Stress relaxation in solid wood bending

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Abstract:

It is widely known that wood has viscoelastic properties. These properties have to be considered after bending during the stabilisation.

For the bending process, a strap has to be used on the convex side of the bending, if the ratio between the form and the thickness of the wood exceeds 6% (beech, *fagus sylvatica l.*). Wood usually allows only little expansion due to tension. Therefore this strap is to limit the tension forces on the convex side of the bending. During the bending, two kinds of deformation appear: plastic (or viscous) deformation and viscoelastic deformation. Because of the viscoelastic ratio, a long relaxation time (6 h - 36 h) is required in which the workpiece is fixed with clamps and the strap. If the workpiece is released too soon, after-bending breaks may appear.

The relative amount of plastic and viscoelastic deformation and the time of uninfluenced viscoelastic relaxation are measured. Then the wood is exposed to a radio frequency field. The appearance of thermal gradients, decrease of moisture, stress relaxation and the energy in this field are traced.

There is a direct relation between the stress relaxation and the decrease of the moisture content. Depending on the position of the electrodes, the thermal gradients react differently.

1 Introduction

Solid wood bending is a well known production method. In former times, bended wood was mainly used for planking hulls of ships. In the middle of the 19th century, the German carpenter Michael Thonet developed a method for solid wood bending. He noticed that wood while bending always splitted on the outermost side. He stopped the breaking by supporting the wood by a metal strap on the convex side. Therefore, the wood bending method by using a strap is also called the Thonet Method.

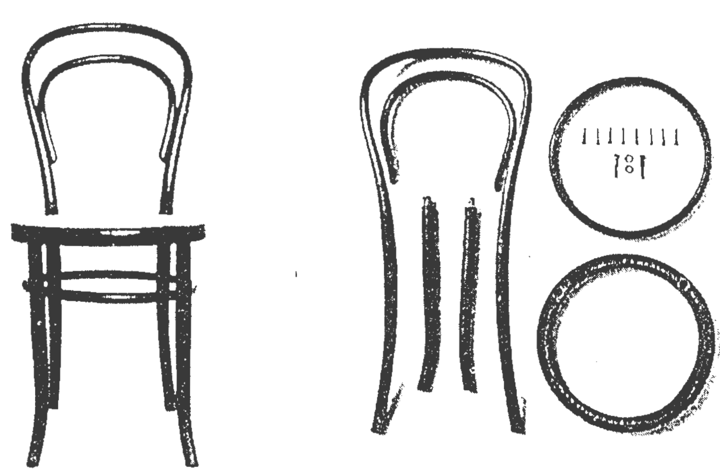

Figure 1: Typical bentwood chair (Thonet No. 14)

Since those days, the major field for wood bending is chair production. Figure 1 shows a typical bentwood chair. Due to good material properties, bentwood was also used in aircraft production (mainly until the end of W.W.II) and it is still used for different types of sport sledges.

Even if wood bending is widely used and a long-known production method, some questions are still unsolved. One of them is, why does wood split after the bending operation, even if the bending was done well? Another question is, how should a radio frequency field be applied to accelerate the process.

2 Solid wood bending

2.1 Stages of the process

During the solid wood bending, three stages have to be passed: softening - bending - stabilising, figure 2.

While softening, the wood is heated up to a temperature of at least 80°C and a moisture content of more than 15% relative moisture has to be reached. Together, the influence of moisture and temperature softens the wood /1 - 4/ to a viscoelastic state.

In the bending stage, the workpiece gets its shape. There are different ways to bend solid wood, depending on pre-treatment, material thickness perpendicular to the bending axis (d) and bending radius (r - inner radius of the workpiece / outer radius of the mould) /5/. In general, wood allows only little expansion due to tension. Beech (*fagus sylvatica L.*), a very common used wooden species for bending operations usually needs to be supported by a metal strap if the ratio d/r exceeds 1/16. This strap is clamped to the wood on the convex side, where the tension load appears, figure 3.

Because of the cellular structure of wood, compression load can be absorbed easily by deformation. This causes simultaneously an increase in density. Because there is no remarkable change in profile while bending, wood can be considered as a non-constant-volume material.

Depending on the type of machine and the kind of geometry, the average time for bending is about 5s to 20s. After bending, the wood is still in the viscoelastic state. That means the relative amount of elastic deformation will spring back, while the relative amount of viscous deformation stays in the reached shape. To avoid this spring back, the workpiece has to be fixed to its position until the relative amount of elastic deformation has changed to viscous deformation. This change can be considered as stress relaxation. Then the clamping can be released. From now on, the workpiece will stay in shape.

