BENDING SOLID WOOD TO FORM

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BENDING SOLID WOOD TO FORM

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Introduction

Wood bending, an ancient craft, is of key importance in many industries
today -- notably furniture, boats and ships, agricultural implements,
tool handles, and sporting goods. Of the several methods commonly used
to produce curved parts of wood, it is perhaps the cheapest, conserves
material, and produces a member of high strength.

Despite its long practical history and advantages over other methods,
however, there is no method of wood bending that guarantees 100 percent
success. Long experience has evolved practical bending techniques, and
skilled craftsmen to apply them. Yet commercial operators are often
plagued with serious losses due to breakage during the bending operation
or the fixing process that follows. There is a long-felt need for more
reliable knowledge about such factors as (1) selection of bending stock,
(2) seasoning and plasticizing of wood to prepare it for bending, (3)
efficient machines for the bending operation, (4) drying and fixing the
bent part to the desired shape, and (5) the effect of bending on the
strength properties of wood.

This report presents results of research on wood bending and related in-
formation as developed at the U. S. Forest Products Laboratory and other
laboratories over a period of years, together with investigations and ob-
servations in furniture factories, ship and boat yards, and other plants
where wood bending is done commercially. At the outset, however, it should
be understood that much fundamental information is still lacking about the
basic factors involved, and that the conclusions and recommendations given,
while based upon the most reliable data available, are limited by that
fact.

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[1] Maintained at Madison, Wis., in cooperation with the University of
Wisconsin.

<u>How Wood is Bent</u>

It is common knowledge that a very thin strip of wood can be easily bent with the hands to quite sharp curvature. Thin veneers are actually so bent in making baskets and other products, being held in shape by weaving them together or attaching them to other parts. Such bending is done without treating the wood to soften or plasticize it.

This report deals with the bending of thick pieces of solid wood, for which softening with steam or hot water, or plasticizing with chemicals, is essential. Softening permits the wood to adjust itself to the distortions imposed by the bending operation. Briefly dealt with also are the bending of laminated stock and veneered material.

When a piece of wood is bent, it is stretched along the outer, or convex, side of the bend and compressed along the inner, or concave, side. Thus the bent piece is so distorted that its convex side is longer than its concave side. The convex side is stretched, or in tension, and the concave side is pushed, or in compression. These distortions are accompanied by stresses that tend to bring the bent piece back to its original straightness.

The purpose of softening wood by the action of moisture and heat or by means of plasticizing chemicals is to restrict the development of these stresses. Plasticized wood can be compressed considerably but stretched very little. The objective in bending, therefore, is to compress the wood and restrain it from stretching along the convex side. The usual method of doing this is to place a metal strap around the convex face of the piece and pressure blocks and fittings at its two ends; together the strap and pressure blocks function to prevent, or at least greatly minimize, tension in the convex side as bending force is applied.

Figure 1 illustrates the actions that occur in bending a piece of wood. A tension strap and end fittings are used to prevent stretch. A mathematical analysis of the bending action and reaction is given in the Appendix to this report.

The resistance of wood to bending forces at the point of contact of the piece and the bending form, point 0 in figure 1, is approximately constant at all times as bending proceeds. The unbent part of the piece is, in effect, a lever and point 0 a fulcrum as bending force is applied. As this lever arm, represented by the distance L plus X, becomes shorter, the bending load, P, needs to be increased. At the same time, however, the resistance to end pressure, or push, represented by $\underline{P}'$, is also constant, and as a result PX must remain constant. Since $\overline{X}$, representing the length of the end fitting, is a constant, the load P must also remain constant. P, however, cannot remain constant, because as the stick is bent the lever arm L+X becomes shorter. P, therefore, must be increased as the bending progresses. If P increases, PX increases, and the end

pressure is thereby increased. Since the resistance to end pressure, P', remains constant, the increased end pressure must result in crushing of the end of the stick, or in back bending or buckling. As a result, this type of apparatus applies either too much end pressure during the late stages of bending or too little during the early stages.

A simple device that automatically compensates for the higher end pressure induced by increased bending loads is shown in figure 2. This device is known as the reversed lever. By exerting pressure on the convex face of the piece, it prevents the end block from overturning. If the end block overturns, the end pressure is lost. Preventing the overturning of the end block assures the application of end pressure. The pressure against the block is generated by the piece itself as it is bent. The force required to bend the piece has no effect on the amount of end pressure thus generated. The reversed lever must extend back as far as the last point of contact between the stick and the form in order to regulate end pressure and prevent reverse bending near the end of the piece. An approximate mathematical analysis of the stresses in the steel strap and in wood bent with this type of apparatus is given in the Appendix.

Various devices used to bend wood are discussed in this report. Basically, however, the efficiency of a given operation may be judged to a great extent according to whether it satisfies the requirements that (1) tension must be avoided and deformation of the wood achieved by compression, and (2) end pressure must be regulated as bending proceeds. The two most efficient devices yet found by the Forest Products Laboratory to satisfy these requirements are the tension strap complete with end fittings, and the reversed lever.

Selecting Bending Stock

The selection of bending stock is governed largely by the species of wood used in the manufacture of the article in which the bent members are to be used. If the curvature of the bent member is severe, however, the material used must be selected primarily for its bending quality.

Bending quality varies widely, not only among different species of wood, but also in material of the same species. As a rule, the bending quality of hardwoods is better than that of softwoods, and certain hardwoods have better bending quality than others. Insufficient data are available, however, to permit the listing of species in the exact order of their bending quality. Data have been developed[2] that show relative bending quality based on the radius of curvature for steamed 1-inch material at which breakage does not exceed 5 percent when the wood is bent under end pressure.

[2]Stevens, W. G. and Turner, N. Solid and Laminated Wood Bending. Forest Products Research Laboratories, Princes Risborough, England.

According to these data, a few American species of known good bending quality have been rated in the following order of descending quality: American elm, white oak, locust, American beech, yellow birch, and red oak. Mahogany from Central America is listed as having moderately good bending quality and is superior to khaya, "African mahogany," in this respect.

Numerous hardwood species were ranked at the U. S. Forest Products Laboratory in accordance with the percentage of breakage sustained during a uniform bending test made without end pressure. With this test the species were rated as follows in descending order of bending quality: hackberry, white oak, red oak, chestnut oak, magnolia, pecan, black walnut, hickory, beech, American elm, willow, birch, ash, sweetgum, soft maple, yellow poplar, hard maple, chestnut, water tupelo, cottonwood, black tupelo, mahogany, American sycamore, buckeye, and basswood. The species commonly used in industry for making bent members are: white oak, red oak, elm, hickory, ash, beech, birch, maple, walnut, mahogany, and sweetgum.

Softwoods have poor bending quality, as a rule, and are not often used in bending operations. Yew and Alaska-cedar are exceptions. Douglas-fir, southern yellow pine, northern and Atlantic white-cedar, and redwood are often bent to moderate curvature for ship and boat planking after being steamed or soaked.

Pieces of wood cut from a particular species do not possess uniform bending quality. An extensive study was made of white oak cut from 20 trees grown in four different localities in Ohio and Kentucky. The bending quality of the wood from the four localities varied; and in most cases, the bending quality of wood cut from trees in the same locality also varied. An attempt was made to correlate bending quality with specific gravity, rate of growth based on the number of growth rings per inch, end pressure developed during bending, and standard toughness values. No good correlation was found between bending quality and any of these factors. In fact, the wood of highest bending quality was almost identical to that of lowest bending quality in specific gravity and rate of growth.

Despite the fact that little correlation has been found between basic physical properties and bending quality, stock can be selected with reasonable assurance that it will bend without undue breakage. The principal precaution to be observed is to guard against stock that contains defects which reduce strength. These defects are decay, cross grain, knots, shake, pith, surface checks, and brash wood.

Even wood containing incipient decay fails under slight tensile stress and cannot be compressed nearly so much as normal wood. Figure 3 shows a bent chair part that developed numerous wrinkles due to end compression; the piece was found to contain incipient decay.

Straight-grained wood is, in general, much less likely to fail during bending than cross-grained wood. The grain should slope not steeper than 1 inch in 15 inches along the length of the piece. Local cross grain is also to be guarded against because of its weakness under bending loads.

Knots are objectionable primarily because they are invariably accompanied by distorted grain, and also because they resist compression.

Shakes, which are longitudinal separations parallel to the annual rings, are responsible for failures in shear during the bending operation; pith introduces similar lines of weakness. Surface checks, which are cracks perpendicular to the annual rings, are likely to cause compressive failures if on the concave side of the piece as it is bent; on the convex side they are not so detrimental. Surface checks in combination with cross grain are likely to cause pyramid-shaped pieces to be forced out of corners that are in compression and slivers out of corners subjected to slight tension. Exceptionally lightweight wood is likely to be brash and fail during bending; even if it is bent successfully, it may not have the necessary strength in service.

Minor defects are permissible if they are located beyond the portion to be bent, or if on the convex side. Minor defects, such as small pitch streaks, burls, and small checks, may be allowed on the concave side of mild bends, but with severe bends such defects are likely to cause compressive failures because they cause concentration of stress.

Seasoning Bending Stock

From the standpoint of the bending operation alone, most curved members could be produced from green stock, or wood with considerable free water in the cell cavities. It is only when sharp bends are made and the wood must be severely compressed that the large amount of free water present in green wood is a handicap. A point may be reached where the cells contain too much water to permit their walls to deform when the wood is compressed during the bending operation. Under this condition, the wood may wrinkle along the concave face because of hydrostatic pressure.

Most green wood, however, contains a considerable volume of void space. At a moisture content of 65 percent, about 22 percent of the volume of green white oak consists of empty space in the cell cavities; at a moisture content of 85 percent, about 15 percent of the volume of red oak is similarly empty; and at a moisture content of 65 percent, about 19 percent of the volume of winged elm is empty. Until some part of the piece is compressed to the extent of its void volume, no hydrostatic pressure develops. Wood that is compressed 15 to 22 percent can take moderately severe bends; most commercial bends do not require that much compression. Moreover, green stock has an additional advantage in that it is free from checks.

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The moisture content of bending stock, however, should be suitable not only for bending but also for the drying and fixing of the bend, as well as for the drying process needed to bring about a moisture content suitable for the finished product. For these reasons, green or only partly seasoned stock is not suitable for the bending of many items. The difficulties that may result from its use are illustrated with bent boat or ship members, which may develop stresses while drying in place that can distort the frame of the vessel as well as cause the bent parts to check and split. A piece bent while green is likely to check and split during the drying and fixing process. Furniture parts, which are often bent in a hot-plate press, are dried and their curvature fixed while they are still between the plates of the press; if not seasoned sufficiently, they may check under the severe drying conditions imposed by the hot plates. Green stock bent over a form will develop similar checks, and, if prepared before bending to fit a mold or form, may shrink sufficiently to become unsuited for its intended use.

From a theoretical standpoint wood probably bends best when its moisture content is at the fiber-saturation point, which is about 30 percent moisture content. Wood in this condition is water-swollen to its fullest extent, but the cell cavities are empty, and bending can take place without hydrostatic pressure. The wood at the fiber-saturation point is still likely to check, split, and shrink excessively during the drying and fixing process.

On the other hand, wood that is too dry, as is most kiln-dried lumber, is not suited for bending. Dry wood is relatively stiff and, even if heated to a high temperature, is not sufficiently plastic to bend well. Dry wood must be steamed or boiled enough to absorb the moisture needed to make it sufficiently plastic to bend well.

To avoid both the drying troubles that result from use of stock that is too green, and the bending difficulties that occur with stock that is too dry, a compromise is necessary. For example, in hot-plate press bending, where the curvatures are relatively mild and the drying conditions severe, the optimum moisture content for the bending stock is lower than that for stock that is bent over forms by hand or by machine. Forest Products Laboratory research has shown that the optimum moisture content for southern oak chair-back posts to be bent in a hot-plate press is 12 to 15 percent. Stock at a higher moisture content was found to check during drying, while stock at a lower moisture content required a long steaming treatment or failed during bending. For chair-back rails and slats, the curvature of which is less severe than that of chair-back posts, bent in a hot-plate press, the optimum moisture content is probably 12 percent. For furniture parts bent over forms, stock at a moisture content of 15 to 20 percent is preferred.

Bending stock, ideally, should be air dried to the desired moisture content, generally 12 to 20 percent and stored under controlled conditions. A temperature of 70° to 80° F. and a relative humidity of 80 percent will

maintain wood at a moisture content of 15 to 16 percent. At the same temperature, and a relative humidity of 65 percent, wood will remain at a moisture content of about 12 percent.

If bending stock is cut to length before drying, an end coating will reduce end checking and splitting. The end coating will, during the steaming process, prevent excessive absorption of moisture by the ends. It will also minimize the tendency to end check and split during the drying and fixing process following bending.

Machining of Bending Stock

The basic principle governing machining of stock before it is bent is that as much of the sawing, surfacing, and shaping as possible should be done on the straight piece beforehand. In all such machining, however, several factors need to be considered. These are: (1) the minimum thickness to which stock can be cut with due allowance for deformation and shrinkage after it is bent; (2) accurate cutting of stock to length in order that it will fit tightly in the bending apparatus; (3) surfacing to assure uniform thickness and remove saw marks that may induce bending failures; and (4) where possible, selecting rough stock for machining with the objective of shaping the stock for convenience in bending -- that is, with due consideration given such factors as direction of growth rings with respect to the plane of the bend and to keeping the width of the stock greater than its thickness.

Since thin stock is more easily bent than thick stock, it is good practice to reduce the thickness of the bending stock as much as possible before it is bent. There are limits, however; the stock cannot be dressed down to the thickness dimension of the final part because it is compressed during the bending operation and because there will be some shrinkage during the drying and fixing process. Even air-dried stock at, say, 20 percent, will shrink appreciably after it is bent if it is to be used in furniture or other indoor woodwork that reaches a moisture content of 6 to 8 percent in use. Boat frames, on the other hand, can be cut to their approximate thickness for use before being bent if well air-seasoned, allowance being made chiefly for final dressing to remove slight bending irregularities.

The importance of cutting stock to accurate length in order to assure a tight fit in the bending apparatus lies primarily in the need for steady and evenly distributed end pressure during the bending operation. The stock, and the bending apparatus as well, should be long enough to allow for end trimming after the stock is bent. Stock with a long, straight leg beyond the zone of the bend, facilitates both the designing of the straps and end blocks and the application of the force necessary to bend the piece. Where several pieces are bent together to a single form, as is done with many furniture parts in hot-plate presses, all should be of the

same length. Such cutting can be conveniently and accurately done with an equalizing saw.

Careful surfacing of stock before it is bent has several advantages. In the first place, it is more convenient to run straight stock than bent pieces through a planer or jointer. Removal of rough saw marks can and does avoid many minor bending failures, and passing the stock through the planer before it is bent assures uniform thickness, which is especially important when stock is bent in groups, as in the hot-plate presses commonly used in furniture plants. Even if surfacing is unnecessary so far as the use of the final part is concerned, as in large ship frames hidden by planking and ceiling, it is advisable to surface the face that is to be next to the form during the bending operation. Boat and ship frames are often roughly molded before bending is done. Such parts of furniture as rounds and dowels are turned before being bent. It is not permissible, however, to drill holes or cut mortises in the piece before it is bent.

In ripping bending stock from lumber, bending can be facilitated and breakage often reduced if the rough cutting is judiciously done. In this respect, the direction of the annual growth rings with respect to the plane of the bend has some practical significance. For parts requiring severe bends, stock cut so that the annual rings are flatwise -- that is, perpendicular to the plane of the bend -- bends with less breakage than if the grain is edgewise to the bending form. In bending stock with the grain flatwise to the form, experience has shown that it is advantageous to place the side of the piece that was closest to the center of the tree against the form because this face is less likely to have severe surface checks. Since most commerical bends are relatively mild, however, the direction of the growth rings with respect to the plane of the bend is not of primary importance.

It is reported by commercial operators that sapwood gives a greater bending yield than heartwood of the same species. If this is true, the selection of sapwood for bending stock and heartwood for straight stock would be expected to reduce breakage.

If possible, stock should be ripped from lumber so that it is wider than it is thick. Bending difficulties arise when stock is greater in thickness than in width; in particular, there is a tendency toward lateral buckling unless side restraint is provided during the bending operation. It is frequently possible, when the finished part has greater thickness than width, to bend wide stock and then rip it into several parts of the proper width. Such furniture parts as chair-back posts and rockers, which are greater in thickness than in width, are frequently bent in groups in hot-plate presses; the pieces support each other laterally except for the two outside ones, and these often buckle laterally unless supported.

