angle has an influence on the total cutting force, not only through the wedging force but also in another way because with these differences in specific wedging force P, the wedging force K will be at its smallest when the cutting angle is largest. ($K = Pt/2 \operatorname{tg} \alpha$)

(c) At a cutting angle of 45°, the wedging force was about 10 per cent higher at a cutting speed of 20 cm/sec. than at one of 7 cm/sec. for both warm and frozen wood.

(d) Tangential cutting showed a wedging force of 20—30 per cent more than radial cutting.

(e) The influence of MC and temperature. Frozen sapwood showed a more than double wedging force as compared with that of frozen heartwood. With a 45° cutting angle, the specific wedging force in frozen heartwood never exceeded 150 kp/cm^2 while up to 350 kp/cm^2 was recorded for frozen sapwood. Frozen heartwood showed only about 10 per cent more specific wedging force than warm heartwood.

3. The slope of the curve in the latter stages of penetration of the knife into the wood represents the specific friction force U, and some other factors. During penetration towards the centre of the log, the cutting direction changes from radial to tangential, causing an increase in both wedging and frictional forces. In the case of pieces where cutting was almost tangential, the specific frictional force seems to be about 20 kp/cm^2 for warm wood and 15 kp/cm^2, on the average, for frozen wood. The latter figure may change with changes in the heartwood content of the wood. Thus the pressure on the sides of the knife seems to be about 50 kp/cm^2 for both frozen and warm wood.

5. The investigation of damage

5.1. Choice of method

In an inquiry, Hartler indicated the following four ways of studying crush damage.

1. Polarised light on microtome-sliced wood.
2. Staining of mm-thick disk.
3. Treatment with acid followed by measurements of the brittleness, of the wood; e.g. by means of compressed air.
4. Pulping, paper preparation, and test of paper strength.

Hartler used methods (1) and (4) himself (Bausch & Hartler, 1960), (Hartler, 1963b). Method (2) appeared at first very suitable for this investigation. It had not, however, been tested enough and therefore method (1) was chosen. Method (3) was even less tested and was therefore never considered. Method (4) gives no indication about what happens in the wood and is, moreover, very elaborate.

All three methods are based on the fact that crushed fibres are more readily penetrated by certain kinds of liquid, causing increased staining, increased brittleness by the acid, and increased effect of the (pulping) liquid in reducing the strength of the fibres.

Thus method (1) was finally chosen. The microscopic examination made it possible to study cracks (splits) and other damage in excess of the crushing damage.

5.2. Procedure

The method was tried in autumn 1963 on wood sheared in the spring. Two samples were chosen and from these one centimetre thick disks were sawn parallel to the sheared surface. The disk closest to the sheared surface almost fell apart; the tests were therefore made on the second disk. From this disk 1×1 cm test samples, with one side in the radial direction, were cut with a sharp knife. The samples were then sliced in a saturated condition into from ten to 20 μ thick radial slices with a microtome. The slices were then filled with water and put on a test glass. Sometimes the water was replaced by glycerin before the

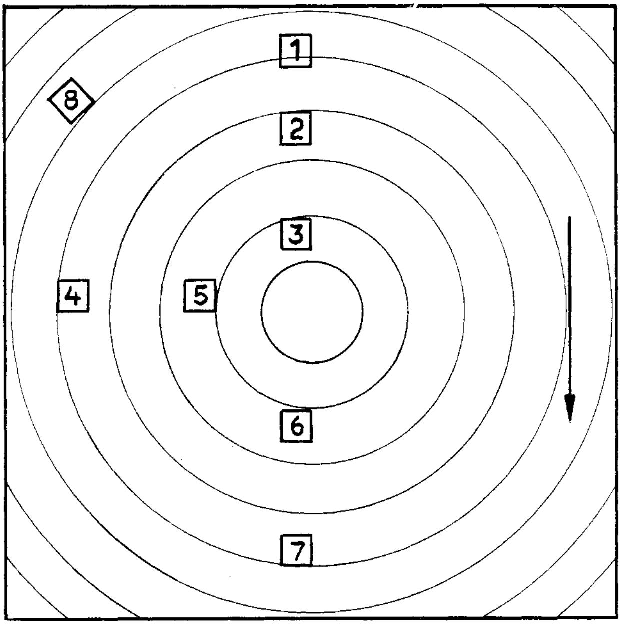


Fig. 11 Samples for microtome cutting

cover glass was put in place. The slices then became semi-permanent. The specimens were then studied under a microscope with polarised light, which showed the "slip lines" as light (in some cases, dark) oblique lines across the secondary walls.