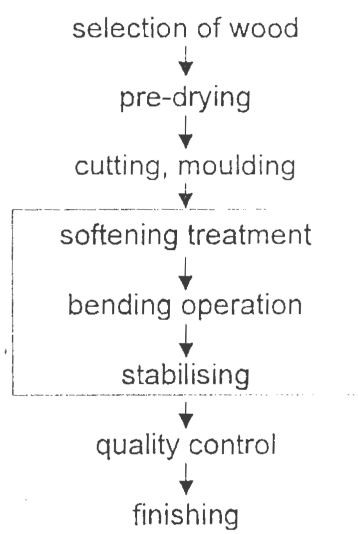

Figure 2: Stages of the wood-bending process

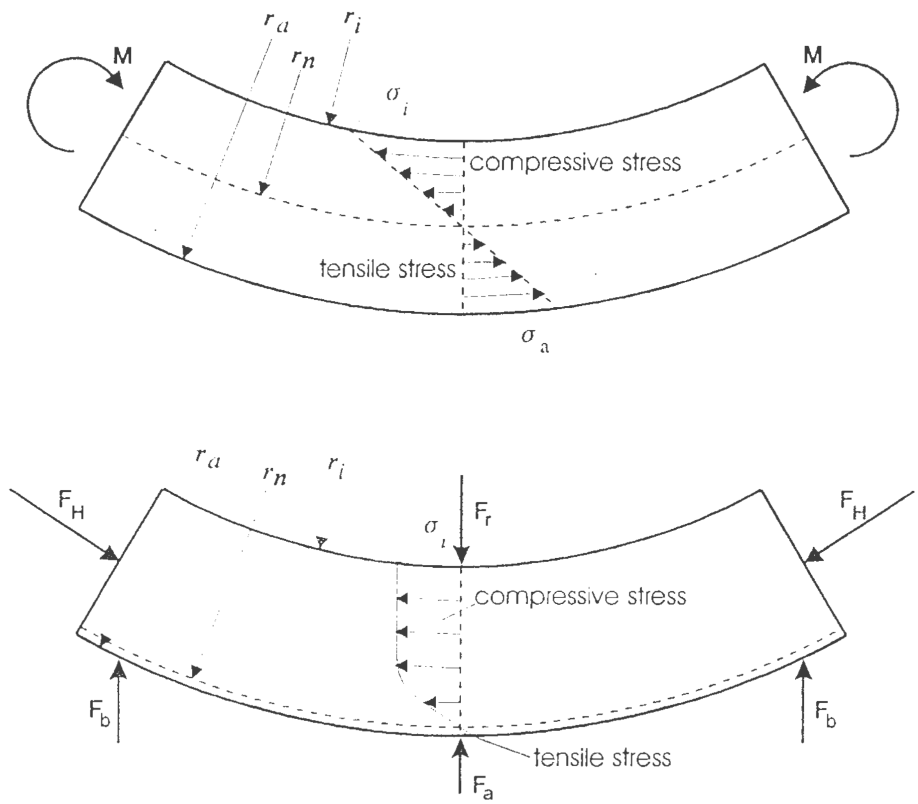

Figure 3 : Wood bending using a metal strap

It has to be considered however, that the natural sorption properties of wood can cause slight changes in curvature due to moisture change /6/. The time required for stress relaxation depends on the geometry of the work-piece and on the environmental conditions. Without any technical support, exposed to a static climate of 20°C, 55% r.h. and without the influence of sunlight, the relaxation time after bending for a chair frame part with a thickness of about 30mm takes between 10 and 30 hours.

2.2 Material properties of wood

It is widely known that materials having a non crystal microstructure react by a time-related response on a constant load. This reaction is called viscoelastic. Wood has a cellular set-up, and due to this structure it has viscoelastic properties /7 - 22/.

A widely used model for viscoelasticity contains a single spring (elastic element, ε_{el}), a single damping unit (viscous element, ε_v) and a parallel combination of one spring and one damping unit (viscoelastic element ε_r). This Burger-Kelvin Model /23, 24/, is shown in figure 4.

Investigations of Kollmann /7 - 9/, Kühne /10, 11/ and others showed that with an increase of moisture contents, wood gets softened. Together with other authors, Mukudai described the creeping of wood under bending load under certain circumstances. He defined a linear and a non-linear range of deflection and proved the influence of the moisture content on the creeping of wood /16/.

A closer approximation of the material properties could be done by adding more mechanical elements to this set up. In fact, even if this set up of elements can be considered as rather simple, there is probably no need for a closer approximation for the model to real behaviour, because tests on the Young's modulus (bending) showed that for example the mechanical properties of one species vary more than +/- 30% even in a single stem.