Plasticizing the Stock

The purpose of all plasticizing treatments is to soften wood sufficiently to enable it to take the compressive deformation necessary to make the curve. Heat and water, or steam, accomplish generally satisfactory results on certain species; likewise, a few chemicals have been found to soften wood. Research has not, however, produced a satisfactory explanation of the phenomenon of plasticization, and softening methods are still, therefore, based largely upon trial-and-error experience.

Softening with Steam or Hot Water

Despite considerable experimentation with various chemical treatments, plasticization with steam or hot water remains the most practical and satisfactory method yet evolved to soften wood for bending purposes. Water alone softens wood somewhat, as evidenced by the fact that green wood is more readily bent than dry wood. Heated wood, likewise, is more readily bent than cold wood. Together, heat and moisture can produce a degree of plasticity roughly 10 times that of dry wood at normal temperatures.

In general, hardwoods are more readily softened than softwoods, and certain hardwoods more so than others. The degree of softening is thus one index of bending quality.

It is rarely, if ever, necessary to soften wood to its maximum degree of plasticity for bending purposes. Indeed, excessively softened wood may fail sooner than wood that is not so soft; presumably, softening weakens wood. Evidence of the effects of over-plasticization is found in Forest Products Laboratory tests on the steaming of white oak for different periods of time and at different steam pressures (table 1). Steam pressure is, of course, a measure of temperature.

The results given in table 1 indicate that steaming at 35 pounds gage pressure, even for a period as short as 10 minutes, is detrimental. Although steaming at 17-1/2 pounds gage pressure caused more bending failures than steaming at zero gage pressure, the number was not significantly greater from a statistical standpoint. The increase in number of failures, however, indicates that steaming at 17-1/2 pounds gage pressure may be disadvantageous. All the specimens that were steamed at zero gage pressure bent equally well, indicating that steaming at this pressure for as long as 60 minutes had no deleterious effect.

In other experiments, the effect of steam pressure on bending was measured by its effect on the maximum endwise compression steamed wood will assume to the point of failure (Appendix). Steaming at 0, 35, and 70 pounds gage pressure exhibited an increasingly adverse effect on endwise compression

(table 2) by reducing the amount the wood could take to the point of fracture. Longer steaming periods at 35 and 70 pounds gage pressure also lowered the amount of compression the wood could take to the point of fracture.

The temperature of saturated steam at atmospheric pressure, about 212° F., is generally sufficient to plasticize wood for bending. This is an advantage in several respects. In the first place, the use of steam at atmospheric pressure obviates the need for expensive high-pressure retorts. Secondly, it is easier to secure saturated steam within a closed retort or steam box when the steam is injected at low pressure; high-pressure steam becomes superheated and "dry" when released from pressure, because pressure is lost more rapidly than temperature. Thirdly, the operation of a retort or steam box is simplified where steam at zero or low-gage pressure is used. With high-pressure steam, the steam valve must be closed and some time allowed before the door of the retort can be opened, thus delaying operations. One type of steaming retort manufactured for use with steam at low pressure is designed so that opening the door closes the steam valve and closing the door opens the valve. With this arrangement the steam valve is closed a minimum time, which speeds operations and reduces the possibility of loss of moisture from the surface of the steamed stock during the times when the steam is shut off.

It is good practice to inject steam into a retort through water standing in the bottom. This make certain that the steam within the retort is saturated or wet. If the steam is not injected through water, the retort should be designed so that a certain amount of condensate accumulates on the bottom of the retort before running into the drain. These measures increase the probability that the steam within the retort will be saturated. The line leading from the boiler to the retort should contain wet or saturated steam. Leaving a run of pipe near the retort uninsulated will also help to obtain wet steam in the retort.

Treatment of wood with boiling or nearly boiling water is approximately equivalent to steaming in saturated steam at atmospheric pressure. Boiling water is more convenient when only a portion of a stick needs to be plasticized.

It is often necessary to add moisture to wood, particularly to the surfaces, during the plasticizing process. If the stock has a moisture content of 20 to 25 percent, no additional moisture is needed, even for severe bends. At 15 percent moisture content it is probable that no additional moisture is needed for making moderate bends; for severe bends, however, additional moisture is needed in the surface zones. To make relatively dry stock, at 12 percent or less, plastic enough for any but mild bends requires that moisture be added during the heating process. Most of the moisture added is absorbed by the surface zones. The concave surface must assume the maximum compressive strain and therefore needs the optimum degree of plasticity brought about by sufficient heat and moisture. The conclusion is reached that dry wood should be both heated

and moistened, but that wet wood need merely be heated without loss of moisture to accomplish a degree of plasticization suitable for bending. Bending stock selected from general-use lumber coming into the factory is probably too low in moisture content for satisfactory bending. To increase its moisture content and avoid excessively long steaming periods, the dry stock should be soaked in water for several days, end coated to prevent excessive absorption by exposed end grain.

The steaming or boiling period required is influenced by the thickness, moisture content, and species of the stock, and by the degree of plasticization needed, which is dependent on the severity of the bend. Because these factors vary, it is not possible to specify exact steaming periods. Other things being equal, wet stock can be plasticized sufficiently by steaming for a shorter period than dry stock. Likewise, stock to be bent to a mild curvature can be steamed for a shorter period than stock to be bent to a severe curvature. It is also probable that different species become plastic at different rates, and therefore some species may need longer steaming periods than others. As a general rule, wet stock should be steamed or boiled 1/2 hour per inch of thickness and dry stock 1 hour per inch of thickness.

There is some danger of oversteaming or overboiling stock, but when the steaming is done at atmospheric pressure the danger is not great. In table 1 the stock steamed at 0 gage pressure for 20, 40, and 60 minutes produced about the same number of successful bends, 37 out of 40. Identical stock, except that it had a moisture content of 15 instead of 25 percent when steamed, produced 29, 35, and 37 successful bends out of 40, after steaming at 0 pound gage pressure for 20, 40, and 60 minutes respectively. Therefore, to accomplish similar results in bending, stock at a moisture content of 15 percent needed a steaming period of 60 minutes, while stock at 25 percent moisture content needed only 20 minutes.

In commerical bending, the plasticizing treatments should be coordinated with other bending operations. The retorts or steam boxes must be long enough to hold the stock and should have sufficient capacity to keep the bending apparatus in continuous operation. The individual retorts should be relatively small; large retorts sometimes require a long unloading period that may cause the surfaces of the steamed stock to dry before the stock can be placed in the bending machine. Numerous small retorts also allow more flexibility in adjusting steaming periods to the thickness and character of the stock. Efficient operation occurs when the capacities of the retorts and machines are so balanced that the time required to load, steam, and unload the stock from the retorts is correlated with the time required to load, bend, and unload it from the bending machines. Under such conditions the steamed stock is placed in the machine and bent with minimum delay.

Since moisture diffuses more rapidly along the grain of wood than across the grain, the ends of the pieces of bending stock absorb more moisture

during the steaming or boiling treatment. Such pieces may end check during the drying and fixing process that follows bending. The overly wet ends are also easily mutilated by the devices applying end pressure. A moisture-resistant coating applied prior to the plasticizing treatment will reduce the absorption of moisture at the ends and will reduce the hazard of checking and mutilation.

Plasticizing with Chemicals

Certain chemicals, such as urea, urea-aldehyde, tannic acid, and glycerine, have been tried as wood plasticizers. It has been found[2] that soaking wood in tannic acid solution has no important effect on plasticity. Experiments at the Forest Products Laboratory with glycerine as a plasticizer failed to yield favorable results. Treatments with urea alone[3] or together with formaldehyde or dimethylolurea cause wood to become highly plastic. The effect produced by urea alone is the most marked. Urea causes wood to become thermoplastic, in which state it can be bent when hot even though the moisture content is low. However, such stock does not bend so well as, and is weaker than, stock plasticized by steam.[2,4] Limited tests at the Forest Products Laboratory (table 3) show that urea-treated wood bent less successfully than steamed wood and developed more tensile failures during drying and fixing than steamed wood. Urea may, moreover, discolor wood and make it more hygroscopic than untreated wood. It is not definitely known how chemicals accomplish plasticization, but evidence supports the hypothesis that lignin and the less stable forms of cellulose are chemically attacked. The fact that wood can be pulped by the use of urea supports this hypothesis.

Other chemicals, such as alum, soap powder, or kerosene, are sometimes added to the water in the steam box or tank. No advantages for treatments such as these are known to the Forest Products Laboratory.

Bending

There are two broad classes of bends, free bends made without end pressure, and those that are made under end pressure. Free bending is feasible only where the curvature is slight, and the upset, or difference in length between the outer and inner faces of the bent piece, is not greater than about 3 percent.

Rims and hoops for baskets are made by a free-bending process. Boat frames and planking are often steamed or boiled, and then bent when installed on the boat, being forced into position and fastened to other framing members. Thin strips of other kinds are also bent without end pressure.

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[3]Loughborough, William Karl. Patent No. 2,298,017, Process for Plasticizing Lignocellulosic Materials. Assigned to the Secretary of Agriculture of the United States of America.

[4]Howes, D. E. and Howes, D. E. Jr. Chemical and Mechanical Aids in Wood Bending. Report of Sixth Vermont Wood Products Conference. 1946.

Of course, wood can be bent to a slight curvature without a plasticizing
treatment. When it is steamed before being freely bent, however, advan-
tage is taken of the fact that heat and moisture affect the stress-strain
relation to a greater extent in compression than in tension. This makes
it possible for the inner, or concave, side to assume a certain amount of
compressive strain before enough tensile strain is developed to cause fail-
ure in the fibers of the outer, or convex side. In bending of this nature
it may be advantageous to overplasticize the wood, thereby reducing the
stress-strain value in compression. Chair-back rails, slat, and pickets
are often bent in a hot-plate press without applying any end pressure.
Bends made by intrusion, or by forcing the stick or dowel into and through
a split mold, are generally made without applying end pressure other than
that obtained by friction.

Free bends are not highly permanent, even after drying and fixing, since
the deformation obtained during bending is relatively slight. In such in-
stances it may be necessary to overbend slightly. To retain the curvature,
it is usually necessary to fasten the ends of the strip together, as in a
hoop, or to fasten the curved piece to other members of the structure.
Some free-bent members, such as chair parts, are, however, required to
retain their curvature without restraint from other members.

Bending with End Pressure

For most bending, end pressure is necessary to secure the required com-
pression and to prevent tensile failures. End pressure can be applied in
several ways, but the most common is by means of a metal strap with end
fittings, such as end blocks or clamps. The metal strap is placed against
the outer or convex side of the stick to assume tensile stress that would
normally be assumed by the convex side of the wood. If the strap can be
made to operate with 100 percent efficiency, no tensile stress is present
in the wood, the whole stick being subjected to compressive stress. In
actual practice, however, it is improbable that the metal strap often
assumes all of the tensile stress. The convex face of the stick is
therefore subject to a slight tensile stress. Under these circumstances
the convex surface of the stick is stretched slightly in the lengthwise
direction. This is an advantage unless a tensile failure develops, be-
cause it reduces slightly the amount of deformation in compression that
is required on the concave side. To make a successful bend, the wood must
be distorted without developing visible failures either in tension or in
compression.

Bends that are moderate to severe, and as a consequence must be made under
end pressure, can be divided into three general classes: (1) a simple bend
in a single plane, (2) a re-entrant or "S" type of bend in a single plane,
and (3) a compound bend in more than one plane. The different classes of
bends require different methods of strapping and bending, as well as of
restraint while drying and fixing. A simple bend in a single plane may be

made by hand, in a hot-plate press, or in any type of bending machine. The pieces may be bent singly, in groups, or in multiple widths to be sawed later.

The strapping of a simple bend in a single plane is relatively easy. The strap is continuous from end to end and is in contact with the convex side of the stock. The strap is equipped with end blocks to apply pressure to the ends of the stick, or is clamped to the piece at the ends or at points beyond the length to be curved. Provision may be made for adjusting the distance between the end blocks, or for regulating the amount of end pressure applied. When slender pieces are bent, a means of reducing the amount of end pressure applied is necessary to avoid buckling of the unbent part during bending.

The re-entrant, or S type, of bend really consists of several simple bends reversing in direction. Since the convex and concave sides of the stick are interchanged as the bend reverses, multiple straps are needed. Where there is only one reversal of curvature, the straps are fastened to the form or table at the central end, and are equipped with an end block at the outer end. Bends of this sort are generally made by hand, one at a time, the straps being arranged so that they function on the convex side of the section being bent (fig. 4). For re-entrant and S-type bends the bent pieces are clamped to the forms and dried and fixed.

Compound bends, which are in two or more planes, are made with a complicated system of straps and devices for applying end pressure. Bends of this nature are made by hand by highly skilled workmen. The general scheme is to complete one part of the bend, clamp it to the form, and proceed to the next part, constantly manipulating straps and end blocks to maintain the required end pressure at all times. The combination back and leg piece of a bent wood chair is an example of this class of bend. The piece is bent to a metal form and must be dried and fixed while fastened to the form.

The actual bending technique, although subject to minor variations with the different classes of bends, has more or less general established features. After the plasticizing treatment, the stock should be placed in position for bending with as little delay as possible. In some types of equipment, the strap and end-block assembly automatically locate the piece with respect to the form. Some bending apparatus is designed so that the strap and end-block assembly hold the stock in position, preventing it from shifting on the form; in other machines, the fixed end of the stock must be clamped to the form or some device employed to hold the stock near the midpoint of the form.

The stock should fit snugly against the end blocks before bending is started. This may be accomplished by equipping the end block with a screw and bearing plate that can be screwed tight, or by inserting wood or metal shims between the stock and the end block. Some clearance between the end of the stock and the end block may be permissible in the early stages of bending because, after bending starts, the clearance will soon

disappear and the end blocks will come into play. Generally, however, some end pressure should be applied at the very start of bending. Where a number of pieces are bent together in a common strap and end-block assembly, it is highly important that they be cut to a uniform length so that each will bear its share of the end pressure. An attempt to shim individual ends is a time-consuming process.

The bending load should be applied slowly so that the plasticized wood will be distorted more or less uniformly along its length. In some apparatus, such as hot-plate presses, the stock is prevented from backing away from the form during bending by the nature of the machine and the character of the imposed forces. In other types it is necessary to hold the portion of the piece already bent in contact with the form. In bending heavy pieces, such as boat parts, for example, it is generally necessary to apply force to the portion already bent to keep it in contact with the form, as is shown in figure 5. The bending slab or table is equipped with holes for pins or dogs which, in combination with wedges or screws, are used to force the piece against the form to prevent it from backing away (fig. 5).

Where end blocks are equipped with a screw and a bearing plate, it is customary to release the end pressure to some extent as bending progresses. This operation is particularly necessary when a reverse bend or buckle starts to form in the still unbent portion of the piece. This reverse bend is more likely to occur in slender pieces or with end blocks that have no reversed lever or too short a reversed lever. End blocks possessing a suitable reversed lever or back bar tend to prevent reverse bends. Releasing the end pressure during bending may reduce slightly the chance of compressive failure but invite tensile failure. Although it has been widely recommended in the past, there is some question concerning the need for releasing end pressure as the bending progresses, except to relieve the tendency to buckle or form reverse bends. Measurements of end pressure during bending tests at the Forest Products Laboratory have shown that this pressure increases up to a certain point and then remains practically constant throughout the rest of the bending process. From a theoretical point of view the end pressure could remain constant, diminish, or increase during a bending operation, depending on the stress-strain relations developed in the wood during a particular bending operation.

Many devices and machines have been made for bending wood. For some bends and sizes of wood, the piece can be bent by hand around a form by means of a strap and a device for applying end pressure. Some machines consist of rollers between which the strips of wood are passed. The diameter and position of the rollers determine the shape of the bend. One hand-powered machine for bending several pieces at once consists of a battery of straps and end blocks fastened to a central steam-heated form. Each piece is placed in its strap and bent to the form until a complete load is obtained. The pieces are then allowed to remain until dried and fixed. For bending heavy members such as ship and boat parts, a bending slab or

table with the form attached is used. One end of the piece is generally fastened and the free end pulled around the form by means of tackle and a power unit (figs. 5 and 6).

Hot-plate presses, widely used to bend furniture parts, consist of hollow metal male and female forms or platens heated by steam. The bending stock is placed between the forms, either with or without a pan, and the forms are brought against the stock by hydraulic pressure (figs. 7, 8, 9, and 10). Some mechanical fastening is used to keep the plates in position after closing. The bent pieces are held to shape and dried between the heated plates.

A common type of machine for bending simultaneously several heavy pieces, such as wheel rims, or a larger number of such parts as chair-back posts, bevels, or rockers, consists of two heavy arms connected to a heavy strap (figs. 11, 12, 13, and 14). Power is applied to the arms, which are arranged so that they can shift position as the outer ends are pulled upward. The upward motion of the arms, transmitted to the heavy steel strap, pulls the stock upward around the form. In some machines the bend is made by moving the form downward. A minor strap is generally used with this type of machine. When the bend is completed, tie rods across the ends of the minor strap permit the bent stock to be removed from the form and main strap.