According to Kisser and Steininger (1952), "slip lines" are displacements in the secondary walls. These occur at approximately half the breaking load. These displacements are, according to Frey-Wyssling (1959), sudden changes in the direction of the micro-fibrils which causes a loosening of the fibres. This makes it easier for liquids to penetrate. The change in the direction of the micro-fibrils changes the polarisation of the light, thus causing the light (dark) lines.

Figure 11 shows a disk and the place from which the test samples were cut. Samples 1, 2 and 3 displayed similar and the most penetrating damage. Samples 6 and 7 showed damage of about the same depth, but these samples were studied primarily for the sake of checking, since such shearing did not occur when two knives were used against each other. Samples 4 and 5 showed short but intensive damage, while sample 8 was more like sample 1. During the investigation, samples were therefore taken from the same place as 1 and 5. The distance from the centre was varied so that samples were obtained from both heartwood and sapwood.

5.3. The problem of the slip lines

In some cases "compression damage" was found in unsheared wood and thus was present in the wood before it arrived at the Wood Research Institute. The damage may have been caused by a storm or during the felling. Such damage was found scattered in the wood and made the analysis of shearing damage difficult.

Fig. 12 shows the most typical damage from radial shearing (obtained from sample from location 1, fig. 11). The damage comprises an annual ring separated from its neighbouring rings by cracks. It shows how the slip lines begin to occur up in the summer wood and increase in number towards and in the spring wood. Thus the ring has acted like a deflected beam. This strongly supports McKenzie's hypotheses (McKenzie 1961), which will be discussed further in Chapter 6. Thus deflection damage occurs when the shear forces are exerted perpendicular to the grain and compression damage when they are absorbed parallel to the grain. Here the microscopic compression damage must not be confused with the macroscopic crush damage.

The deflection damage is relatively easy to distinguish from other damage, as it is surrounded by cracks and has a characteristic apperance. Where it occurs, mainly in warm wood, a distinct end of the damage can be noticed. This is because once the "beam" has deflected, no more compression damage can extend further into the wood. In frozen wood the cracks can penetrate farther into the wood than the deflection damage and there also compression damage can occur farther in the wood. Here the difficulty arises of distinguishing between damage existing before and that created during shearing. Especially in frozen sapwood, the development of the damage does not always follow that of a "deflecting beam" but that of a "buckling buttress"; thus the compression damage plays an important and uncertain part. Therefore attempts have been made in the analysis of the damage to find a definite and comparable limit beyond which the damage, if it exists, could be considered negligible.