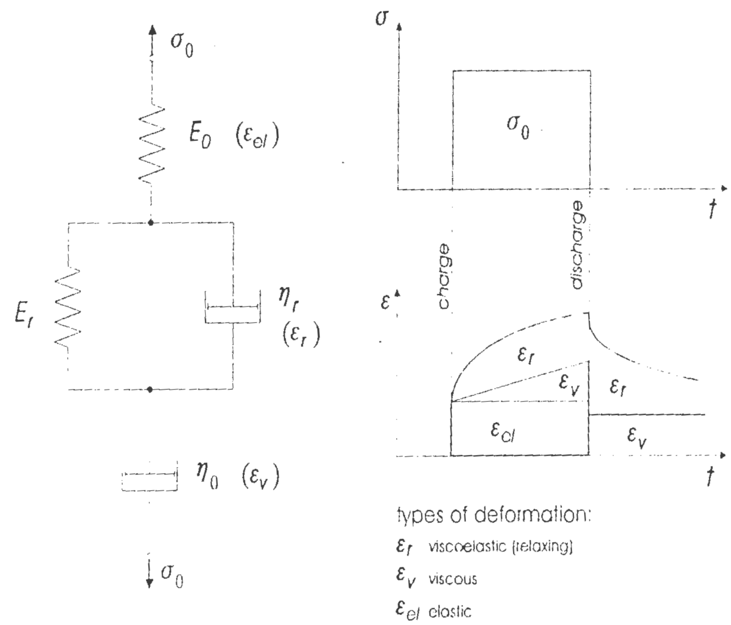

Figure 4: Burger-Kelvin model of viscoelastic material properties /25/

Models of viscoelasticity helped to investigate and understand the influence of parameters like moisture content and temperature on the stability of form. Investigations however of how to affect the stress relaxation of bentwood and how to accelerate this process have not been known up to now.

3 Behaviour of wood while bending and stabilising

3.1 Description of set up

The investigation of the behaviour of wood during the bending and stabilisation process means first of all, to collect in-process data about tensions and forces while bending. The following set-up was used to monitor the torque while bending wood and the compression force of wood in this process, figure 5.

The wood species for all the described investigations was beech (*fagus sylvatica L.*), because in Europe at the present time beech is used for about 95% of all bendings.

The set up is based on a wood bending machine for symmetrical bendings which was supplied by *GHEbavaria*, Eibelstadt (Germany). A metal strap and a fixing between the two edges of the wood carries the reaction forces due to the compression of the wood while bending. The second principal stress force is applied by a pneumatic piston which presses the bentwood to the mould.

To monitor all mechanical loads, the described machine is equipped with sensors. Wire strain gauges are mounted to the columns. The length of the lever arm depends on the bending angle. Therefore, position values from an angle indicator are transferred to the data acquisition software in a personal computer, where the torque is calculated from the bending force and the lever arm value.

The compression pressure on the edge of the wood is measured by a pressure head, which is attached to a hydrostatic cylinder. This cylinder is used as fixing between the strap and one edge of the wood. A second pressure head is used for monitoring the pneumatic pressure between the wood and the mould. Since pressure remains constant in all tests, the data is not shown. All data are transferred to an A/D board of a personal computer and collected by acquisition software.