A machine for bending chair-seat rims or rails consists of a horizontal table to which a form is attached. In some machines the form and table rotate, winding up the stock; in others, the form and table are stationary, the stock being bent by fastening one end of the stick and carrying the other end around the form. With both types of machines a strap and end block are used, and because the stick is slender, the end pressure is released as the bending progresses. If the stock is wound in a single plane, the ends are scarfed beforehand.

Bending Laminated Members

The forming of curved members by laminating, bending a number of thin pieces and gluing them together, into the curved form is not included in this report. There is another form of laminating to produce curved members that is analogous to the production of solid curved members. This consists of building up a straight piece of considerable thickness by gluing together a number of thinner pieces, such as 1-inch boards. The laminated member is then bent like a solid piece. The advantages of this method are the easier and faster drying of the thin boards and the opportunity to select the best boards for the faces, particularly the face that is to be the concave one. The only requirements are that the glue joints be good, and that the glue withstand the steaming treatment.

Applying Veneer to Improve Bending Quality

Wood of poor bending quality can be improved by gluing veneer of good bending quality to the concave surface.[2] The veneer assumes the maximum amount of compressive deformation and supports the inner surface of the wood of poor bending quality.

This method was tested at the Forest Products Laboratory with 1/8-inch birch and Douglas-fir veneer glued to 1/2-inch sweetgum heartwood. The sweetgum was of poor bending quality. The specimens of solid sweetgum and sweetgum and veneer, all 5/8 inch thick, were at 20 percent moisture content when steamed. After steaming at atmospheric pressure for 20 minutes they were bent under end pressure to a radius of 3-1/2 inches. The results of the tests are given in table 4.

The data in table 4 show that the poor bending quality of the sweetgum, 6 successful bends out of 40, was vastly improved when birch veneer was glued to the compression face. The Douglas-fir veneer, however, could not assume the required deformation, and as a consequence only one specimen of this group was bent successfully.

Types of Bending Failures

In a successfully bent piece, the deformation, chiefly compression is distributed nearly uniformly over the curved portion, and consists of myriad minute failures, for the most part folds or wrinkles in the fiber walls and perhaps some slippage of the wood elements past each other. The wrinkling is greatest on the concave surface of the piece, and decreases as the convex surface is approached. If the strap and end blocks have functioned perfectly, the point of zero deformation is at the convex surface; if they have not functioned perfectly, the zero point is slightly below the convex surface, which has assumed some tensile strain.

Failures occur if the plasticized wood is stressed beyond its tensile or compressive limit. In free bending, failures are nearly always in tension because plasticized wood cannot be stretched more than 1 or 2 percent of its length. If tensile failures occur when end pressure is applied, it is because the strap and end blocks are not exerting sufficient pressure to keep the stretch of the convex side below the limit of 1 to 2 percent. This is the most common type of failure in commercial bending operations, and, as a rule, it is due to poorly designed or worn apparatus or to poor bending technique. Figure 15 shows tensile failures in a chair part bent in a hot-plate press. Irregularities such as distorted grain, cross grain, and seasoning checks may contribute to tensile failure.

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[2]Stevens, W. G. and Turner, N. A Method of Improving the Steam Bending Properties of Certain Timbers. Wood. March 1950 (pages 79-84) Illus.

Tensile failures also take the form of small slivers that break away from the convex face during bending. These are generally associated with slight cross grain. The metal strap, if it is as wide as the stock, helps to prevent slivers from breaking out. If the strap is narrower than the stock, slivers may break out on the edges. A device for exerting pressure against the face of the stock at the point of tangency of the stock to the form has been found helpful in reducing slivering.

Compressive failures occur (1) when the plasticized wood is compressed excessively; (2) where there is a concentration of stress due to the presence of some defect (fig. 16) resulting in a localized compressive deformation as opposed to uniformly distributed and very small deformations; or (3) where there are lines of weakness along which shear failure may develop. The compressibility of the stock depends on the species of wood used and the plasticizing treatment. A species of poor bending quality is severely limited in the amount of compressive distortion that it can take without failing (fig. 17). Improper plasticizing treatments also reduce compressibility.

Failure in compression may take the form of a crosswise fold or wrinkle, a longitudinal separation of fibers followed by lateral buckling, or a shear failure roughly along the longitudinal axis of the piece, followed by separation of the fibers and buckling (fig. 18). The mildest form of visible compressive failure is a bulge or wrinkle extending from edge to edge on the concave side (fig. 18). Compressive failure may also occur in green stock, since the space occupied by the excess water reduces the available void volume, causing hydrostatic pressure to develop when the wood is compressed beyond a certain amount.

Compressive failures by lateral buckling in a plane perpendicular to the plane of the bend are common where pieces are bent edgewise without lateral support. Such pieces are too thin or narrow to act as a column under the compressive stress, and bend like a beam. A similar effect is produced where the piece contains surface checks on the concave side (fig. 19). The surface checks set up lines of shear that in effect reduce the wide piece to a series of narrow strips that tend to buckle laterally, as does a single strip when bent edgewise. Surface checks, when combined with either spiral or diagonal grain, may, particularly if located near an edge or corner, cause a sliver-shaped portion to shear from a corner of the piece.

Shear failures may occur in stock that is bent to compound curvatures because of the need for twisting the stock at the points where the plane of the bend changes. Figure 20 shows a shear failure in stock bent to form the back and leg part of a bent-wood chair.

Some distortion of cross section during bending is inevitable. The piece is compressed between the strap and form and simultaneously by the end blocks, thus tending to become thinner and wider. Unless restrained, it widens most on the concave side, in contact with the form. The increase in width is due to the fact that the plasticized wood tends to flow in

the direction perpendicular to the lines of force. It is probable that this increase in width provides some of the space needed by the compressed and folded fibers. In cutting or machining stock to dimension before bending, therefore, allowance should be made for the distortion of cross section during bending.

Mutilation of stock during bending takes place principally at the ends. A common form is crushing or splitting of the ends because pressure is not applied uniformly to the entire end surface (fig. 21). The ends of a steamed piece unless end coated, are often plasticized to a greater extent than the rest of the piece because of greater absorption and penetration of moisture during the plasticizing treatment.

Removal of Discolorations Caused in
Bending

Steaming or boiling causes wood to change in color, taking on a lifeless appearance. This effect is restricted to the surfaces. A more serious source of discoloration is the reaction of such materials as extractives in the wood with metal parts of bending apparatus. Tannic acid and iron are the chief offenders. When hot, wet oak comes in contact with iron, it becomes a dark purplish-black color. This may occur in the steaming retort or boiling tank, or when the hot wood comes in contact with the straps, end blocks, form, or bending table.

If the stain is detrimental to the final product, various protective measures can be taken. The stock should be protected from drip or kept from contact with iron shelves in a retort. Although it is difficult to avoid stain while wood is soaking or boiling in steel or iron tanks, coating the inside of the tank will help. The water in the tank should be replaced at intervals to reduce the amount of iron in it. Paper or cellophane can be placed between the stock and the iron parts of bending apparatus to prevent stain. Iron or steel parts can be galvanized to eliminate most of the staining, although galvanizing is not permanent and will need to be renewed. ·Straps of spring brass will not stain most woods other than oak, and it only slightly.

Stain resulting from the action of tannic acid and iron can be removed by bleaching after the bent piece is dried and fixed. A hot 3 percent solution of oxalic acid applied to the stained piece will remove the stain. Afterward, the acid solution should be sponged from the piece with clear water. The process may be repeated several times if necessary.

Repair of Pieces Damaged in Bending

Failures may impair or completely destroy the utility of a bent piece. They weaken it, break the continuity of the surfaces, and impair its

appearance. Tensile failures are generally more detrimental than compressive failures. Sometimes, however, they may be repaired.

If the tensile failure is in the form of a large sliver, it is sometimes feasible to force and fasten the sliver back into place, thus permitting the member to be used where appearance is not important. Boat parts are sometimes repaired in this way. Tensile failures in chair parts are generally cause for rejection of the piece.

Compressive failures, accompanied by buckling and separation of the fibers, generally make the piece useless. In chair parts where the concave side is hidden, however, it is sometimes possible to use a member having a rather severe compressive failure. The member can be reinforced with corner blocks. Parts having moderate compressive failures consisting of wrinkling and bulging of the fibers without much separation can often be used after the bulges are dressed off. Of course, where maximum strength is needed defective members should not be used.

Drying and Fixing (Setting) the Bend

When a piece of wood has been plasticized and bent to a curved shape, the stresses within the piece are not at equilibrium. If a bent piece is released immediately after being bent, it will tend to straighten in order to relieve these stresses, which exist because all of the compressed portions have not been stressed to the point of failure. These compressive stresses are greatest on the concave face and diminish until they vanish at the convex face. In general, it is probable that a slight tensile stress exists at the convex face.

To overcome these stresses, it is necessary to hold the piece in shape with tie rods or wood stays nailed to one or both edges. The release of end pressure at this stage causes the piece to elongate slightly. To counteract this, a minor strap that provides some end pressure is sometimes allowed to remain on the bent piece, and the tie rods are hooked to the ends of this strap. Sometimes the restraining force is applied by clamping the bent piece to the form. When the piece is removed from the machine while thus clamped, no additional restraining members are necessary.

A bent piece with varying curvature along the length is more difficult to hold in shape than one of uniform curvature. If the first type is restrained merely at the ends it will attempt to assume a uniform curvature. Hence it will require more restraining members. The safest way to dry and fix a bent piece possessing nonuniform curvature is to allow it to remain fastened to the form. A scheme that has proved helpful in retaining the curvature of bent members during drying and fixing consists in permitting the inner or concave face to dry more rapidly than the outer. This is accomplished by removing the form and retaining the metal strap, or by using

perforated forms. The more exposed inner face dries first, thereby assuming a set in an expanded condition along the length of the member. This set will help to counteract the tendency of the bent members to close up when the entire piece reaches a low moisture content. Pieces that have been bent to shape by fastening them to other members of a structure, of course, require no restraining devices, nor is restraint necessary when the pieces remain in the bending machine while drying and fixing.

The tendency of bent pieces to straighten immediately after being bent is overcome by cooling and drying them to restore the stiffness of the wood. With mild bends the tendency to spring back is not entirely overcome by cooling and drying. With such bends it is customary, therefore, to over-bend somewhat to compensate for the partial springback. Although cooling and drying both contribute to the restoration of stiffness and the fixing of the bent shape, the drying appears to be the more important.

Bent parts are dried in various ways, depending largely on the use to which they are to be put. Bent parts for boats or ships are sometimes permitted to dry on the framework of the vessel. Ship and boat builders seldom provide special drying rooms, because boat or ship framing members do not require such thorough seasoning as do many other bent parts. Pieces that are bent in hot-plate presses are dried while in the press between the steam-heated plates. The steam pressure may be 20 pounds per square inch or more, which gives a plate temperature of 260° F. or higher. In other types of bending machines, including a steam-heated form, the bent pieces are also dried in the machine.

Chair manufacturers provide heated rooms for drying bent parts. These rooms may be equipped with thermostats, and occasionally with some means of controlling relative humidity (fig. 22). The temperature within drying rooms of this sort may range from 140° to 190° F. Occasionally bent pieces are dried in ovens at excessively high temperatures. Some bent pieces are dried in the shop by applying concentrated heat in one form or another. Many bent members are permitted to stand in the shop while drying and fixing.

Effects of Drying and Fixing

Several things happen to bent plastic pieces as they dry. Plasticity is reduced and stiffness increased as moisture is lost; the properties of the wood become more like those of untreated wood, although its original strength is never completely recovered. As the wood loses moisture and plasticity and shrinks, new stresses are set up within the bent piece. The shrinkage in length and thickness causes the bent piece to attempt to take on a shorter radius of curvature. As the thickness becomes smaller, the difference between the length of the convex side and that of the concave side calls for a general curve of shorter radius. The wrinkled and folded wood on the concave side of the bent piece develops lengthwise

shrinkage in drying. This shrinkage exerts a tensile stress on the concave side that tends to increase the curvature.

If no compression member is placed between the ends or legs of the piece, the tensile stress is transmitted to the convex side and sometimes causes failures (fig. 23). Such failures can be prevented by applying some end pressure to the bent piece, as is shown in figure 24. Figure 25 shows a minor strap being fastened on the side that is to be convex. The strap will absorb some of the tensile stress during bending, and after bending, during the drying and fixing process. If a minor strap or a main strap with end fittings is left on the piece during drying, any tensile stress in the convex side is taken up by the strap. Pieces dried in a hot-plate press with good bending pans are under end pressure. When no compression member is provided between the ends of the bent pieces, their curvature may be increased to a point where they are no longer suitable for the intended use. Overdrying increases the hazards of tensile failure and distortion of curvature. A drying room with controlled temperature and relative humidity would reduce this hazard. Likewise, if the bent pieces are suitably restrained by devices that act both in tension and compression, distortions of curvature are not likely to occur.

Drying also causes shrinkage in the width of the piece that sets up stresses similar to ordinary drying stresses. The greater the loss of moisture during the drying and fixing process, the greater is the drying stress. The hazards of surface and end checking that are present in the original seasoning, are present to a lesser degree in the drying of bent stock. The surface of wood seasoned to a moisture content of 15 to 20 percent is generally set in compression. In such a state the wood is able to withstand exposure to severe drying conditions without developing fresh checks. The steaming or boiling treatment given wood before it is bent may, however, relieve this surface set, and make it possible for the surface to go into tension in the lateral direction when the bent piece is dried. Under such conditions, surface checks may develop in the drying and fixing process.

Surface and end checks are more likely to develop during drying in stock that is steamed and bent at a high moisture content than in stock steamed and bent at lower moisture content. As an example, in a furniture factory having a drying room in which temperature was maintained at 170° F. but relative humidity was uncontrolled, it was found that oak and beech would surface check during drying if the stock was steamed and bent at a relatively high moisture content. In the bending of oak chair-back posts in a hot-plate press and drying between the plates heated by steam at 20 pounds gage pressure, it was found that the percentage of pieces rejected because of checks increased rapidly with increase in the moisture content of the bending stock. Pieces dried in hot-plate presses are highly susceptible to end checking, particularly where the ends have absorbed considerable moisture during steaming or boiling. End coatings reduce end checking.

Conditions for Drying Bent Stock

The most suitable conditions for drying and fixing bent stock have not been determined. The optimum conditions would be influenced by the species, moisture content, thickness, and intended use of the stock. In a commercial bending operation, a variety of bent members of different species and thicknesses may be produced, perhaps with variations in moisture content. Since it is impractical to have numerous drying rooms, all of the bent pieces are placed in 1 or 2 rooms. The temperature and relative humidity of the drying room should therefore be suitable for all of the bent stock. By common experience, it has been established that temperatures of 140° to 160° F., with no supply of vapor to the air, are generally satisfactory for the drying and setting of bent members, unless the member happens to be particularly large, of a species difficult to season, or at a high moisture content.

The length of time that the bent members need to remain in the drying room depends on the adequacy of air circulation, the thickness and moisture content of the stock, and the desired final moisture content. Bent pieces in furniture and chair factories generally are left in the drying rooms for 24 to 72 hours. A common practice is to leave the bent members in the drying room until the restraining device across the ends becomes slack. This condition indicates that the piece will no longer spring back or attempt to straighten when the restraining device is removed. The time required to reach the moisture content needed to fix the bend is usually much shorter than that required to reach a moisture content suitable for service. The amount of time or drying necessary to fix a bend varies with the species of wood and the type of bend. Little information on this subject is available, but it has been found that oak steamed and bent in the green condition becomes "set" even before it dries to the fiber-saturation point (about 30 percent moisture content). It is obvious therefore, that, if a bent member is dried to a moisture content suitable for service, the bend is certain to be fixed.

Behavior of Bent Members

Although it is generally considered that the curvature of a bent member is permanent after it has been dried and fixed, such is not the case. A bent piece that has been bent to a slight curvature will spring back to some extent even after it has been thoroughly dried. A piece that has been severely bent, dried, and fixed will retain its exact curvature only if the moisture content remains constant. A bent piece that is stress-free at a given moisture content becomes stressed immediately with a change in moisture content. The various zones through the thickness of the piece differ in extent of deformation and in the amount of longitudinal shrinkage and swelling they will undergo with change in moisture content. In addition, shrinking and swelling in thickness tend to alter the curvature of the piece. The wrinkled and folded fibers on the concave side, which have been considerably compressed in bending, shrink and swell appreciably

in the lengthwise direction. At the same time, the convex side undergoes negligible lengthwise shrinking and swelling. Consequently, changes in moisture content set up stresses that change the curvature.