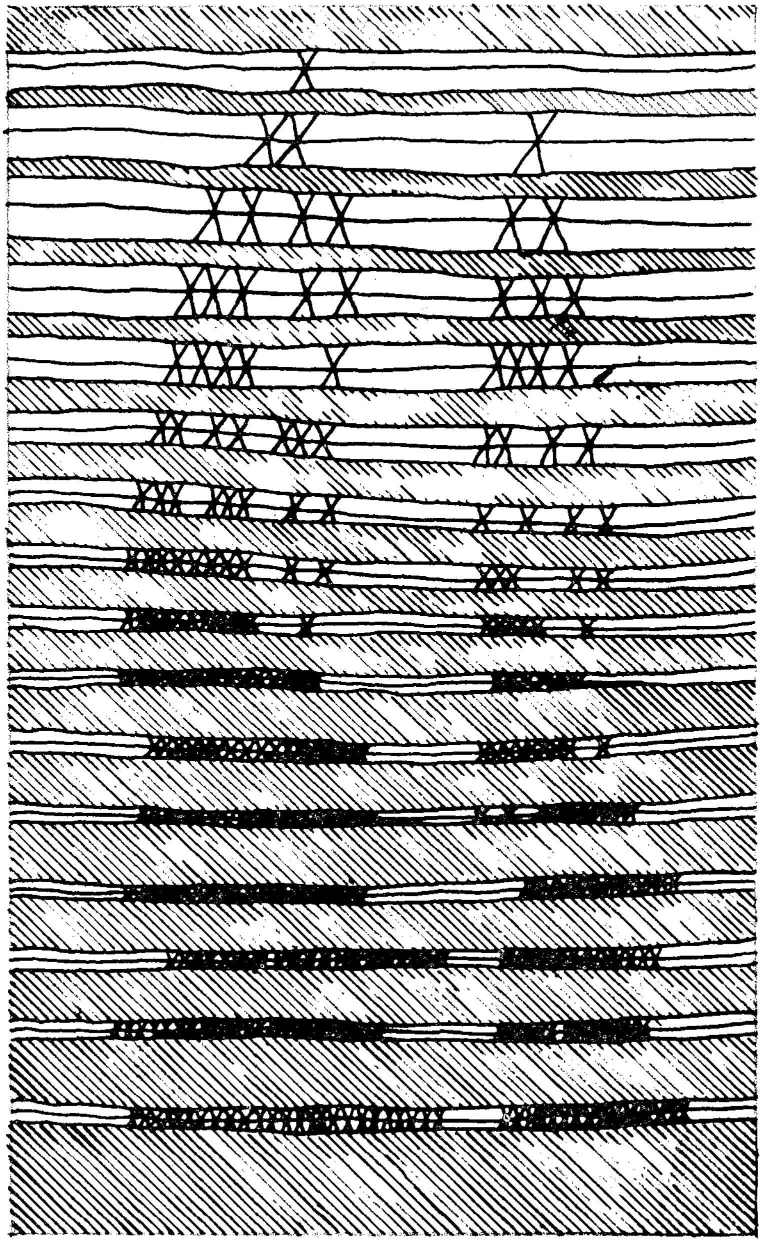


Fig. 12 Bending damage during radial cutting

5.4. Results

The series from November 1963 of the damage investigation gave the following result, shown briefly as follows:

Number of Knife	1	2	3	4	5	6
Extent of Damage (mm)	30—40	13—18	12—15	30—40	50	15—16
Cutting Angle°	45	45	30	45	60	45/30
Thickness (mm)	10	5	10/5	10/5	10/5	9/4

As may be seen, knives 2, 3 and 6 caused very similar damage and the extent of the damage showed relatively little spread.*

Differences in the wood might have influenced the results. Therefore it is difficult to say that one knife is better than another. The knives 2, 3 and 6 can therefore be considered equal.

The knife angle which influenced the forces only to a small extent appeared to influence the damage greatly. Thus a change from 45° to 30° of the knife angle reduces the damage by the same amount as a reduction in thickness from 10 to 5 mm.

The fact that knife number 6 caused such small damage indicates that it is not the edge angle but the wedge angle which is of importance here. As a knife with a 30° edge angle may be too weak for the application, it is possible to obtain the same result, as far as damage goes, by using a double slope with 45° edge angle and 30° wedge angle.

Frozen wood gave a more heterogeneous picture than warm wood. The type of damage in heartwood did not change much with temperature, but the development of cracks was often more extensive.

Frozen sapwood often displayed damage different from that of warm sapwood. The free water in the cells gives the wood completely different compression strength characteristics when frozen (Thunell, 1964b). The compression strength perpendicular to the grain, especially, must change drastically when the cell lumina are completely or partly filled with ice. This means that frozen wood does not deflect as readily as warm wood and so damage of other types occurs. Cracks may occur in the springwood instead of between the spring and summer wood. As mentioned before, the type of damage might be that of a "buckling buttress" instead of a "deflecting beam". Because of this, compression and crushing damage often occur instead of deflection damage, which makes the damage difficult to analyse.

The smaller special samples that were used to separate tangential

* The relative dispersion for knife 2 appears to be greater than that for the other knives, because the table shows the complete range of measurements. Knife 2 was also used more than the others and in many different cases. Within the same tree, however, knife 2 showed less dispersion than most of the other knives.

from radial shearing showed, as a rule, more damage than those that included the complete annual rings. This might indicate less damage to round wood than to squared wood, especially as far as cracks are concerned.

During tangential shearing, the same kind of damage occurred as during radial cutting, although the location of the cracks was not governed by the same natural circumstances as before. However, they seemed to occur at an interval approximately equal to the width of the annual ring, even in tangential shearing. The slip line damage seemed to be shorter and more concentrated, but the cracks appeared to be of the same degree of severity as those after radial cutting.

6. Comparisons with other results

6.1. Mc Kenzie

It is interesting to compare McKenzie's hypotheses and formulae for this very special kind of shearing. The comparison is perhaps slightly illegitimate, partly because this different kind of shearing necessitates a modification of hypotheses and formulae and partly because this modification is somewhat arbitrary, because knowledge about what happens during shearing is rather limited. However, the comparison is worth making as it has much to contribute to the understanding of the mechanics of shearing.