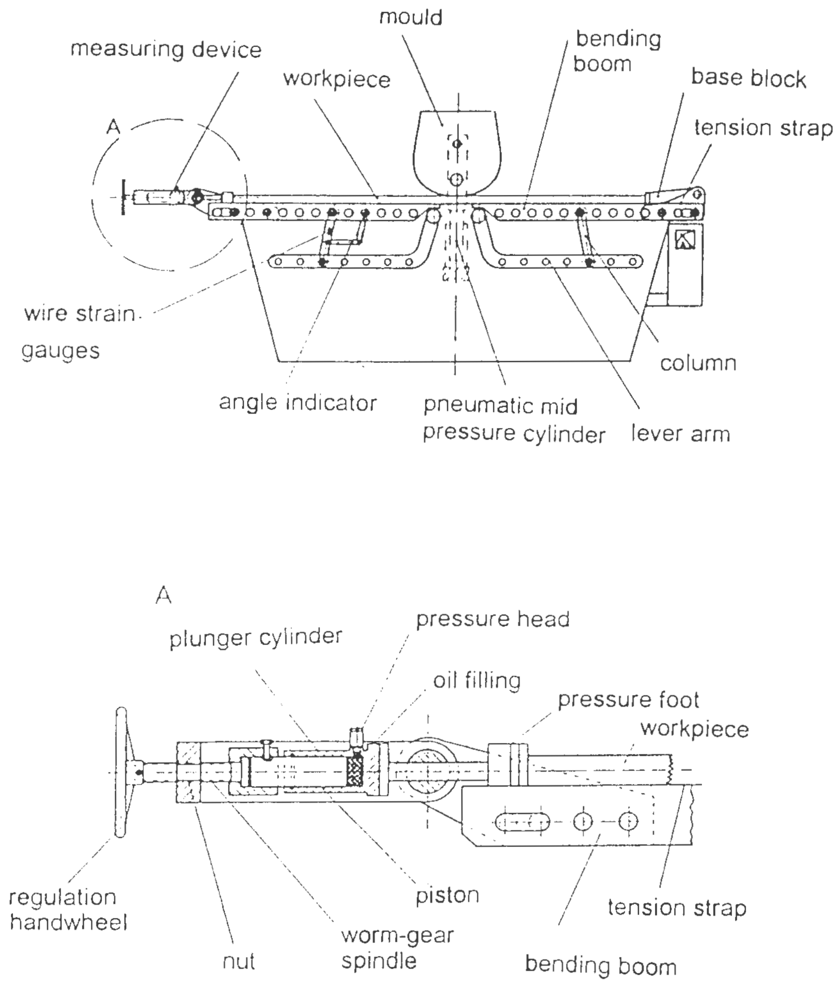

Figure 5: Set up to investigate forces and deformations of the wood - strap system

3.2 Bending process

During the bending process, wooden cells are compressed. The compression depends on the position of each cell, but it can be said that all cells with the same relation between bending radius and distance from the tension-free layer in the direction to the bending axis have about the same compression ratio. The compression pressure however does not only depend on this relation. It was found that the conditions of growth have a major influence to the compression load of the bentwood.

When the compression pressure is monitored, a constant increase can be figured out. The increase depends on a number of points. One major point is the volume being compressed during the bending operation. According to Prodehl /26/ the bending speed also affects the pressure load, but no investigations were made on this point. Figure 6 shows a typical load chart for the compression of the wood while bending.

Beside the compression load of bentwood, the required torque for the bending operation can be measured. For a constant profile and a constant bending geometry, the required bending torque remains constant during the operation /27/. Tests at different speeds did not show a significant relation between the bending speed and the bending torque. Figure 7 shows the torque chart, related to the data of figure 6.

With this set-up the bending speed was changed to several values between 2°/s and 6°/s. There was no significant difference in torque while bending with higher or lower speeds.

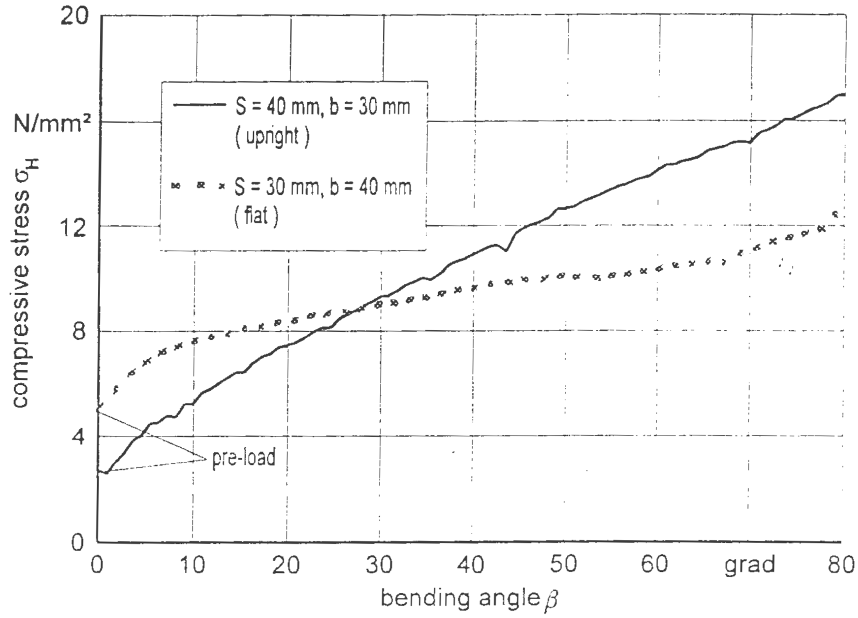

Figure 6: Typical load chart for the compression of wood while bending. R = 170 mm.