The effect of the shrinking or swelling lengthwise and in thickness is cumulative. With shrinkage the curvature is increased, and with swelling the curvature is reduced as the piece tends to straighten. Red oak specimens 1 inch thick, steamed at a moisture content of 25 percent and bent to a radius of 2-5/8 inches, were dried to a moisture content of 8 percent. After the distance between the legs was measured, the bent specimens were brought to a moisture content of 21 percent. At this moisture content the legs were more than twice as far apart as at 8 percent. When redried to 8 percent, the legs were still 60 percent farther apart than originally.

Specimens of the same material steamed at 15 percent moisture content and bent to a radius of 2-3/8 inches behaved in the same manner but with even greater changes in curvature. When the moisture content of these specimens was raised from 8 to 12 percent, the distance between the legs was increased by 20 percent. When the moisture content was increased to 22 percent the distance between the legs was 2-1/2 times that at 8 percent. When redried to 8 percent moisture content, the legs were more than twice as far apart, as they were originally when at the same moisture content.

In these particular instances, although neither set of specimens maintained its curvature under changes in moisture content, the stock steamed and bent at the higher moisture content changed less in curvature with later fluctuations in moisture content. It is evident that a bent piece of wood cannot be expected to retain its curvature unless it is held at a constant moisture content or is firmly fastened to the other members of a structure.

APPENDIX

Mechanics of Bending

Success in the bending of wood is dependent on the prevention, by properly regulated end pressure, of tensile stresses which tend to stretch the wood. This is usually done by means of bending straps and end fittings. The importance of this requirement is made clear by analysis of the forces that come into action during the bending operation.[6] Figure 1 represents a stick in the process of being bent. The stick, of thickness or depth h, is partially bent, the last point of contact with the form being O; that is, the bending is complete to the left of O. The strap of thickness t is securely attached to the end fitting m. The stick bears through plate n against a pivot at the inner end of fitting m. Since the strap can be considered to be perfectly limber, the line of action of P will be at right angles to the end of the stick. If the stick and strap are assumed to be cut along a plane through O and the center of curvature of the form, the action of the portion of the strap and stick to the left of this plane can be represented by:

T, the tension in the strap acting at the center of its thickness and perpendicular to the cutting plane;
C, the summation of the stresses (in the stick) perpendicular to the cutting plane; and
P' the shear parallel to this plane.

Since the summation of forces perpendicular to the cutting plane must be zero, equating external and internal moments about the intersection of the line of action of C with the cutting plane.

$$P(X + L) = Ta \qquad (1)$$

Where a is the distance between the lines of action of T and C. Moments about O', the intersection of the centerline of the strap with the plane of the outer face of the bearing plate n, give

$$PX = P'b \qquad (2)$$

Where b is the distance from the line of action of P' to the centerline of the strap.

P is eliminated by dividing equation (1) by equation (2), and the following equation results:

$$X = \frac{L}{\frac{Ta}{P'b} - 1} \qquad (3)$$

P' must be equal to the tension in the strap at $\underline{0}$'. The tension at this point is equal to $\underline{T}$, the tension at $\underline{0}$, except for the friction force between the strap and the projecting portion of the stick. The friction force depends on the coefficient of friction and on the pressure of the strap on the stick. This pressure depends on the angle through which the projecting portion of the stick is bent. Since the angle ordinarily is small, the friction is small and the tension at $\underline{0}$' is approximately equal to $\underline{T}$. Hence $\underline{P}' = \underline{T}$ very nearly, and without great error equation (3) can be rewritten as:

$$\frac{X}{L} = \frac{1}{\frac{a}{b} - 1} = \frac{b}{a - b} \tag{4}$$

There is to be very little[7] stress or deformation at the convex face of the piece, and the shortening of the stick at point $\underline{0}$ will vary from nothing near the face next the strap to a maximum at the face next the form. This distribution of the shortening or deformation is represented by the abscissas of the small triangle shown at $\underline{0}$ in figure 1. If the stress were proportional to the deformation, then $\underline{C}$, the resultant of these stresses, would act at a distance of two-thirds $\underline{h}$ from the inner side of the strap. Since, however, the stick is strained beyond the elastic limit, stress is not proportional to deformation and the distance is probably slightly less than two-thirds $\underline{h}$. It is greater than $1/2$ $\underline{h}$, however, for if it was exactly $1/2$ $\underline{h}$ no bending could occur, and if less than $1/2$ $\underline{h}$ the bending would be in the opposite direction. Danger of crushing at the end of the stick will be least if $\underline{P}'$ is applied at the center of the height or thickness of the stick, that is, if:

$$b = \frac{h}{2} + \frac{t}{2}$$

Equation (4) shows that the $\frac{X}{L}$ ratio will be the least if $\underline{a}$ is given the largest value it can have, which, since it was assumed that the distance from $\underline{C}$ to the inner face of the strap cannot exceed two-thirds $\underline{h}$, is

$$\frac{2h}{3} + \frac{t}{2}$$

With the substitution of these values for $\underline{a}$ and $\underline{b}$, equation (4) becomes:

$$\frac{X}{L} = \frac{3(h + t)}{h} = 3 + 3\frac{t}{h} \tag{5}$$

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[7]Since the strap is under combined bending and tensile stress, there may be some change in the length of its inner face. Disregarding the deformation of the convex face of the stick, which this would imply, introduces no significant error in the further discussion.

This shows that, in order to maintain approximately the proper end pressure, $\underline{X}$, which is the distance from O' to the point of application of the bending force, $\underline{P}$, must be at least 3 times as great as $\underline{L}$, which is approximately the length of the projecting portion of the stick, and that $\underline{X}$ cannot be kept constant but must decrease as $\underline{L}$ decreases. These same conclusions are reached from a more complete analysis in which the friction between the strap and stick is considered. The more complete analysis[8] also shows that $\underline{X}$ might be kept constant if the distance $\underline{b}$ could be varied[8] during the progress of bending. The force $\underline{P}$ is not subject to variation because with $\underline{X}$ fixed, the value of $\underline{P}$ at any stage of the operation is determined by the moment required to bend the stick at the point of contact with the form.

The above analysis of bending stresses leads to the conclusion that a bending apparatus equipped with end fittings or blocks, of the type shown in figure 1, cannot be made to apply adequate end pressure throughout all stages of bending. Since the force required to bend the stick becomes greater as the bending progresses, the moment resisting rotating or overturning of the end block is too small during the early stages of bending and too great during the late stages. As a consequence, the end pressure may be too slight during the early stages and too great during the late stages. The inadequate end pressure during the early stages of bending may contribute to the formation of tensile failures, while the excessive end pressure during the late stages may cause the stick to take a reverse bend or buckle, or may cause compressive failures and end crushing. In spite of these shortcoming, apparatus of this type may produce successful bends, particularly when the bends have a small angle of curvature -- that is, the angle included between radii enclosing the arc of the bend. The danger of building up excessively large end pressures is present where bends of large angles of curvature are made. If the lever arm extending beyond the end block to which the bending force is applied is relatively short, the moment resisting the rotation of the end block may be too small to prevent its overturning. Under this condition, it is impossible to apply sufficient end pressure to maintain the whole stick in compression, even when bending to a small angle of curvature. This is a common fault with much bending apparatus used commercially.

A simple method for preventing the end blocks from rotating and securing the regulation of end pressure consists in equipping the end blocks with a reversed lever or back plate, as is shown in figure 2. The reversed lever bears on the strap and the convex face of the stick. The reversed lever arm should be long, because a short arm may crush the wood where it bears on the stick. If the stick need not be bent throughout its length, the reversed lever will produce an almost uniform end pressure throughout the bend operation. With this type of end fitting, it is unnecessary to use a pivoted bearing between the block and the end of the stick.

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[8] The bending can be continued to the end of the stick only by making $\underline{b}$ equal to $\underline{a}$.

With the reversed-lever type of apparatus, as illustrated in figure 2, the solution of the problem of preventing the wood from stretching and causing the whole cross section to assume a compressive deformation, lies in the supplying of a sufficiently thick metal strap and sufficiently strong end blocks and reverse levers. Assuming that, (1) the stress curve in the wood is a straight line, (2) the metal strap does not slip on the wood, and (3) the end block is in good contact with the end of the stick at the start of the bending, the position of the neutral axis is given by:

$$c = \frac{t^2 E_s + 2ht E_w + h^2 E_w}{2t E_s + 2h E_w} \tag{6}$$

Where:

$\underline{c}$ is distance from neutral axis to outer surface of strap.
$\underline{t}$ is thickness of strap.
$\underline{h}$ is thickness of stick.
$\overline{E_w}$ is modulus of elasticity of steamed wood.

E_s is modulus of elasticity of strap.

The maximum tensile stress in wood is:

$$1/2 \; \frac{h^2 E_w + t^2 E_s}{h E_w + t E_s} \; \frac{E_w}{r} \tag{7}$$

Where:

$\underline{r}$ is the radius of the form.

If no tensile stress exists in the wood the following relationship holds:

$$t = h \sqrt{\frac{E_w}{E_s}} \tag{8}$$

This is the case that is shown in figure 2.

The tensile stress in the strap and therefore the thickness will be less than that computed by formula (8) since the stress curve in the wood is not a straight line and, therefore the value of $\underline{c}$ is too large.

Where an end block equipped with a reversed lever is used, the force required to bend the stick may be applied at any point beyond the point of tangency of the stick to the form. The total pressure applied to the end of the stick through the bearing on the end plate that is necessary to compress or deform the wood is equal to the sum of the differential stresses over the thickness of the stick. The total pressure is equal to the tension in the steel strap. Ignoring the thickness of the steel strap, the bending force required is expressed by the equation:

$$P = \frac{Ca}{S} \tag{9}$$

Where:

$\underline{P}$ is the bending force.

$\underline{X}$ is the distance from the point of application of $\underline{P}$ to the point of the stick to the form.

$\underline{C}$ is the total compressive force.

$\underline{a}$ is assumed to be two-thirds of the thickness of the stick.

White oak pieces 1 by 2 inches in dimension were steamed at a moisture content of about 30 percent for 20 minutes at atmospheric pressure. They were bent to a 2-1/4-inch radius through an arc of 180 degrees. One of the end blocks was equipped with a hydraulic gage for measuring the total pressure developed. The pressure increased from practically zero at the start to a maximum when the bend was about one-half completed. From this point on, the pressure remained practically constant. The mean maximum gage pressure for several hundred pieces that were bent was about 2,200 pounds, or 1,100 pounds per square inch. At the half point of the bend, the distance from the point of attachment to the point of tangency of the stick to the form was about 17 inches. Using equation (9), the bending force, if applied at right angles to the stick, was calculated as follows:

$$P = \frac{2,200 \times 0.67}{17} = 86.7 \text{ pounds}$$

Since, in bending the 1- by 2-inch pieces of white oak, the pressure remained approximately constant during the rest of the bending operation, the force had to be increased as the bending progressed, because the value 17 decreased.

The total end pressure required can be calculated for any stick if the compressive stress-strain relation for the steamed wood is known. Stress-strain curves have been determined for steamed European beech for both compression and tension.[2] The required end pressure can be obtained from:

$$P = BR \int_{\frac{r}{R} - 1}^{\frac{r + h}{R} - 1} f(e)\, de \tag{10}$$

Where:

$\underline{P}$ is total pressure (compressive).

$\underline{B}$ is width of piece.

$\underline{R}$ is radius of the neutral axis of the bent piece.

$\underline{f}(\underline{e})$ is the function relating stress to strain and is obtained from stress-strain curves.

$\underline{e}$ is strain.

$\underline{r}$ is radius of the form.
$\underline{h}$ is thickness.

The stress-strain relationship curves were taken to the point of failure.

If the compression strain at failure is known for the plasticized stick,
it is not necessary to calculate the total pressure, by the use of equa-
tion (10), to determine the limits of bending. Work has been done at the
Forest Products Laboratory to determine the compressive strain at the
point of failure for the steamed wood of a number of species. The end-
wise-compressibility values so obtained are rough indices of bending
quality, and permit calculations of sharpness of curvature to which woods
can be bent successfully. The use of the mean endwise-compressibility
value gives the calculated radius to which a given species of wood, plas-
ticized in a specified way, can be bent with an expectation that 50 per-
cent of the bends made will be successful. The endwise-compressibility
tests were performed on 2- by 2- by 3-inch specimens steamed at atmos-
pheric pressure for 40 minutes at a wood moisture content of 25 to 30 per-
cent. The specimens were placed between the plates of a hydraulic press
and compressed until failure occurred. A strain gage attached to the
central two inches of the specimen permitted direct reading of the unit
compressive strain at the point of failure. It is probable that, because
the measurements were made over the central 2 inches only, the values ob-
tained are somewhat low. The point of failure was detected by visual
means and by means of a gage indicating the maximum pressure on the ram.
Figure 26 shows an endwise-compressibility specimen with strain gage
attached. The following tabulation gives endwise-compressibility values
determined by this method:

Species	Average endwise-compressibility value
	Inch per inch
Red oak (Wisconsin)	0.354
Paper birch	.287
Overcup oak (southern)	.258
Winged elm	.251
White oak (Ohio and Kentucky)	.250
White oak (Wisconsin)	.246
Yellow birch	(1)
Sweetgum	.172
Black willow	.101
Eucalyptus (Chile)	.071
Coigue (Chile)	[2].057
Sitka spruce	.015

[1] Approximately equal to Wisconsin white oak.

[2] Approximate value.

The values on this tabulation indicate that the wood of the species with values equal to or higher than yellow birch should be suitable for making sharp bends, sweetgum and black willow for moderate bends, and eucalyptus and coigue for slight bends. The low value for Sitka spruce indicates that it is unsuited for bending.

The mean endwise-compressibility value can be used to estimate the minimum bending radius at which successful bends can be expected in 50 percent of the pieces for stock of a given thickness, by the use of the following formula:

$$r = \frac{h\ (1 - e_c)}{e_t + e_c} \tag{11}$$

Where:

$\underline{r}$ is the radius of the form.
$\underline{h}$ is the thickness of the piece.
e_c is the compressive strain, just prior to failure, inch per inch, considered positive.
e_t is the tensile strain associated with e_c, inch per inch, considered positive.

Where an efficient strap and end blocks are used, e_t becomes zero.

When pieces are actually bent to the radius calculated by the use of formula (11) it is generally found that more than 50 percent of the bends are successful.

This is illustrated in the bending of several hundred specimens of white oak. The average endwise-compressibility value, $\underline{e_c}$, was 0.25. By the use of formula (11) the bending radius for 1-inch thickness, should have been 3 inches. The specimens were bent to a radius of 2-1/4 inches with 60 percent successful bends. Had a radius of 3 inches been used the percentage of successful bends would presumably have been even greater than 60.

It is not perfectly understood just why actual bending results exceed the expected, when the bending radius is calculated by formula (11) and a predetermined compressive strain. The value of e_c is probably conservative, however, because of the method used in making the endwise-compressibility test. A zone of weakness in the block used for making the endwise-compressibility test will tend to lower the value of $\underline{e_c}$, while a similar zone of weakness may have little influence on bending failure, unless it happens to be located on or near the concave face. It is also possible that some of the deformation required to accomplish bending is provided by shear deformation. No provision for shear is made in formula (11), consequently the actual results, when bending to the calculated radius, can be expected to be somewhat more favorable than the fifty-fifty basis.

If shear enters into bending, it means that cross-sectional planes do not remain perpendicular to the long axis of the stick.

When a piece of wood is bent, the compressive strain is probably never distributed uniformly over the length of the curved part. The distribution of the strain is presumably affected by nonuniformity of the wood along the length, local minor irregularities, friction betwen the stick and such parts of the apparatus as the strap and form, and the manner in which the stick is forced and held against the form.

Specimens of Wisconsin-grown red oak 1 inch thick were steamed at atmospheric pressure for 40 minutes and bent through an arc of 180 degrees to a radius of 2-5/8 inches. Parallel lines, 1 inch apart, were marked on the edges of the specimens before they were bent. After they were bent, the distance between these lines was measured on both convex and concave sides. The lengths of the lines across the thickness of the stick were also measured. The mean measurements for 11 sticks are shown in figure 27. The zones of maximum compression fall to the right and left of the center of the arc, but from 1 to 2 inches away from the center point. The pieces were clamped to the form at the center before bending commenced. The clamp may have increased the friction between the stick, the form, and the strap in the central portion. The increased friction may have prevented the central portion from assuming the full amount of compressive strain.