The basis for comparison is McKenzie's "Beam 3". Fig. 13.* In the situation in question, we have the case in Fig. 14. P_{I} is the edge or cutting force until the beam is cut completely. Then it becomes a wedging force like P_{II}, $P_{\mathrm{III}} \ldots$ and P_N. The total force thus becomes $P_{\mathrm{I}} + P_{\mathrm{II}} + \ldots + P_N$. The distance from the line of symmetry to the point of action of the force can be said to be:

$$O \text{ for } P_{\mathrm{I}}$$
$$h \times \tan \alpha/2 \text{ for } P_{\mathrm{II}}$$
$$h \times 3 \tan \alpha/2 \text{ for } P_{\mathrm{III}}$$
$$h \times (2N\text{-}3) \tan \alpha/2 \text{ for } P_N$$

This distance must be smaller than $t/2$. Therefore:

$$N \leqq 1.5 + t/2h \tan \alpha$$

According to Hetenyi, the bending moment (M) in a beam on elastic foundation with the load concentrated on a free end and without axial forces, is as follows:

$$M = \text{-}P \times e^{-\lambda x} \sin \lambda x/\lambda$$

$$\text{where } \lambda = \sqrt{\frac{k}{4E1}}$$

Here the approximation for this case of loading appears, since P_I must overcome the axial forces in the particular beam it is acting on before the shearing is completed. However, it was shown earlier that these axial forces have such a small influence that they can hardly

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* McKenzie refers to the following two sources for his formulae for a bending beam. Hetenyi, 1946: Beams on Elastic Foundation, Ann Arbor, Mich. Biot, 1937: Bending of an Infinite Beam on an Elastic Foundation.

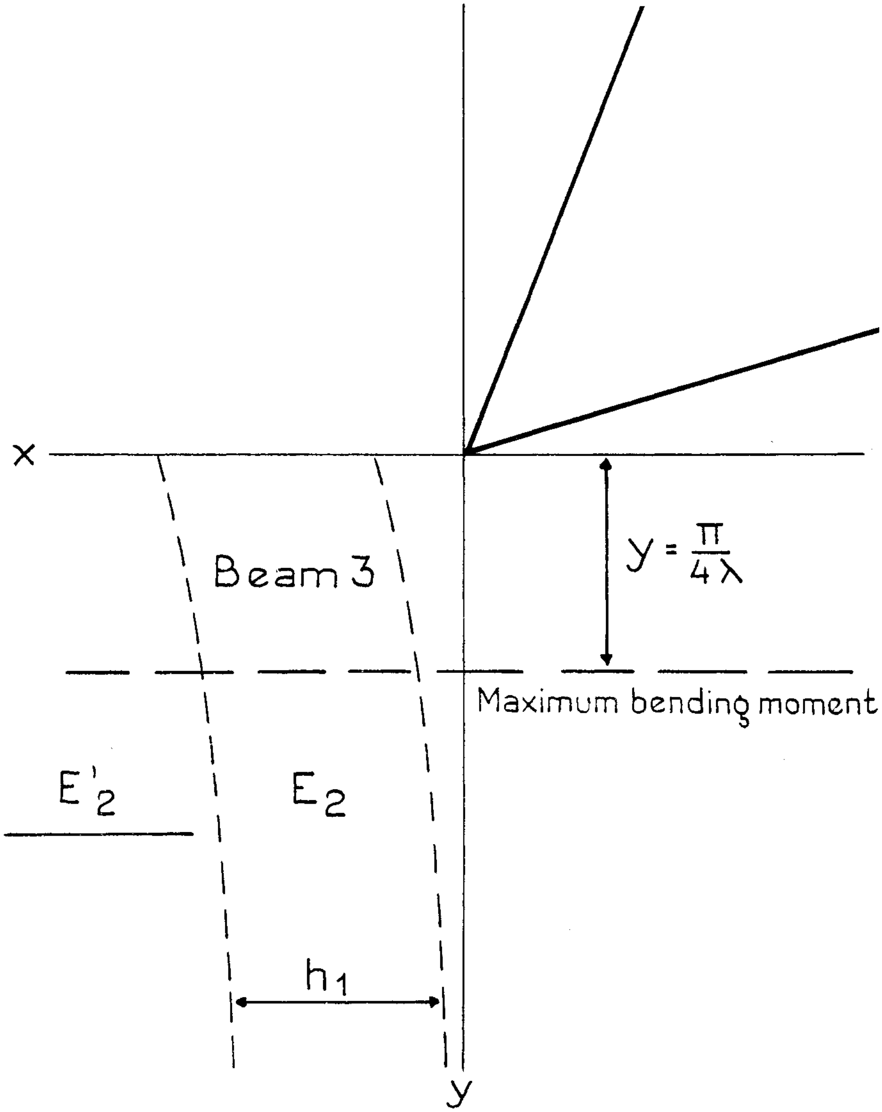

Fig. 13 McKenzie's figure for bending beams (McKenzie 1961)

effect estimates made when using the above formula. Biot expressed k for a squared beam:

$$k = 0.645\,\frac{bE'}{h}\left(\frac{E'}{E}\right)^{1/3}$$

here

$$\lambda = \frac{1.18}{h}\left(\frac{E'}{E}\right)^{1/3}$$

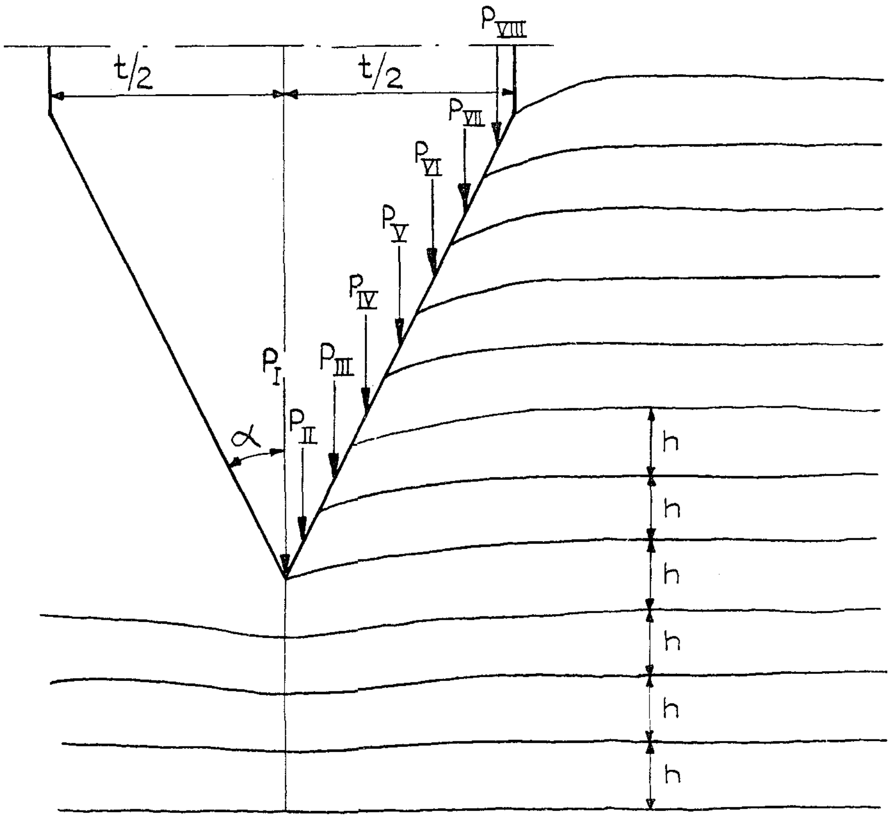

Fig. 14 The beam model during shearing

At maximum bending moment the derivative of M with regards to x shall be zero. This gives tan $\lambda x = 1$. The distance "a" from the point of action of the force to the maximum bending moment ("y" in Fig. 13) is therefore: $a = \pi/4\lambda$. If λ is substitued: $a = 2.66\ h/\left(\frac{E'}{E}\right)^{1/3}$

Therefore:

$$M_{Max.} = (-P/\lambda)(e^{-\pi/4}) \sin \pi/4$$

$$As\ \sigma = M/W, \text{ we get}$$

$$\sigma_{Max.} = 0.274\ Ph/W \left(\frac{E'}{E}\right)^{1/3}$$

In this formula a certain relationship between E' and E and the modulus of elasticity of the wood perpendicular to and along the grain, respectively, exists. McKenzie considered $E = E_L$ and found through comparisons $E' = 3.92\ E_T$. The latter value seems large and might vary with the direction of cut, but in the absence of a better value it must be used here. That the different directions of cut are not separated or defined in McKenzie's work seems to be a serious deficiency. Judging from a figure in his work, he seems to be working midway between radial and tangential cutting.

Only the first beam can be treated like a beam on an elastic foundation. For the other beams other assumptions have to be made. These have been treated here as ordinary cantilevered beams with the free length equal to the distance to the maximum bending moment for the first beam. The investigation of damage showed that the deflection damage was spaced at regular intervals within the beam. This distance may be the same as the distance between the points of action of the forces in Fig. 14. The moment arm will then be the same for all the forces. $= a$.

$$M = P \times a, \quad M = \sigma \times W \text{ gives}$$

$$\sigma_{Max.} = 2.66\, Ph/W \left(\frac{E'}{E}\right)^{1/3}$$

The different forces are then:

$$P_{\mathrm{I}} = A/0.274$$
$$P_{\mathrm{II}} = A/2.66$$
$$P_{\mathrm{III}} = A/2.66$$
$$\vdots$$
$$P_N = A/2.66$$