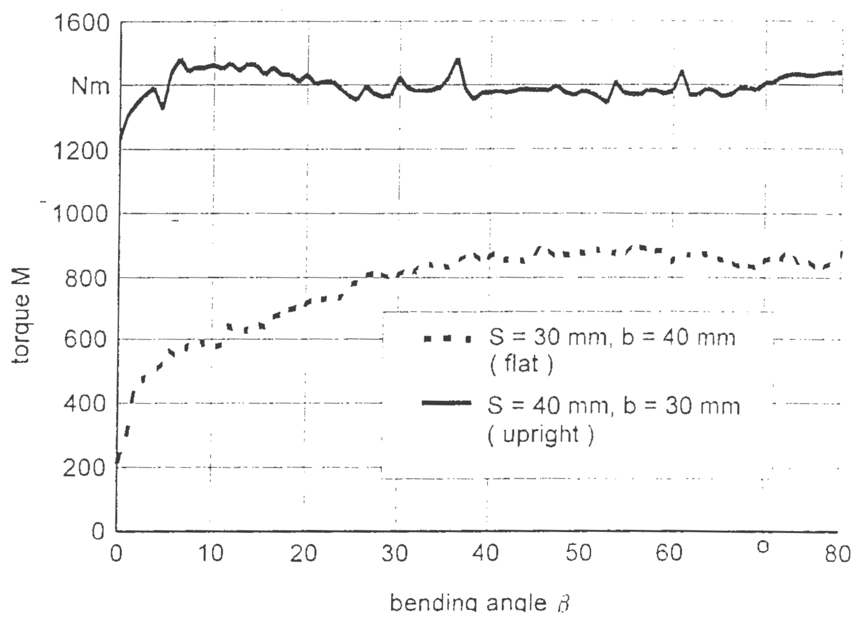

Figure 7: Typical load chart for the bending torque of wood. R = 170 mm

3.3 Uninfluenced stabilisation

During the stabilisation period, bentwood has to be fixed to avoid a spring-back. Besides that, different sources report about wood that splits from time to time during the stabilisation period, when it was released from the strap before. Figure 8 shows the typical behaviour of bentwood for one minute after starting the bending operation. It is obvious that this behaviour is caused by viscoelasticity.

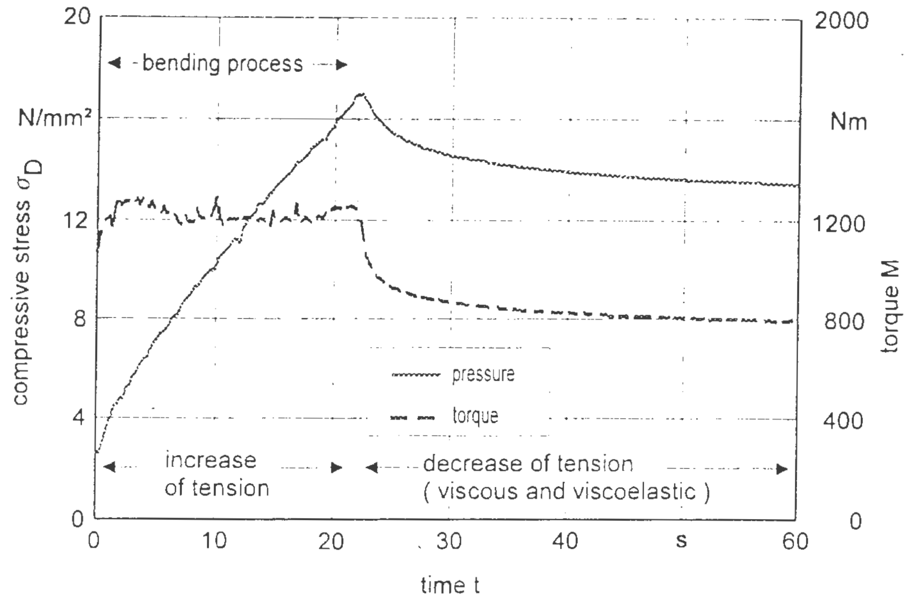

Figure 8: Typical behaviour of torque and end pressure

Where figure 8 only shows a short time period, data of a long time cycle should be collected, too. This is shown in figure 9, where data were taken for 90 minutes. A longer process of data collecting was not seen as useful, because changes after that time were only very little. There might have been a drift in the metering system, too.