The compressive strain was not restricted to the curved portion of the stick but extended for about 1-1/2 inches along each straight leg. Had the stick retained its full thickness of 1 inch during bending, the total amount of compressive strain needed to make the bend would have been about 3.14 inches. According to the measurements on the convex and concave sides, the total amount of compressive strain was 2.97 inches. The thickness of the curved part, however, was reduced during bending from 1 inch to an average of 0.979 inch. On the basis of the reduced thickness, the calculated amount of compressive strain required was 3.12 instead of 3.14 inches. The difference between the calculated amount of compressive strain needed and the strain is 0.15 inch, which may have been due to shear strain.

Table 1.--Bending results for 1- by 2-inch speci-
mens of Wisconsin-grown white oak at
a moisture content of 25 percent
steamed at different steam-gage pres-
sures for various lengths of time and
bent to 2-1/4-inch radius

Steaming treatment		Bending results	
Pressure	Period	Success	Failure
Lb./sq. in.	Min.	Number	Number
0	20	37	3
0	40	38	2
0	60	37	3
17-1/2	20	33	7
35	10	24	16
35	20	25	15

Table 2.--Effect of steaming pressure and time on endwise-compression values of 1-1/2- by 1-1/2- by 3-inch specimens of Wisconsin-grown red oak, steamed at a moisture content of 25 percent

Steaming treatment		Endwise compression
Pressure	Period	
Pounds	Min.	Inch per inch
0	20	0.353
0	40	.350
0	60	.358
35	20	.303
35	40	.309
35	60	.271
70	20	.226
70	40	.157
70	60	.105

Table 3.--The number of successful bends, failures, in bending,
and tensile failures in drying to fix the bend, in
1- by 2-inch specimens of Wisconsin-grown white oak,
steamed or heated at 25 percent moisture content

Chemical treatment	Heating treatment	Bending results		Tensile failures during drying
		Success	Failure	
		Number	Number	Number
None	Steam at atmospheric pressure--20 minutes	37	3	0
Urea	Steam at atmospheric pressure--20 minutes	25	15	4
Urea	Boiled in urea solution 20 minutes	28	12	14

Table 4.--Bending results for specimens of
sweetgum heartwood, solid and
combined with veneer

Type of specimen	Successes	Failures
	Number	Number
Sweetgum (solid)	6	34
Sweetgum with birch veneer, with the grain perpendicular to the length of stick	40	0
Sweetgum with birch veneer, with the grain parallel to the length of the stick	30	10
Sweetgum with Douglas-fir veneer, with the grain perpendicular to the length of the stick	23	17
Sweetgum with Douglas-fir veneer, with the grain parallel to the length of the stick	1	39
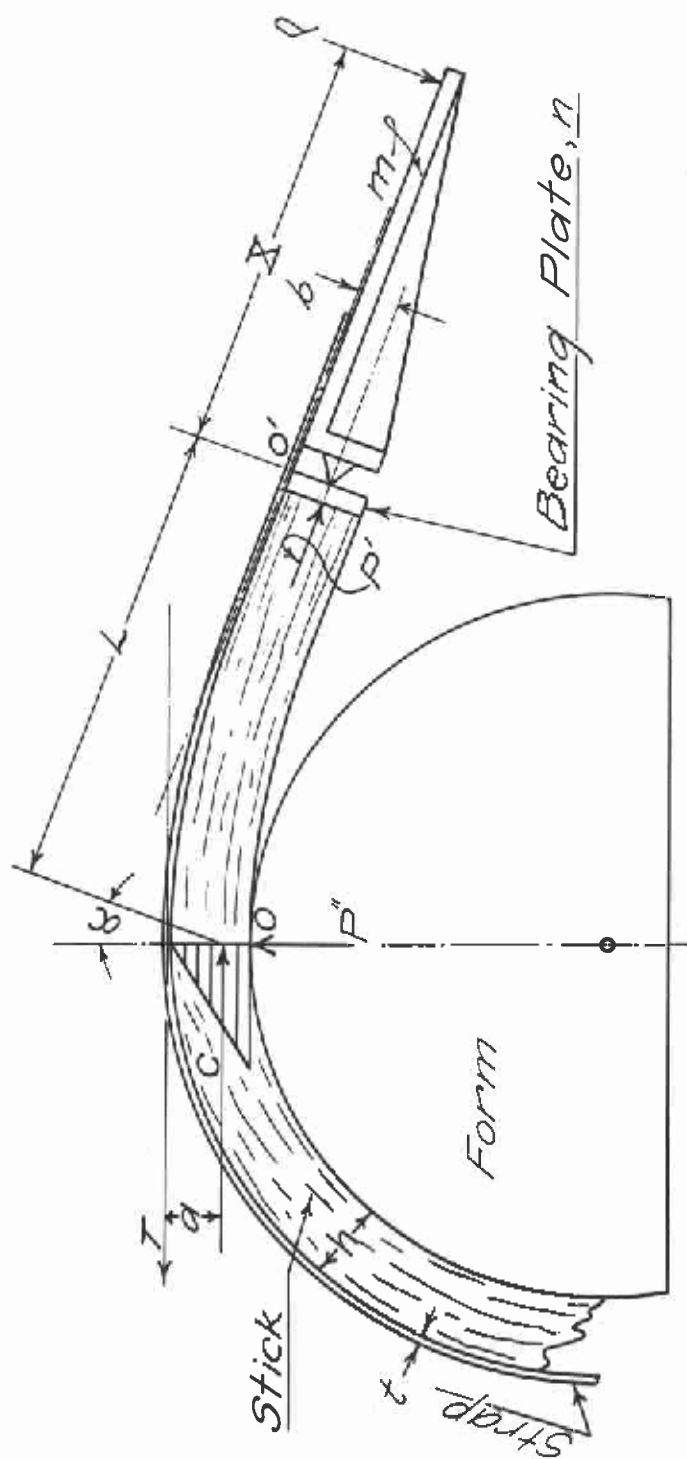
Figure 1.—Diagrammatic presentation of mechanics involved in wood bending under end pressure.
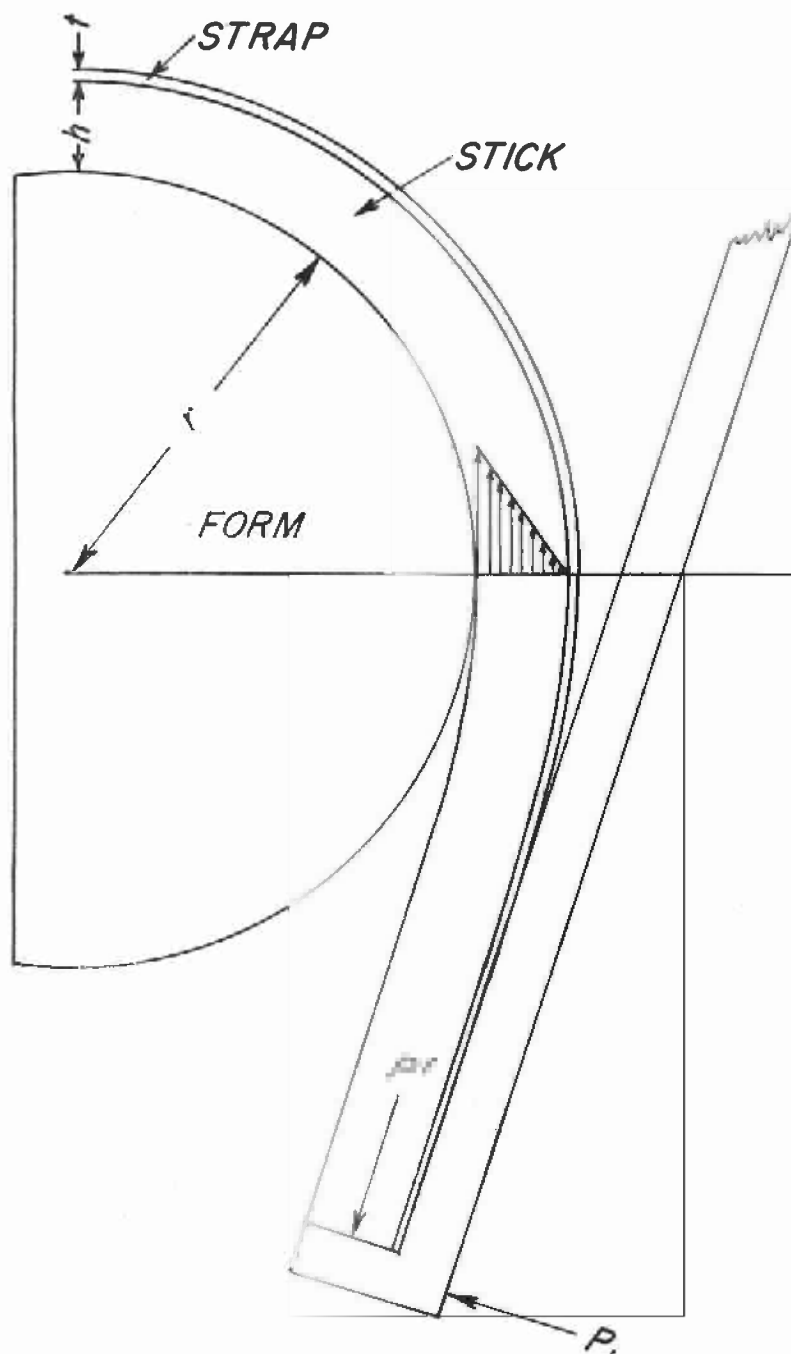
Figure 2.--Automatic regulation of end pressure by means of a reversed
lever.

Z M 82100 F

Figure 3.--A bent chair part of elm that was found to have incipient decay. The impaired strength properties caused the piece to develop the compressive failures in the form of abrupt wrinkles, during bending.

Z M 80834 F
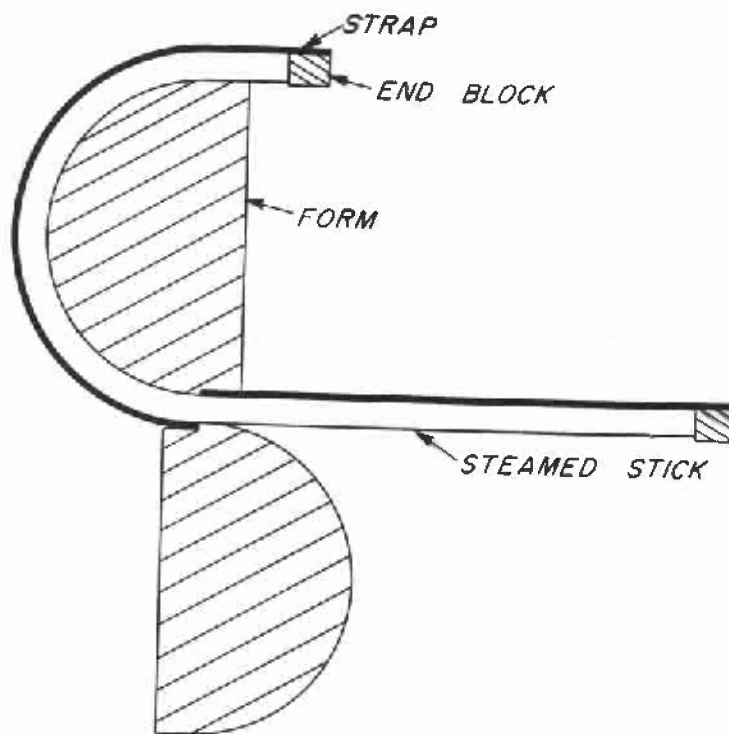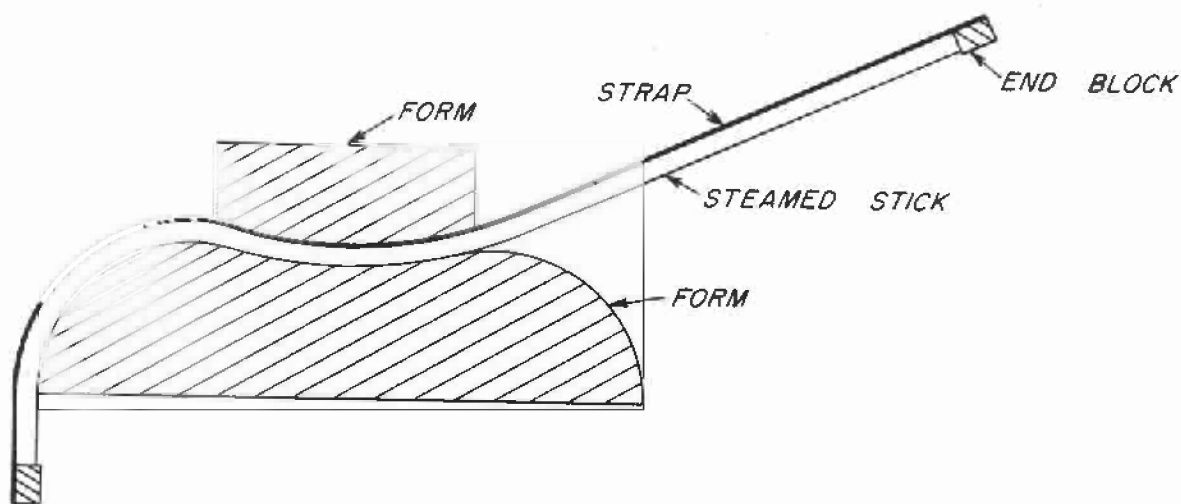
Figure 4.--Diagrammatic sketch of bending apparatus for making (A) an
S type and (B) a re-entrant type of bend in wood. In (A), one end of
each tension strap is fastened to the bending form and the other is
equipped with fittings to apply end pressure. In (B), the piece is
first bent against the male mold, for which in so mild a bend as
shown no tension strap would be needed, and then one or both ends are
bent around the female mold.
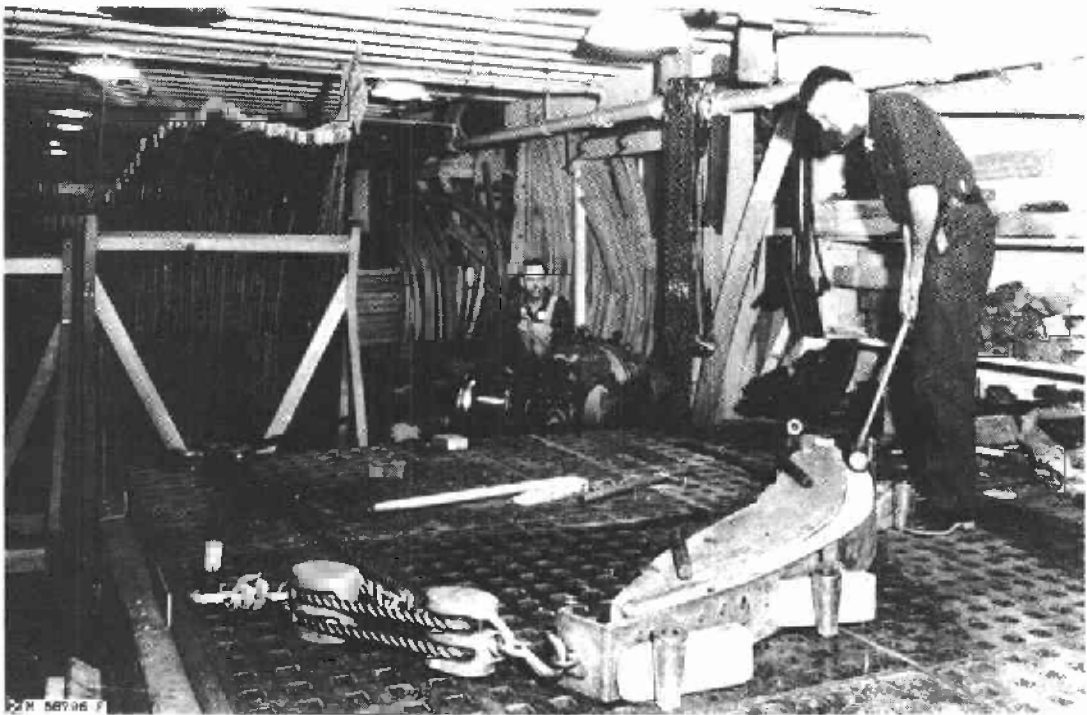
Figure 5.--Bending a boat rib by pulling one end around the form and
holding the bent part against the form by means of dogs and wedges.
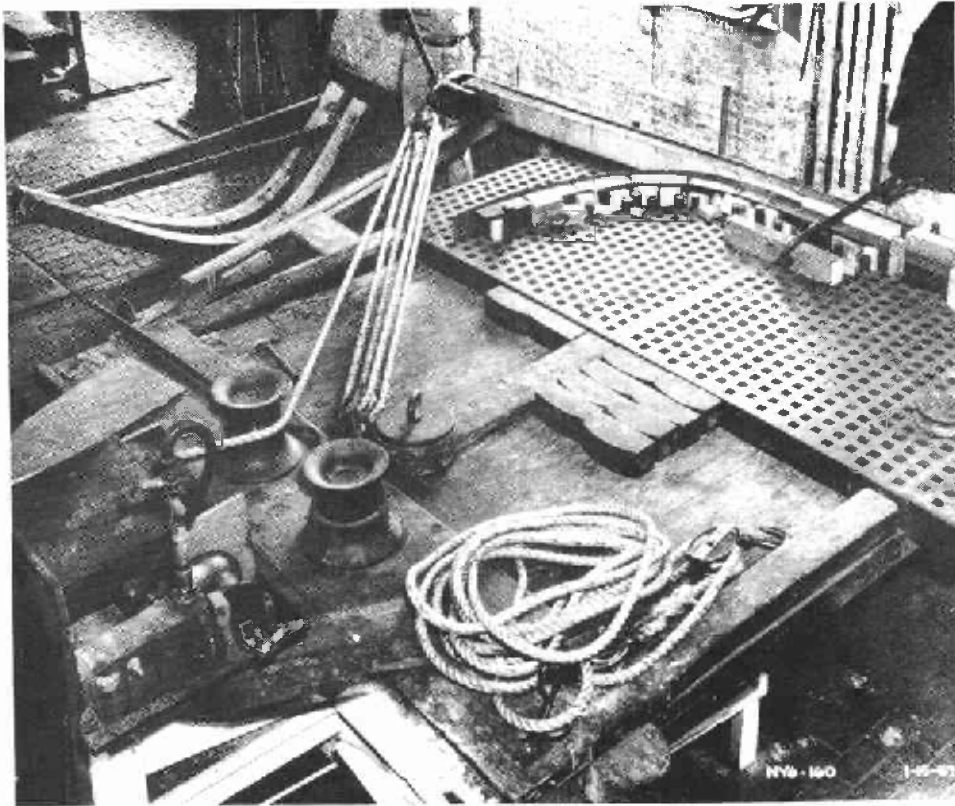
Figure 6.--Bending table and apparatus for bending boat ribs.