Where $A = \dfrac{W}{h}\, \sigma_{Max.} \left(\dfrac{E'}{E}\right)^{1/3}$

The investigation of damage showed (Fig. 12) that only the upper fibres of a ring were free from compression damage after radial shearing. From this can be concluded that the distribution of pressure in the beam during plastic deformation occurring during shearing is approximately as shown in Fig. 15. Suppose the ideal case in Fig. 16 to be true. Then the resisting moment will be $(bh^2)/2$. The total wedging force and edge force would then be:

$$\frac{bh}{2}\, \sigma_{Max.} \left(\frac{E'}{E}\right)^{1/3} \left(\frac{1}{0.274} + \frac{N-1}{2.66}\right)$$

To allow a computation of P during tangential and radial shearing E, E' and $\sigma_{\mathrm{Max.}}$ must be known for these conditions. As mentioned

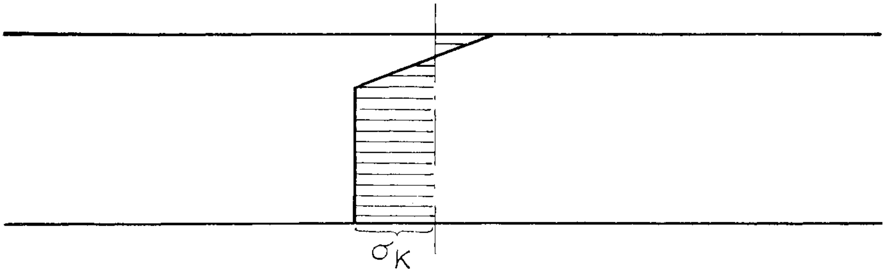

Fig. 15 Distribution of pressure in a plasticized annual ring

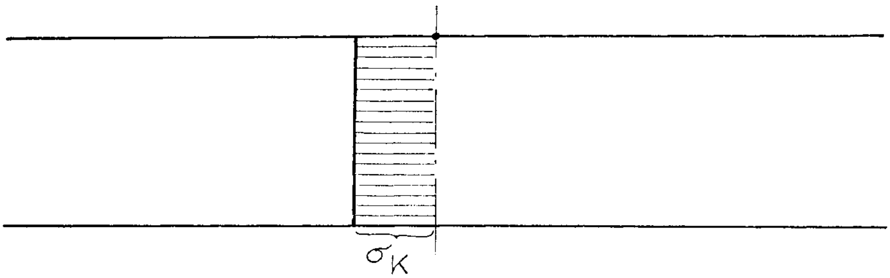

Fig. 16 Ideal plasticity in an annual ring

above, $E = E_L$ and $E' = 3.92\ E_V$. σ_{max} is the maximum compression stress the wood can stand. This value is different for tangential and radial shearing respectively, as during radial shearing the springwood will be most compressed, while during tangential shearing the whole ring will be equally compressed.

With $E_T = 2{,}000$, $E_R = 3{,}000$ and $E_L = 90{,}000$ kp/cm^2 we obtain: (for tangential shearing)

$(E'/E)^{1/3} = (3.92\ E_T/E_L)^{1/3} = (0.087)^{1/3} = 0.443$

In the same way for radial shearing:

$(E'/E)^{1/3} = (3.92\ E_R/E_L)^{1/3} = (0.131)^{1/3} = 0.507$

To allow a comparison with the investigation of damage it might be desirable to find "a" the distance to the maximum bending moment. $a = 2.66\ h/(E'/E)^{1/3}$

In radial shearing $E'/E)^{1/3} = 0.507$ according to the above. Then for a width of an annual ring of 2 mm, "a" $= 2 \times 2.66/0.507 = 10.5$ mm. This value coincides roughly with the concentration of slip lines that can be thought to represent the maximum bending moment.

The factor $\sigma_{max}(E'/E)^{1/3} =$ is therefore at tangential shearing $= 89$ ($\sigma_{max} = 200$ kp/cm^2) and at radial shearing $= 71$ ($\sigma_{max} = 140$ kp/cm^2). Calculated per centimeter of the length of the edge, $b = 1$ cm.

Now one can calculate the values of K_{tot} for any knife, i.e. Knife 2: $t = 5$ mm, $\alpha = 22.5°$, $\tan \alpha = 0.414$. Assume the width of an annual ring $h = 2$ mm.

$N \leqq 1.5 + 5/1.65 = 4.81 \qquad N = 4$

Therefore, for tangential shearing with knife 2:

$K_{tot} = 0.2 \times 89(1/0.274 + 3/2.66) = 85$ kp/cm.