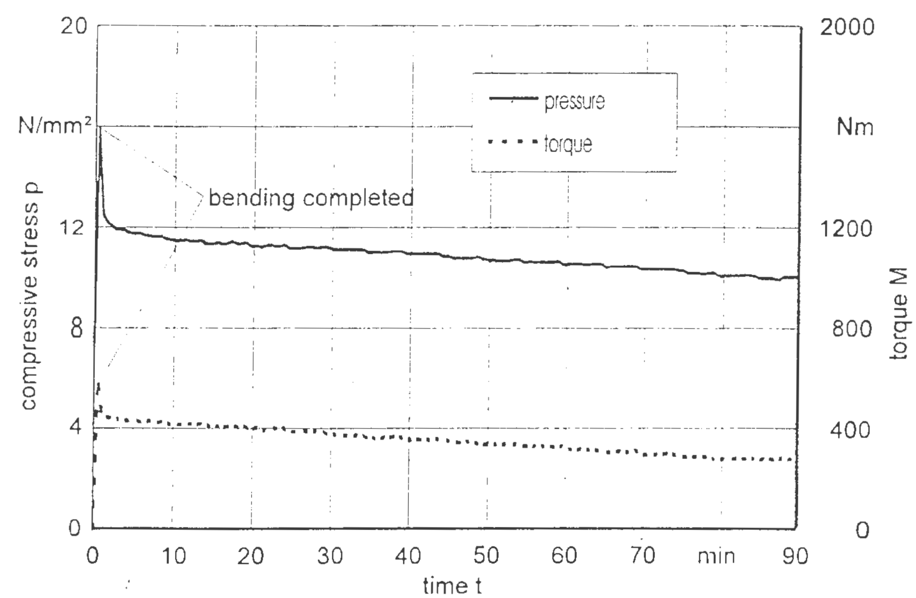

Figure 9: Decrease of forces of reaction of wood after a bending operation.
Beech (*fagus sylvatica L.*), 40 x 30 x 720mm²

The graph of the end pressure and the graph of the torque show exactly the same behaviour after the bending operation has stopped. For about 40 s after the bending machine has stopped, there is a strong decrease in the torque of reaction and the end pressure of reaction. During this period, about 30% of the total tensions are discharged. According to the Burger-Kelvin model it is suspected, that during this period first there is a viscuos

4 Behaviour of bentwood when heated in a radio frequency field

4.1 Description of set up

It is widely known that wood can be softened or stabilised by a radio frequency field. Investigations on the softening treatment by exposing wood to a radio frequency field are widely known. Therefore, the following tests focus the stabilising process. But because of technical reasons, the set-up described in chapter two could not be used for the following investigations. Mainly a defined radio frequency field could not be applied on the workpiece without influencing the machine and all attached sensors.

A small veneer press was used for the following investigations. The described press is hydraulically operated and was equipped with a bending device as shown in figure 10. The radio frequency field was applied to the workpiece by two electrodes, acting like a capacitor with the workpiece in between. The anode consisted of a metal layer which covered the mould (isolator), where the metal strap of the bentwood worked as cathode. To guard personal and measuring devices, the working space was surrounded by a faraday shield.

Data for the bending torque was taken by a pressure head from the hydraulic feed system (force) and a linear measure (lever arm) outside the shield. For data analysis the above described system was used. Where thermocouples had to be used for temperature measurement, the radio frequency power was interrupted during the measuring and then re-established.

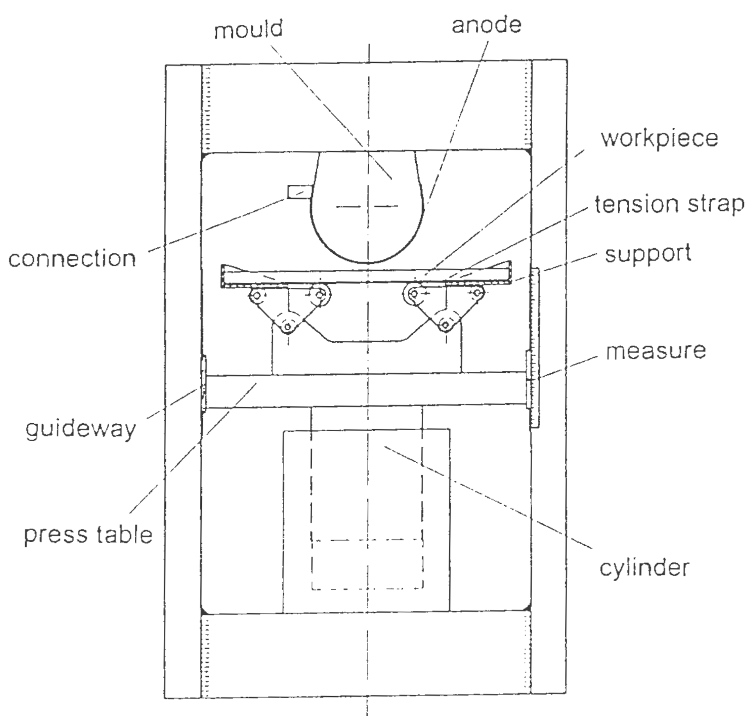

Figure 10: Bending device based on a small veneer press

4.2 Stabilisation

In figure 9 it could be seen that the viscuos behaviour of the end pressure and bending torque have the same characteristic. That allows us to monitor only the behaviour of the torque and then to estimate the behaviour of the pressure tension.

When exposed to a radio frequency field, the remaining viscuos and viscoelastic tensions decrease rapidly. As a sign for that, the torque chart can be monitored and compared to the torque chart of an uninfluenced (not exposed to a radio frequency field) stabilisation, as can be seen in figure 11.