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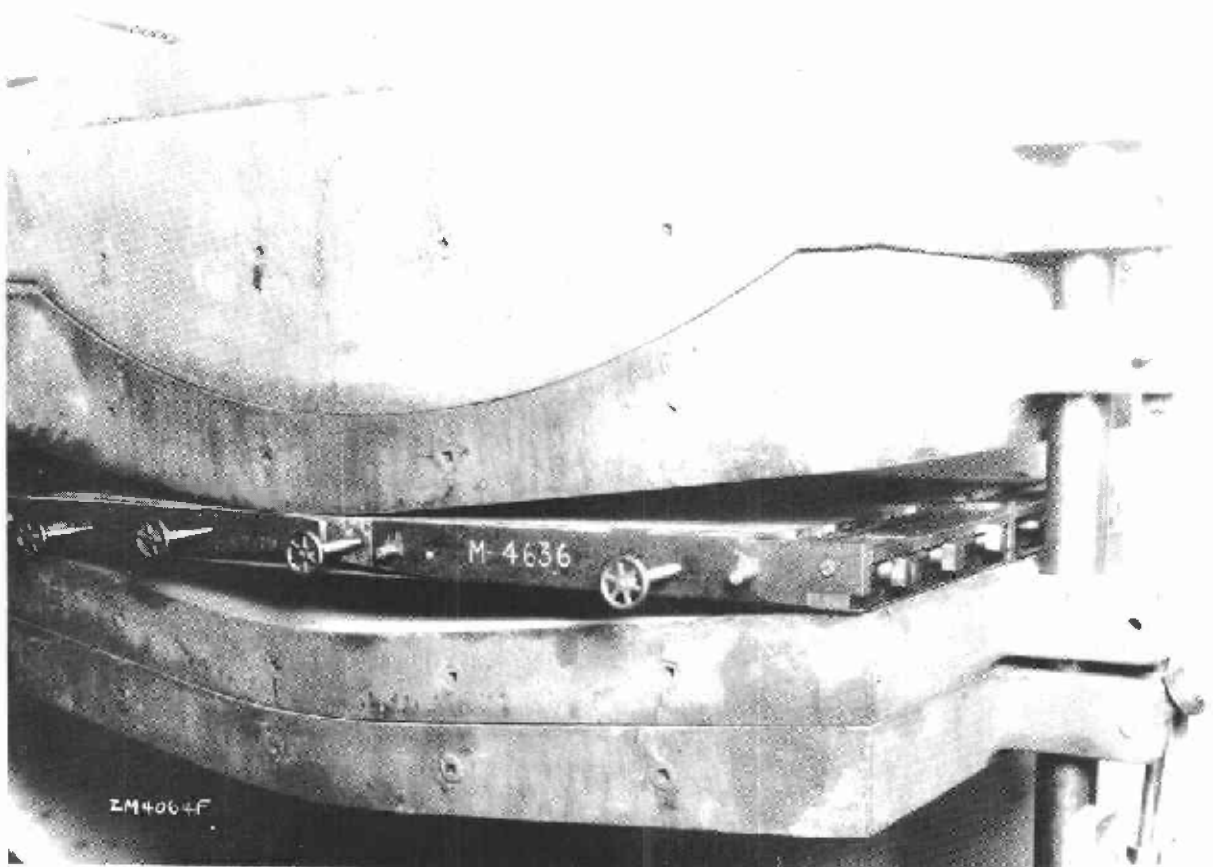
Figure 7.--A hot-plate press for bending chair parts. The pan used to apply
end pressure is equipped with reverse levers and devices for applying pres-
sure to prevent lateral buckling.

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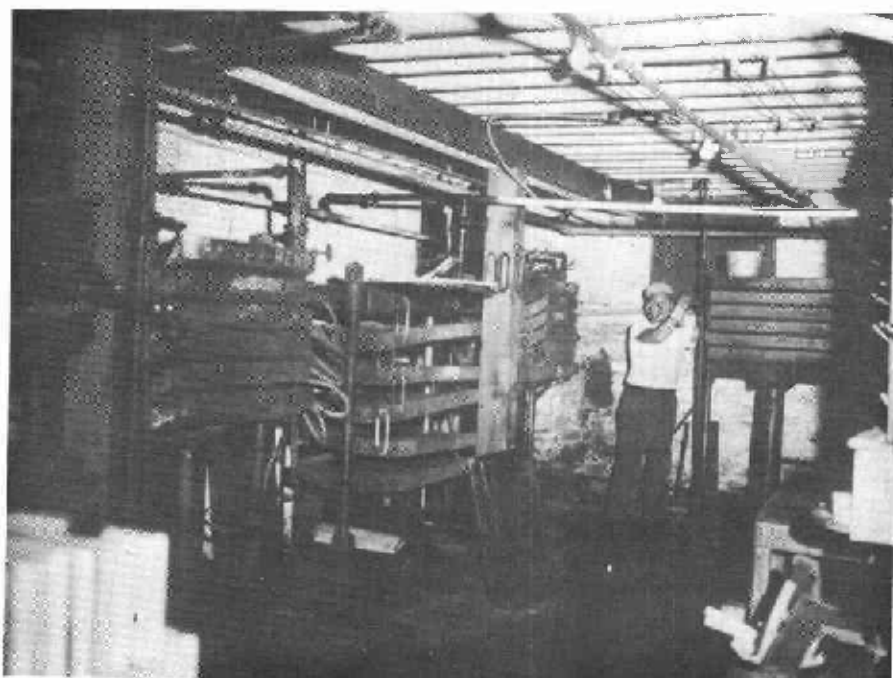
Figure 8.--Battery of hot-plate presses in a chair factory.
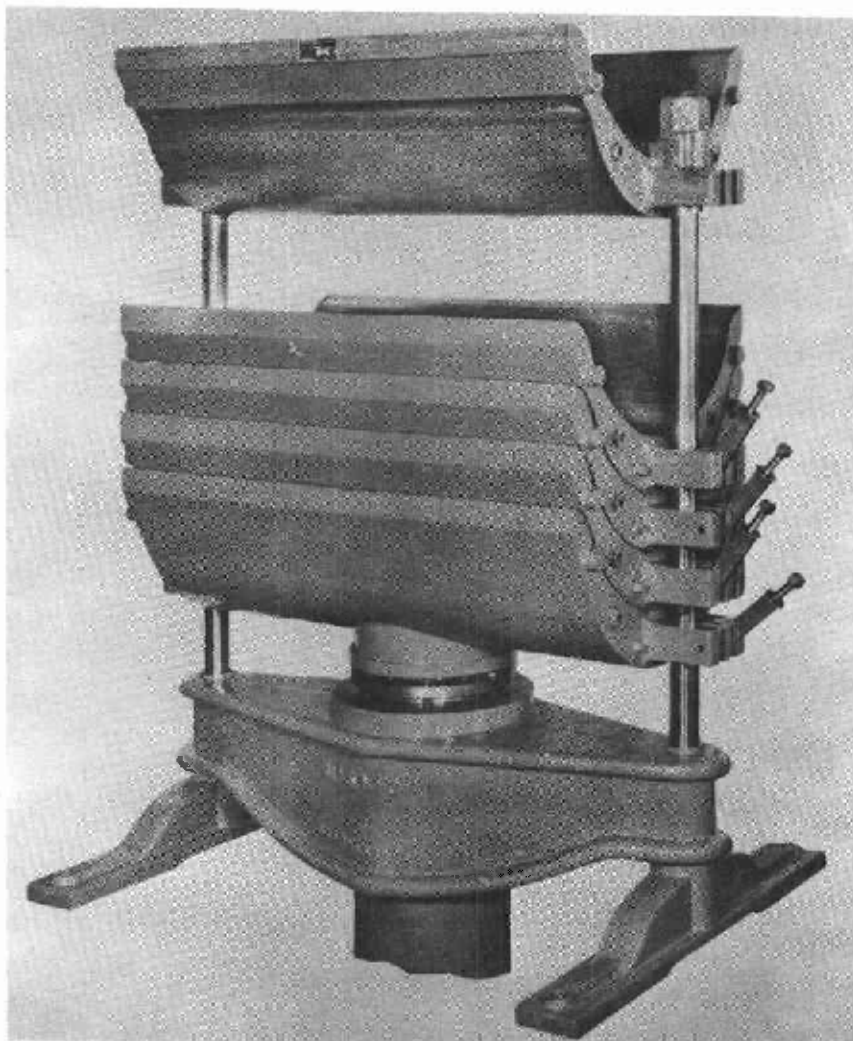
Figure 9.--Hot-plate press for bending chair parts. (Photo courtesy of L. G. McKnight and Son Co.)

Z M 105 256
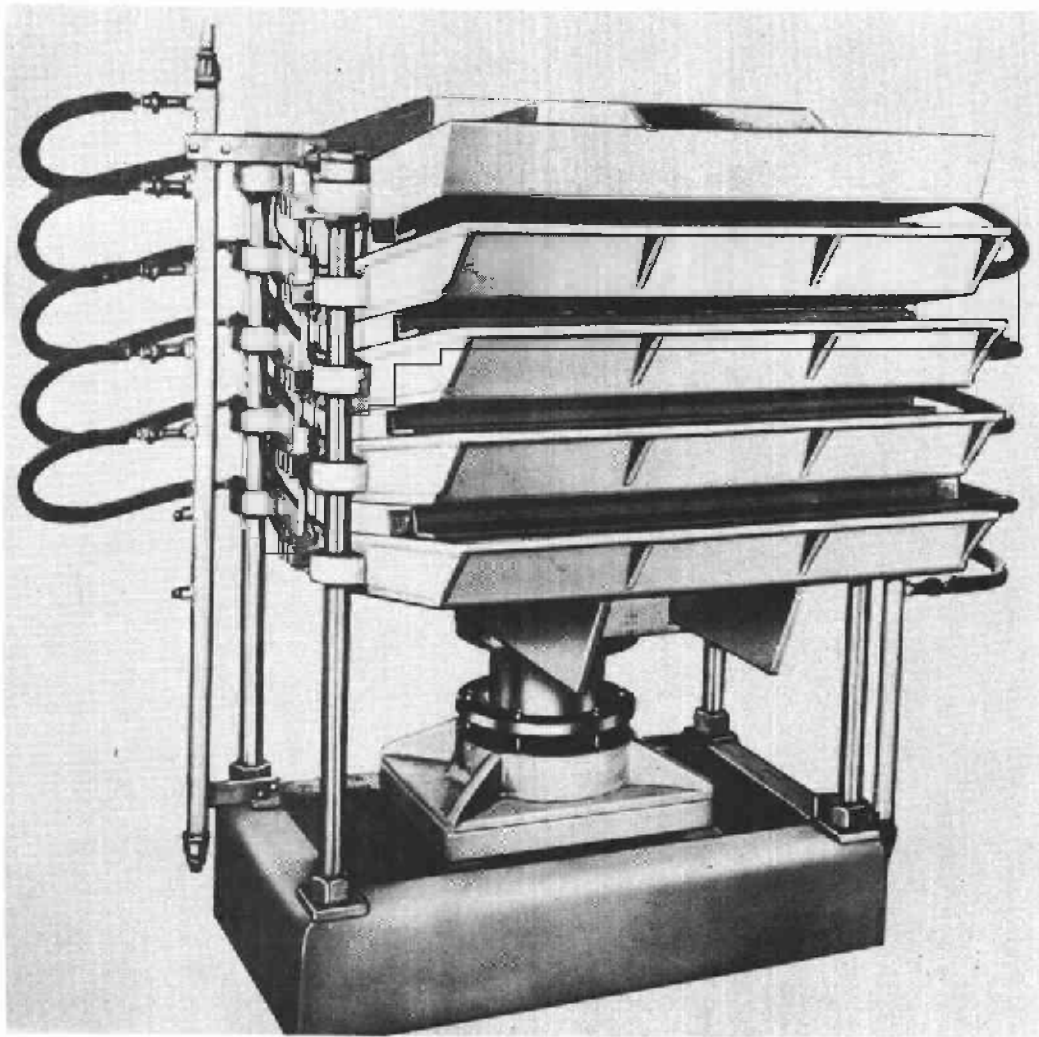
Figure 10.--Another type of hot-plate press for bending chair parts.
(Photo courtesy of J. A. Richardson Machine Co.)

Z M 105 254
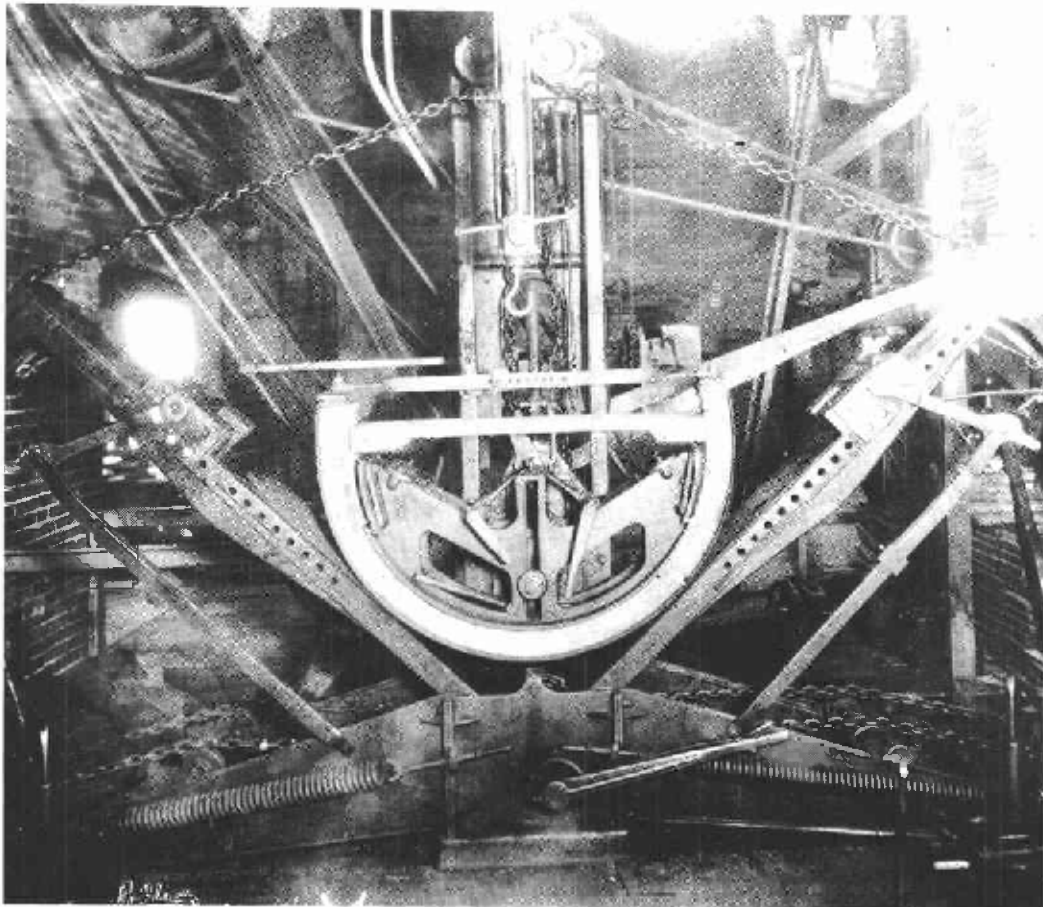
Figure 11.--Rim-bending machine. Bending arms are partly
  released to show bent piece held to form by means of tie
  rod fastened to ends of minor strap.