Similarly for radial shearing with knife 2:

$K_{tot} = 0.2 \times 71 \times 4.78 = 68$ kp/cm.

The calculations explain what was discussed about actual cutting force in Chapter 4. Apparently, this is the part of the cutting force due to the elastic foundation, while what was discussed as wedging force is the addition caused by the pressure distribution in the beams themselves. This explains the differences in cutting forces pointed out by Kivimaa (1952) and Hartler (1963a) on the one hand, and those measured on the Busch Combine (Samset 1962) and by the author, on the other. The "cutting force" measured by the author should therefore be called "base force" instead. This base force probably explains the discrepancy between the measured wedging force and the measured total cutting force. For it seems very probable that a larger edge angle would cause a wider foundation from the underlying wood and thereby a larger base force. Unfortunately, the investigation did not provide data possible to analyse from this point of view. Therefore, the base force is still an unsolved problem. From the previous discussion it is, however, possible to conclude that the actual cutting force is so low that sharpness of the edges does not affect the cutting force very much.

7. Summary

7.1. Conditions

The investigation was carried out on squared fresh spruce and with a knife against a static anvil. The edge and the anvil were parallel to each other and perpendicular to the direction of cut. The thickness of the knives was 5—10 mm, the edge angles were 30°—60° and the cutting speed 4—22 cm/sec. The width of the wood was 6—20 cm and the height 6—16 cm. The width of the anvil was 7.5 cm. All shearing was perpendicular to the grain.

The above-mentioned conditions do not entirely correspond to those which might occur in practice. The investigation was therefore limited to include trends and magnitudes within certain ranges influencing cutting forces and damage. The major objective of the investigation was thus to acquire further knowledge of what happens in the wood from this new application of shearing.

7.2. Results

The values given below should be regarded as rough guides extracted from the results. Discussion and limitations appear throughout the body of the publication.

7.2.1. The base force

The base force is believed to be of the order of magnitude 50 kp/cm of the length of the edge. The sharpness of the edge is probably of less importance.

7.2.2. The specific wedging force

For warm wood this is of the magnitude of 100 kp/cm^2 of projected surface of the edge* at an edge angle of 30°, 125 kp/cm^2 at an edge angle of 45° and 160 kp/cm^2 at an edge angle of 60°. This gives wedging forces of 95, 75 and 70 kp/cm respectively for 5 mm thick knives. The low value for the 60° angle is insufficiently verified and is

* The projection is on a plane parallel to the plane of cut so that the projected surface of the edge = the surface of the edge times cos α.

contradicted by its high value for the total shearing force. For frozen wood the variations are larger, depending on the amount of heartwood, but the wedging force is then about twice as large as that for warm wood.

7.2.3. *The specific frictional force*

This is of the magnitude 20 kp/cm^2 of the surface on the knife for warm wood and 15 kp/cm^2 for frozen wood, when the pressure on both sides is approximately 50 kp/cm^2. Thus for a 5 cm active width of the knives the frictional force is of the magnitude 100 kp/cm for warm wood and 75 kp/cm for frozen wood.

The total shearing force for a 10 mm thick knife was approximately 50 per cent larger than that for a 5 mm thick knife. This was probably due to the doubling of the wedging force caused by the doubling of the surface of the edge. The total shearing force for a 60° edge angle was approximately 30 per cent larger than those for 45° and 30° edge angles.

7.2.4. *Knots*

These increased the shearing force up to 50 per cent.

7.2.5. *Damage*

A 10 mm thick knife with an edge angle of 45° caused damage of about 30 mm on warm wood. A 50 per cent reduction of the thickness of the knife resulted in a 50 per cent reduction of damage. A reduction of the edge angle to 30° had the same effect. An increase in the edge angle to 60° caused a doubling of the damage. The wedge angle seems to have a greater influence on damage than has the edge angle.

Frozen wood split more. The splits extended approximately 50 per cent further in the frozen wood than in the warm wood.

7.2.6. *What happens to the wood?*

Usually, splits occur parallel to the grain in front of the edge. In this way they occur periodically and form "beams". In radial shearing the splits occur at the abrupt transition between the spring wood and the summer wood of adjacent annual rings. In tangential shearing splits occur and "beams" of about the same height as the width of the annual rings are formed. These beams are bent by the edge of the knife. The resistance they cause originates partly from the pressure distribution in the beam itself and partly from the foundation formed by the underlying wood.

In radial shearing (similar for tangential shearing) each annual ring thus behaves like a beam on an elastic foundation. It should therefore be possible to calculate the resistance using formulae from mechanics of materials. This has been tried by the author. Such calculations must, however, be very rough approximations. This is partly because of the limited knowledge of all strength characteristics of wood and partly because of the decreasing accuracy of the formulae when the deformations are as large as those in this case.