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As can be seen in this chart, the tension decreases and finally disappears within six minutes when exposed to the radio frequency field. In this field the electrical power consumption is 7 Wmin/cm³. The value of the power consumption corresponds to the decrease of humidity of the workpiece, figure 12.

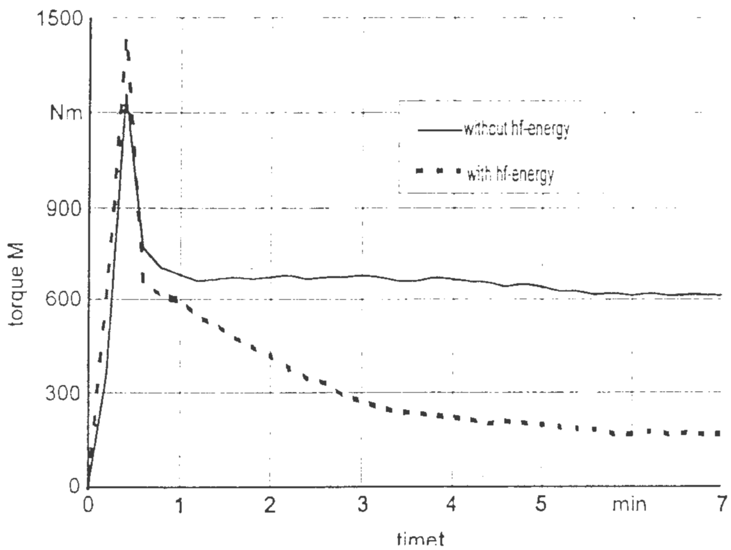

Figure 11: Relaxation of bending torque with and without exposure to a radio frequency field

As a second sign for the stess relaxation, the change of curvature can be considered. This method was invented by Aoki and Norimoto /6/ and refers to the spring back of bentwood after a certain period in time. If there is a complete stress relaxation, no change in curvature should be noticed over a period of two days or more.

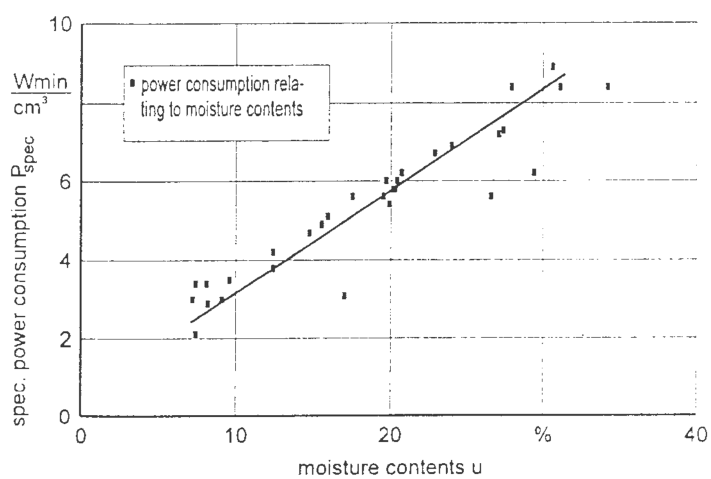

Figure 12: Power consumption in relation to moisture contents. Beech, 30 x 30 x 720 mm³

Figure 13 shows the change in curvature within a period of 48 hours after the stabilisation in a radio frequency field, depending on the final moisture content. A number of 30 samples were monitored. The length of the tangent was measured right after the stabilisation in the radio frequency field. After two days in a constant climate, the length of the tangent was measured again. After the high frequency stabilisation, more than half of the samples had a moisture content of less than 13.4% and a change in curvature of less than 3mm. With a total length of the tangent of 425mm, the change in curvature was less than 0.7%. It is estimated, that this final change in curvature originated by internal drying tensions.