Z M 12382 F
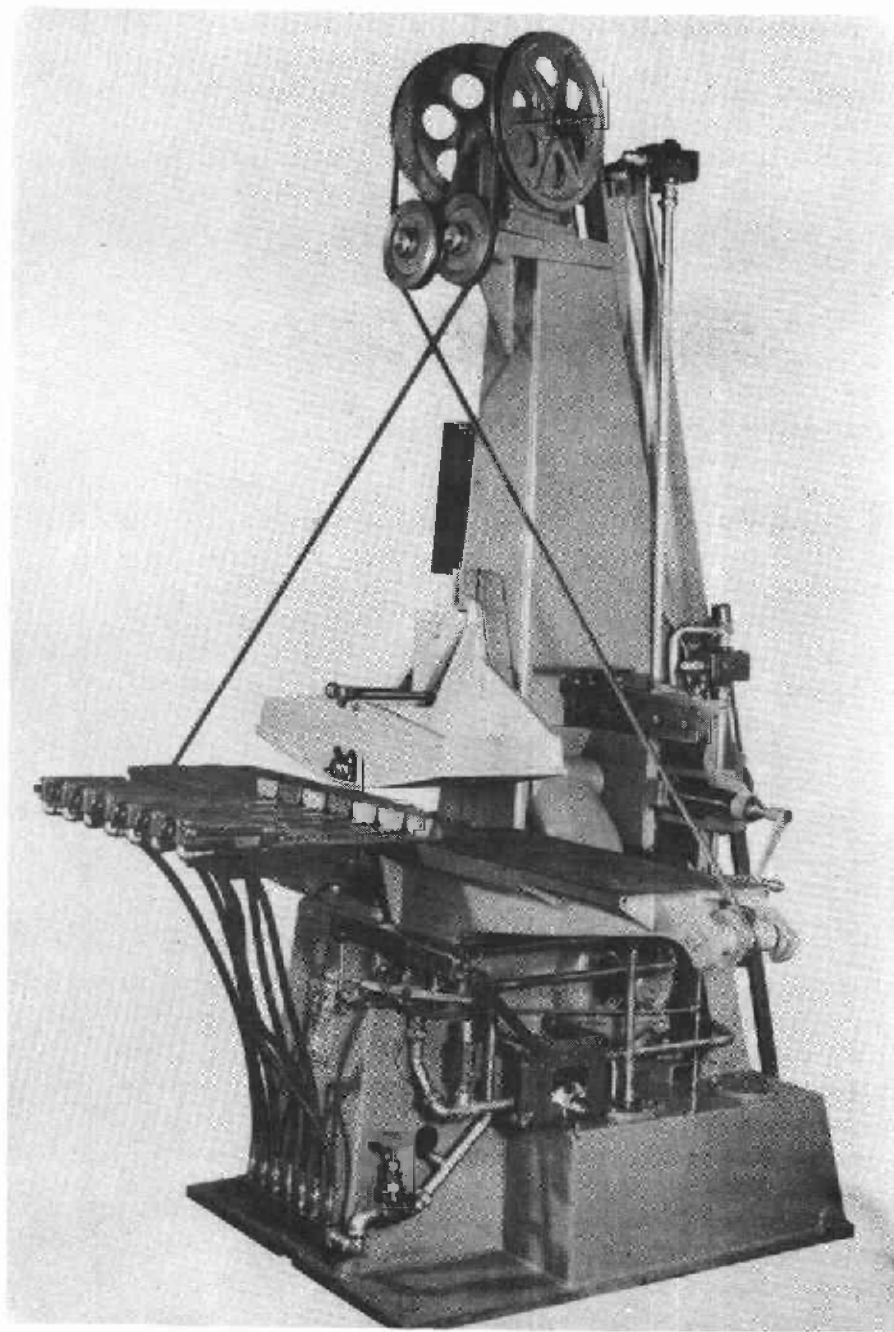
Figure 12.--Rim-type of bending machine equipped with devices
for providing lateral support. (Photo courtesy of J. A.
Richardson Machine Co.)
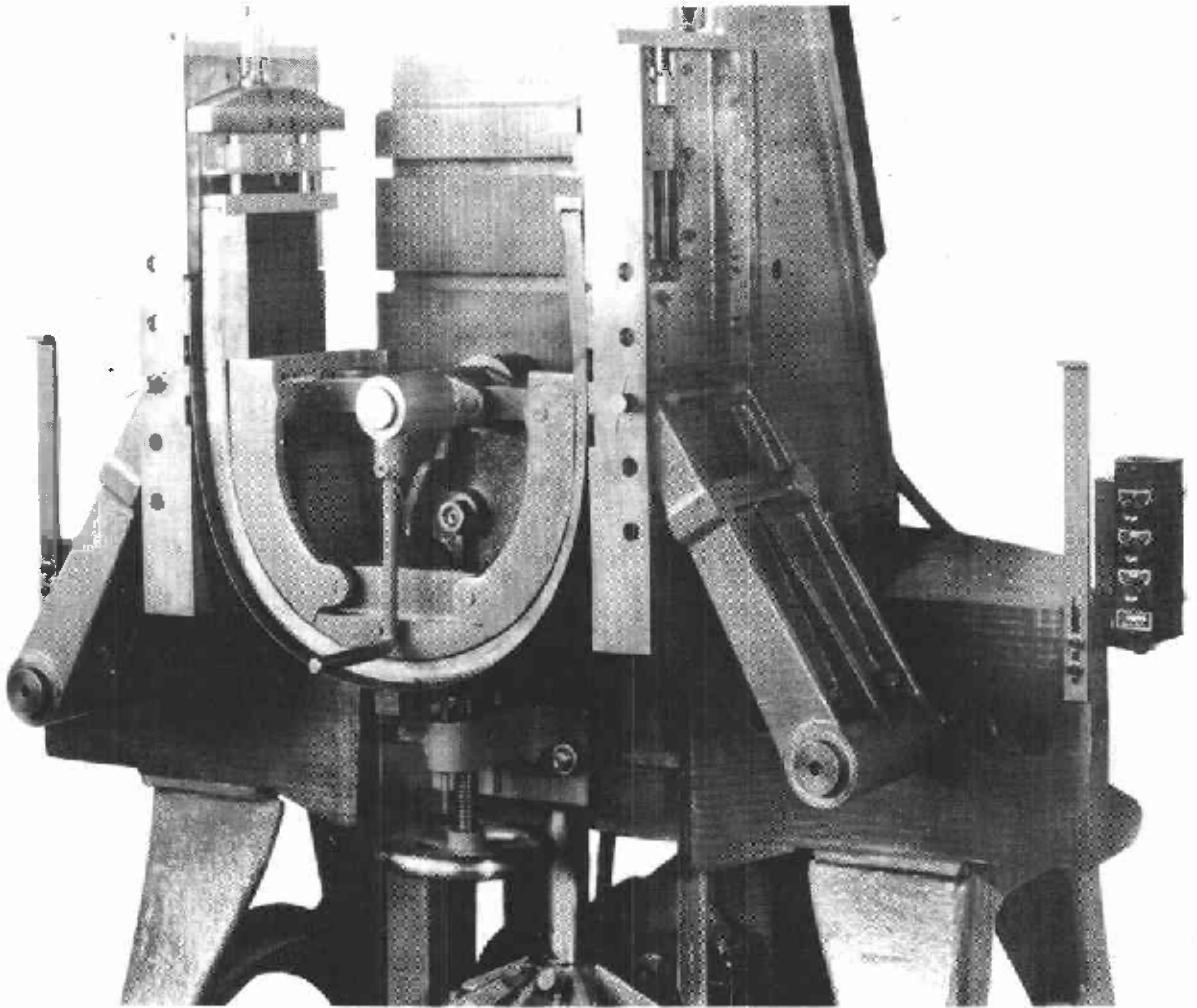
Figure 13.--Rim-type of bending machine with a chair part bent through an arc of 180°. (Photo courtesy of L. G. McKnight and Son Co.)

Z M 105 257
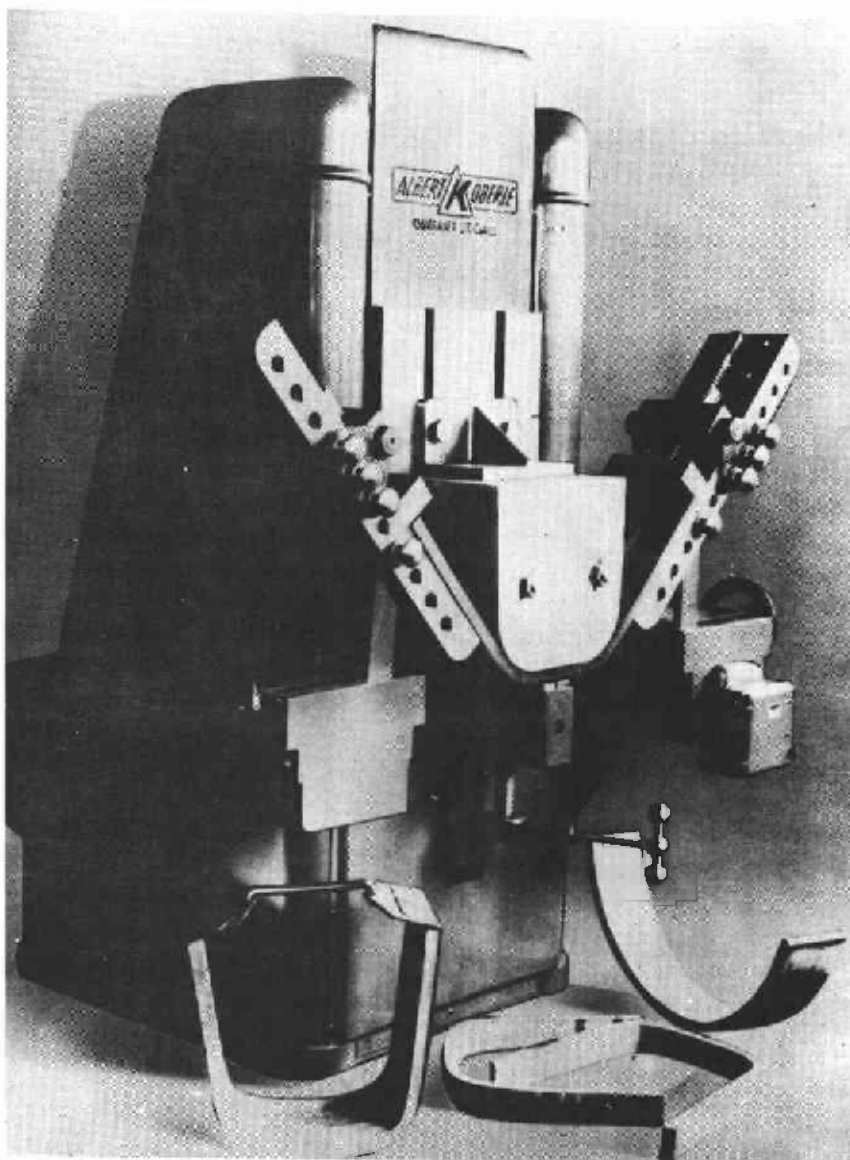
Figure 14.--Rim-type of bending machine, "Bendiko." (Photo
courtesy of Woodworking Precision Machinery and Tool Co., Inc.)

Z M 105 258
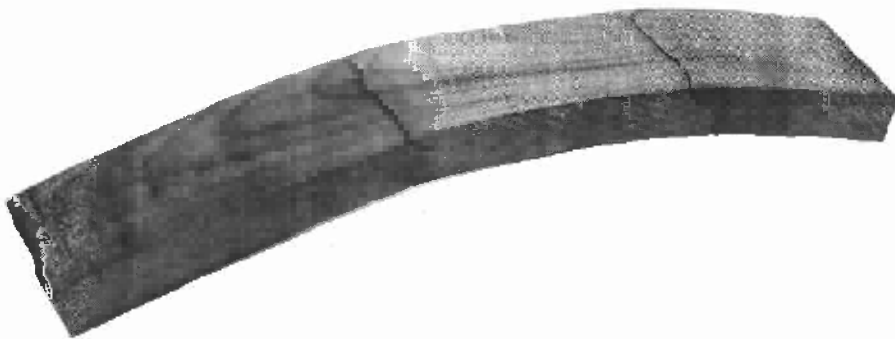
Figure 15.--Tensile failures in a chair-back slat bent with insufficient end pressure.

Z M 80832 F
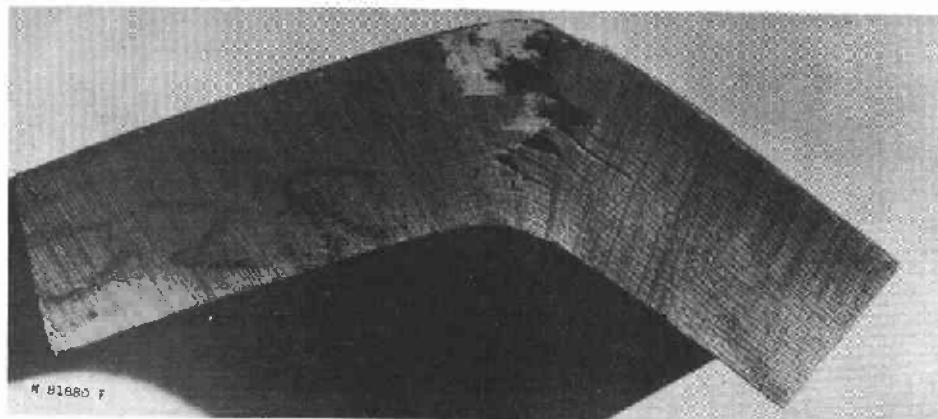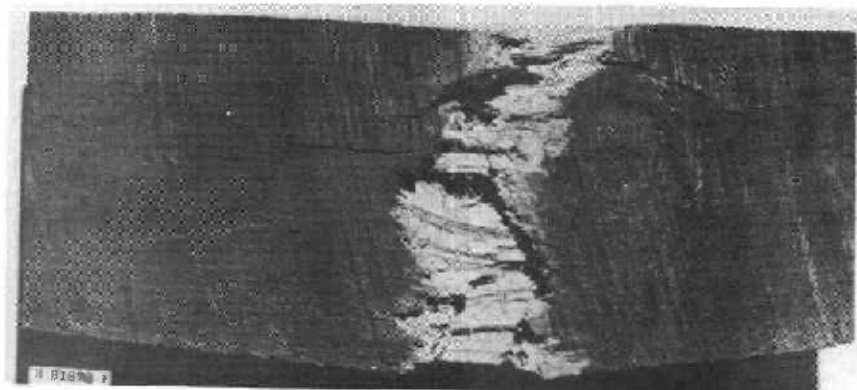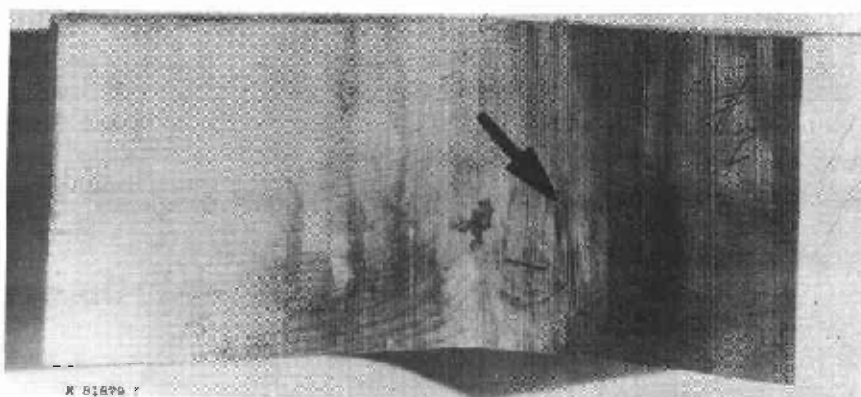
Figure 16.--Failure in a bent boat frame caused by the presence of a knot. The knot could not be compressed, and the stick developed a sharp kink that caused the outer face to fail in tension.