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Sammanfattning

Krafter och skador vid hydraulisk trädklippning

1. *Förutsättningar*

Undersökningen har utförts på fyrkantsågat, färskt granvirke och med en kniv mot ett fast mothåll. Eggen och mothållet har varit parallella, vinkelräta mot skärningsriktningen. Knivtjocklekarna har varit 5 till 10 mm, eggvinklarna 30° till 60° och skärhastigheten 4 till 22 cm/sek. Virkesbredden har varit 6 till 20 cm, virkeshöjden 6 till 16 cm och mothållsbredden 7,5 cm. All skärning har skett vinkelrätt mot fiberriktningen.

Ovanstående skärförhållanden motsvaras inte helt av dem som kan tänkas uppstå i praktiken, varför undersökningen begränsats till att omfatta tendenser och storleksordningar av vissa inflytanden på skärkrafter och skador och huvudsakligen inriktats på att ge ökad kunskap om vad som händer i träet vid detta nya sätt att skära.

2. *Resultat*

Nedan angivna värden kan anses som grova riktvärden hämtade ur resultaten. Diskussion och begränsningar framgår av arbetet som helhet.

Krafter. Baskraften är troligen av storleksordningen 50 kp/cm egglängd. Eggskärpan torde spela mindre roll.

Spec. kilkraften är vid varmt virke av storleksordningen 100 kp/cm² projicerad eggyta vid 30° eggvinkel, 125 kp/cm² vid 45° eggvinkel och 160 kp/cm² vid 60° eggvinkel.* Detta innebär vid 5 mm tjocka knivar kilkrafter på 95, 75 resp. 70 kp/cm. Den låga siffran för 60°-vinkeln är dåligt verifierad och motsäges av 60°-vinkelns höga totala skärkraft. Vid fruset virke är variationerna större beroende på kärnhalten, men kilkraften är då ungefär dubbelt så stor som vid varmt virke.

Spec. friktionskraften är av storleksordningen 20 kp/cm² knivyta vid varmt virke och 15 kp/cm² vid fruset virke. Friktionskoefficienten är därvid ca 0,20 på varmt och 0,15 på fruset virke och trycket på båda knivsidorna ca 50 kp/cm². Vid 5 cm verkningsbredd på knivarna blir alltså friktionskraften av storleksordningen 100 kp/cm vid varmt virke och 75 kp/cm vid fruset virke.

Totala skärkraften vid 10 mm tjock kniv har varit ca 50 % större än den vid 5 mm tjock kniv. Troligen beror detta på den fördubbling av kilkraften, som logiskt följer med en fördubbling av eggytan. Totala skärkraften vid 60° eggvinkel har varit ca 30 % större än den vid 45° och 30°.

Kvistar ökar skärkraften med upp till 50 %.

Skador. En 10 mm tjock kniv med 45° eggvinkel orsakar skador av stor-

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* Projektionen tänkes utförd på ett plan parallellt med snittplanet, så att den projicerade eggytan = eggytan gånger cos α.

leksordningen 30 mm på varmt virke. Halvering av knivtjockleken medför halvering av skadorna, liksom även en minskning av eggvinkeln till 30°. Ökning av eggvinkeln till 60° medför fördubbling av skadorna. Kilvinkeln tycks vara mera bestämmande för skadorna än eggvinkeln.

Fruset virke spricker något mera — sprickorna går ca 50 % längre in i virket än de gör vid varmt virke.

Vad händer i virket? — Det vanligaste är att virket spricker längs fibrerna framför eggen och på så sätt skiktar upp sig i balkar. Vid radiell skärning sker sprickbildningen i den tvära övergången mellan vår- och höstved, sett i skärningsriktningen mot centrum av virket. Vid tangentiell skärning bildas också balkar av ungefär samma höjd som årsringsbredden. Dessa balkar böjs ut av kniveggen, och det motstånd de därvid ger upphov till bildas dels av tryckfördelningen i själva balken, dels av det stöd det underliggande virket ger. Varje årsring beter sig alltså vid radiell skärning (motsvarande gäller även vid tangentiell) som en balk på elastiskt underlag, och dess motstånd mot utböjningen borde alltså kunna beräknas med formler från hållfasthetsläran. Förf. har försökt göra detta, men sådana uträkningar måste bli mycket approximativa, ty dels vet man för litet om träets alla hållfasthetsegenskaper, dels blir alla formler mycket approximativa när deformationerna blir så stora som i detta fall.