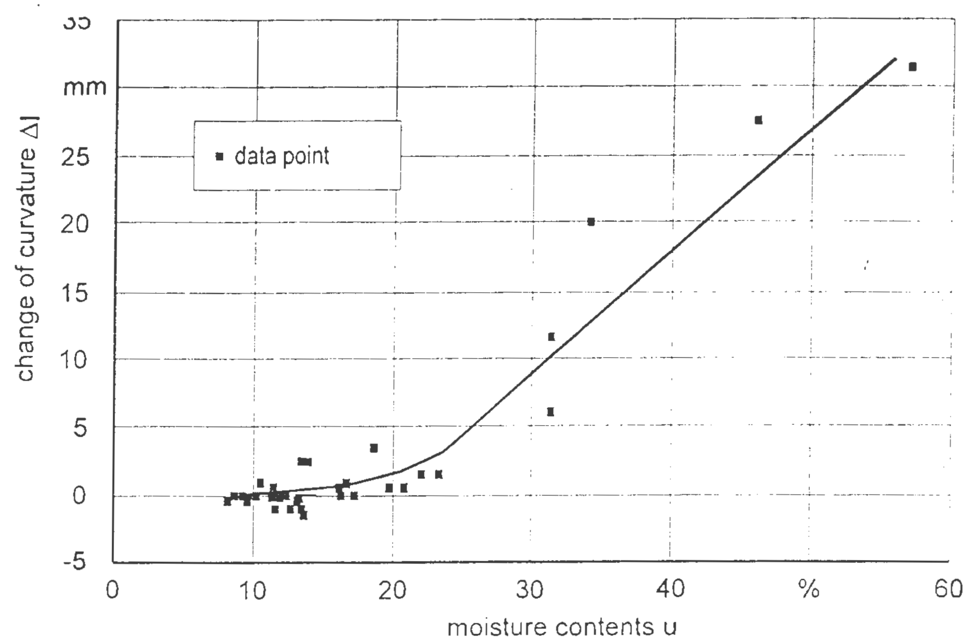

Figure 13: Change of curvature after 48 hours, when first stabilised in a radio frequency field.

4.3 Thermal behaviour

The thermal behaviour of wood when heated in a radio frequency field can be an indicator for the mechanism of heating. If in a standard atmosphere the temperature should not exceed a level of approximately 120°C, then the temperature could be a sign of the internal vapour pressure of the wood. It could be said that only the polarising energy of the radio frequency waves heat the water molecules. If the temperature exceeds the estimated level of 120°C distinctively, other influences may superimpose the radio frequency field. Figure 14 shows the thermal progress.

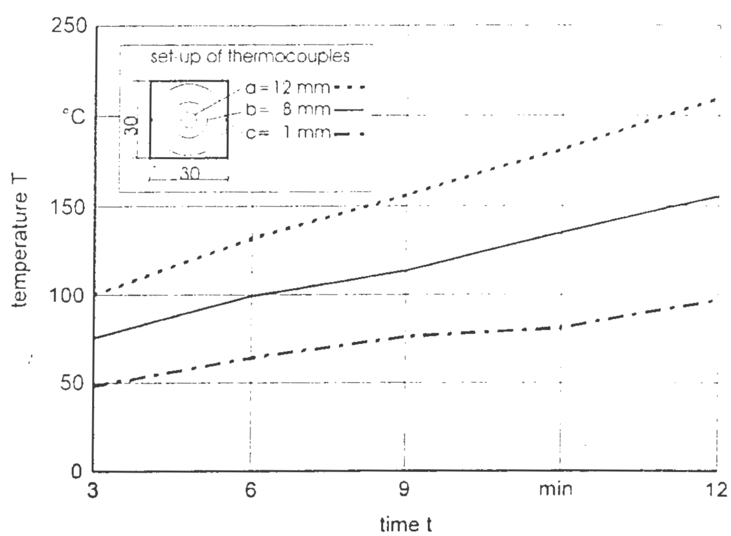

Figure 14: Thermal progress of wood when heated in the bending press (see fig. 10)

Because the electrodes are touching the workpiece on both sides, it could be imagined that there might be an addition to the electromagnetic energy, by a resistance heating according to the law of Ohm. To monitor the thermal behaviour, thermocouple elements were attached to the wood when the electromagnetic energy was interrupted.

It can be seen that the temperature has a linear increase according to the time. When the temperature exceeds t = 250°C, a thermal disintegration process starting in the centre of the material can be noticed. It can be said that the electric resistance of wood enables the resistance heating which exceeds the vaporisation point of water inside the wooden cells remarkably. If there would have been a pure heating by the radio frequency field, the temperature would be constant over the profile and would not exceed the vapour temperature.

5 Summary

After the bending operation wood has to be fixed in shape to avoid a spring-back. The internal forces which cause spring-back result from the viscoelastic properties of wood.

The fraction of viscoelastic tensions has to be converted to plastic deformation to avoid after- bending damages and to ensure no unwanted deformation after the bending process. This can be done by drying the wood in the bended shape and with the strap still on it. If the moisture content can be reduced to less than 14% after the bending operation, a high accuracy in shape of the bending parts can be reached.

Wood can be dried by a radio frequency field. If bentwood is stabilised by drying in a radio frequency field, the viscoelastic tensions decrease rapidly and change to plastic deformation. In this process, beech requires an electric power of about 7 Wmin/cm³.

There are two ways to heat wood in a radio frequency field. If the material does not touch the electrodes, only the water molecules are heated. Then, the temperature does not exceed the vaporisation point. If the electrodes are touching the workpiece however, there is a superimposing of the effects of the radio frequency field and a resistance heating. This superimposing leads to temperatures of more than 200°C. This effect can lead to thermal disintegration of the material.

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