Z M 105 259

Figure 17.--A piece of willow that developed a compressive failure during bending. Since willow does not have good bending quality, the wood was unable to assume the necessary distortion. This piece had been bent to a sharper curvature than shown, having lost some of it before being photographed.

Z M 80831 F
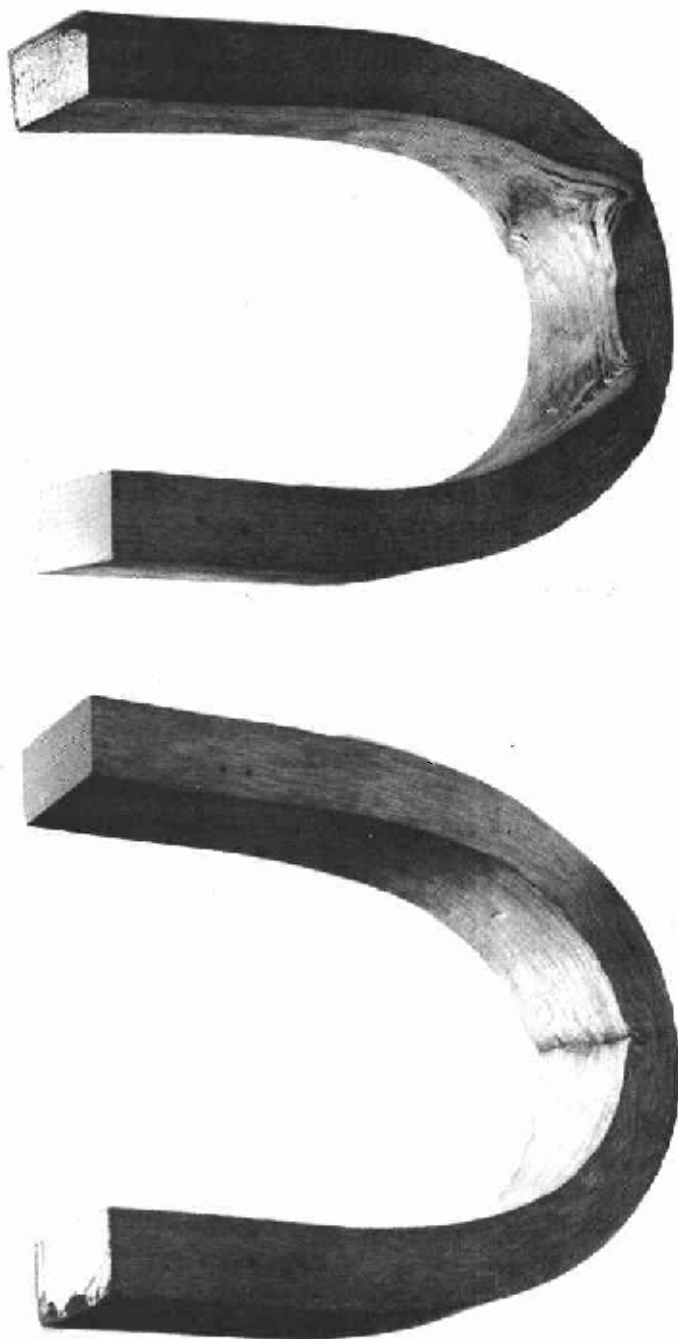
Figure 18.--Two types of compressive failure. Left, cross fold or wrinkle typical of wood of poor bending quality or that has been improperly plasticized; right, lateral buckling preceded by shear failure.

Figure 19.--Compressive failures brought about by presence of surface checks on concave face of stock.
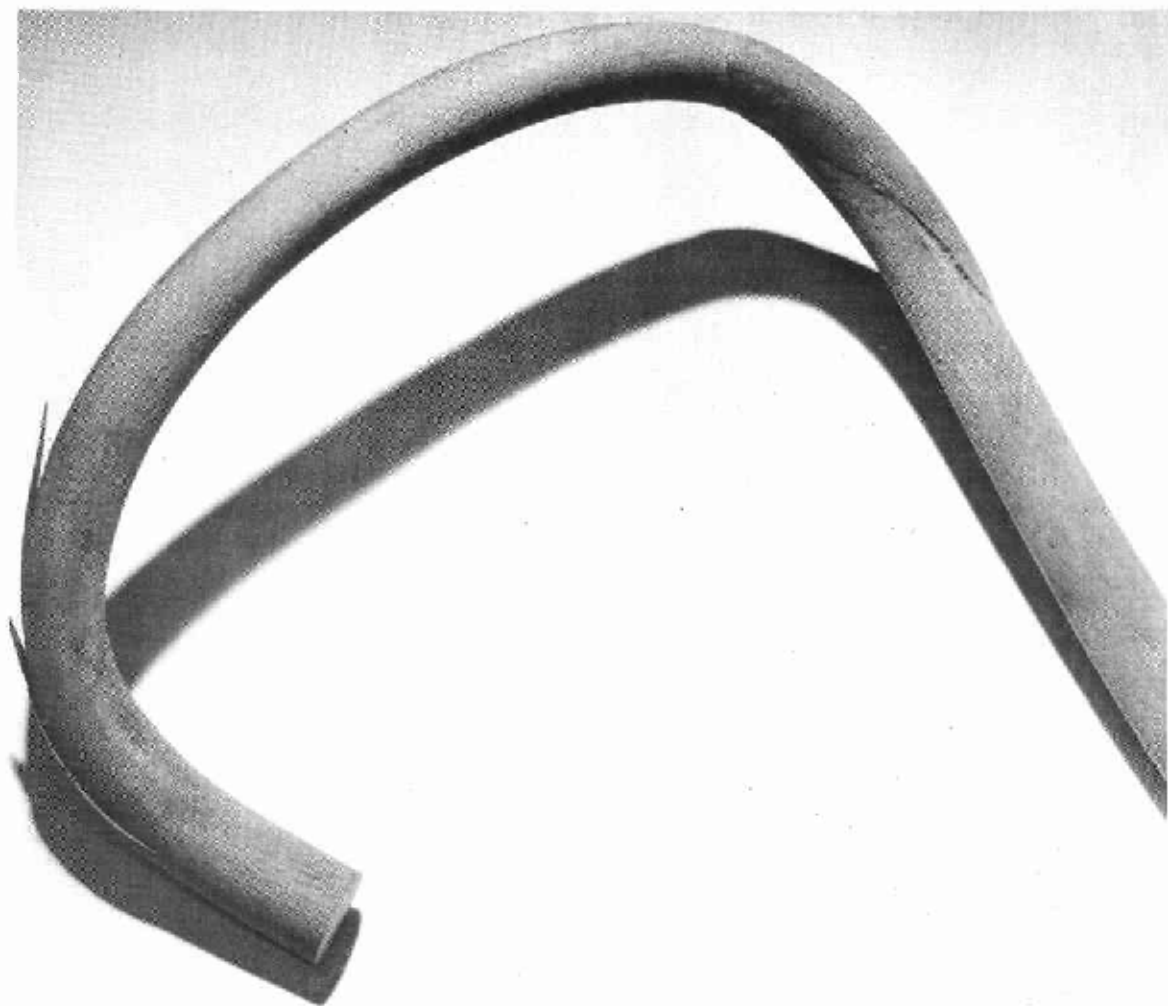
Z M 66664 F

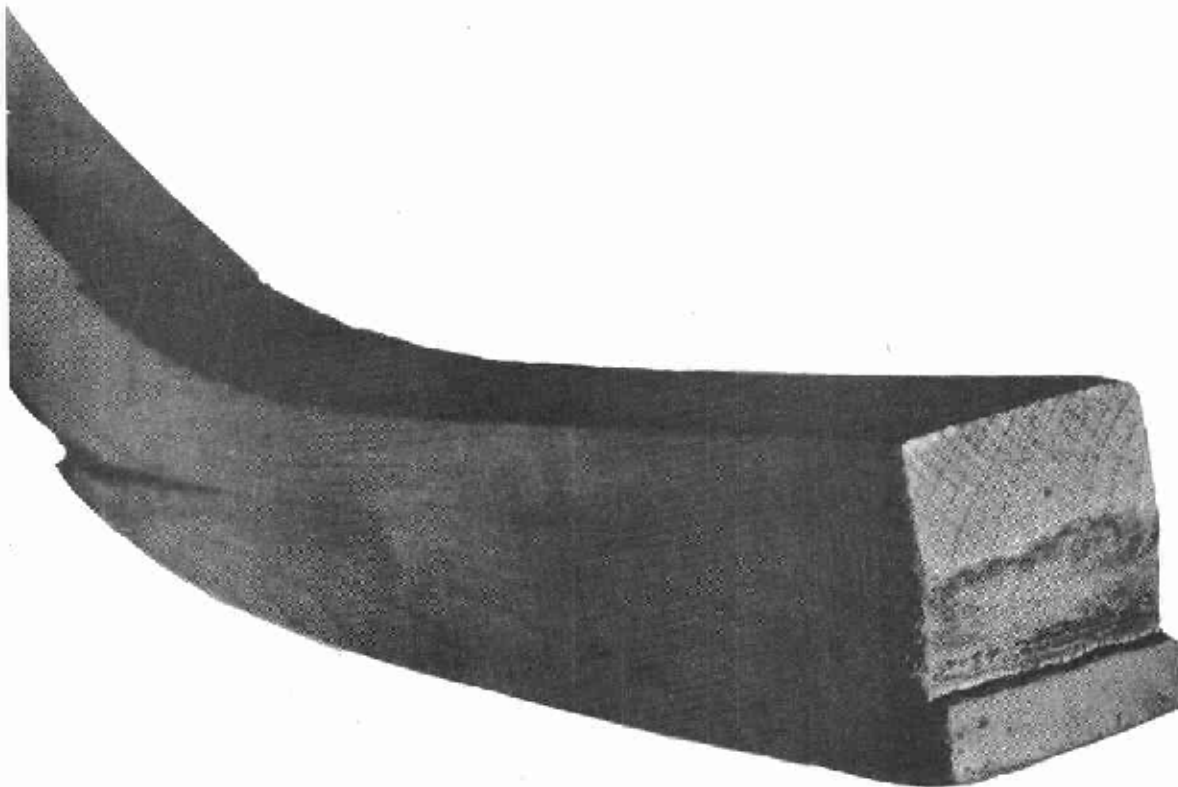Figure 20.--The failure in the upper right hand corner of this part is a shear failure due to twisting.

Z M 105 178

Figure 21.--Crushing of the end of a bent chair-back post, caused by improper bearing of the end block. The inefficient application of end pressure was evidently the principal reason for the tensile failure that developed on the convex side.

Z M 80833 F

Figure 22.--Drying and fixing room in a chair factory. The
temperature and relative humidity of the air are controlled.
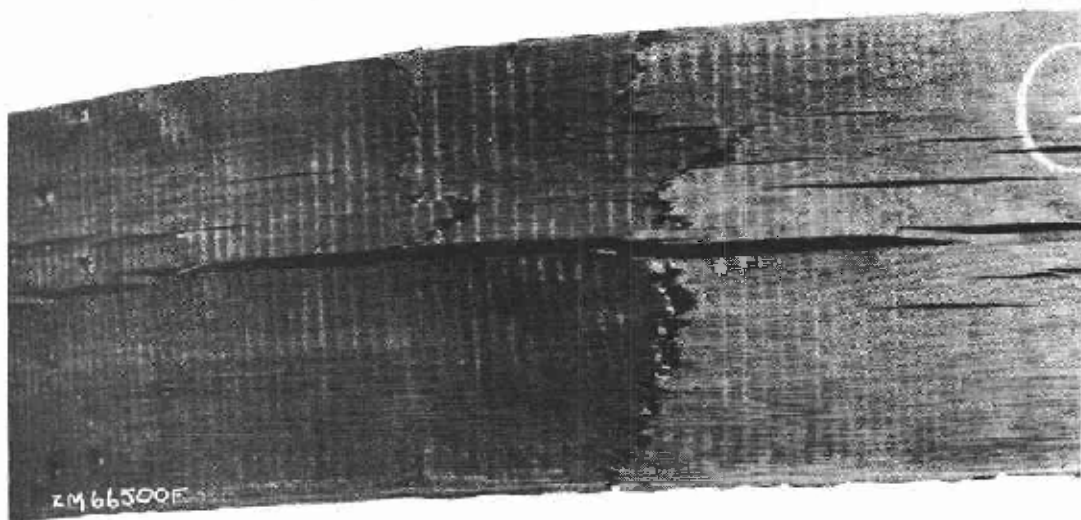
Z M 105 251

Figure 23.--Tensile failures that occurred in bent boat frame during
drying and fixing.

Z M 66500 F

Figure 24.--Bent boat member prepared for drying and fixing, showing minor strap, tie rods, and wood stays.
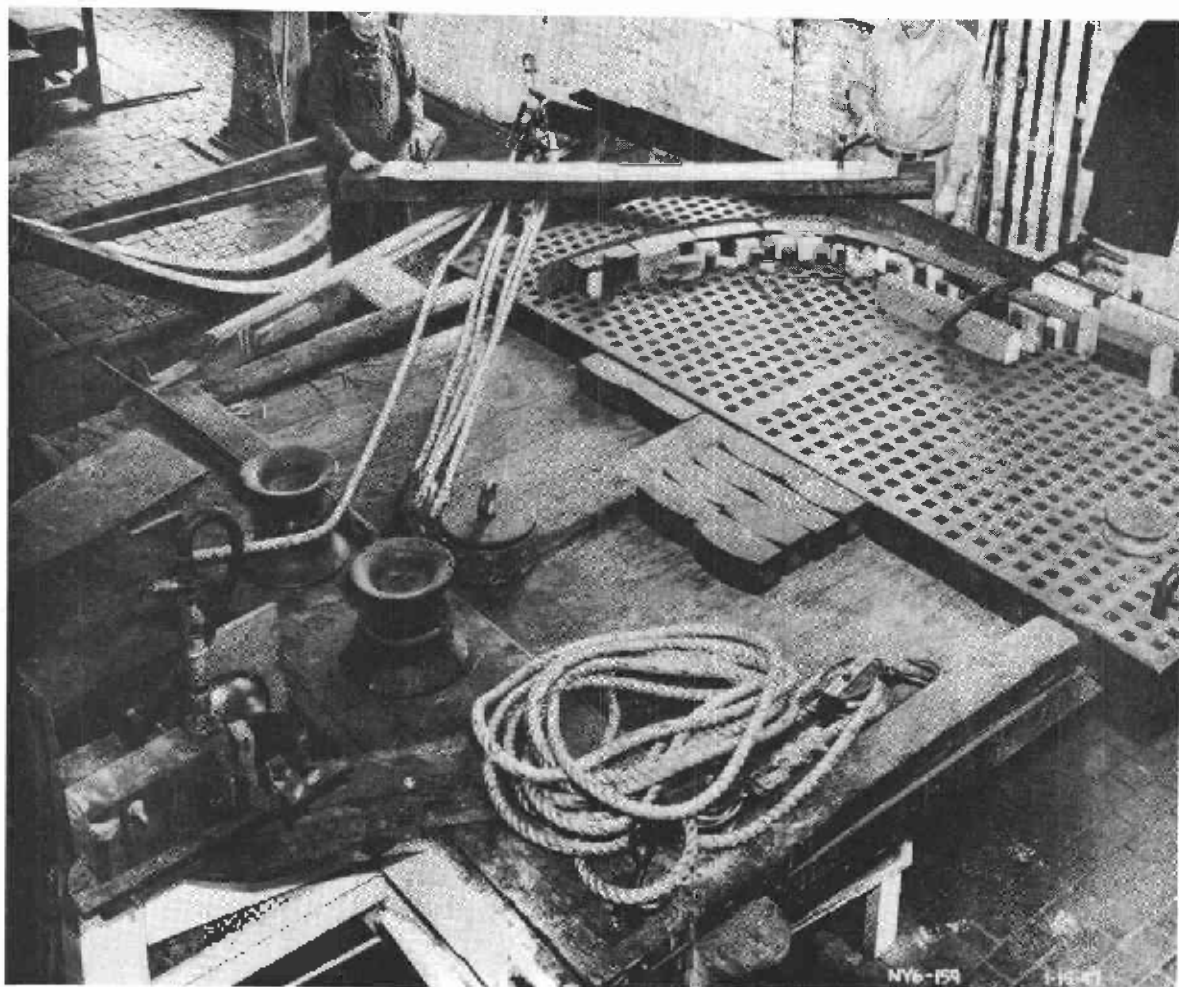
Figure 25.--Spiking a minor strap to the outer face of a piece that is to be bent to form   a boat rib.
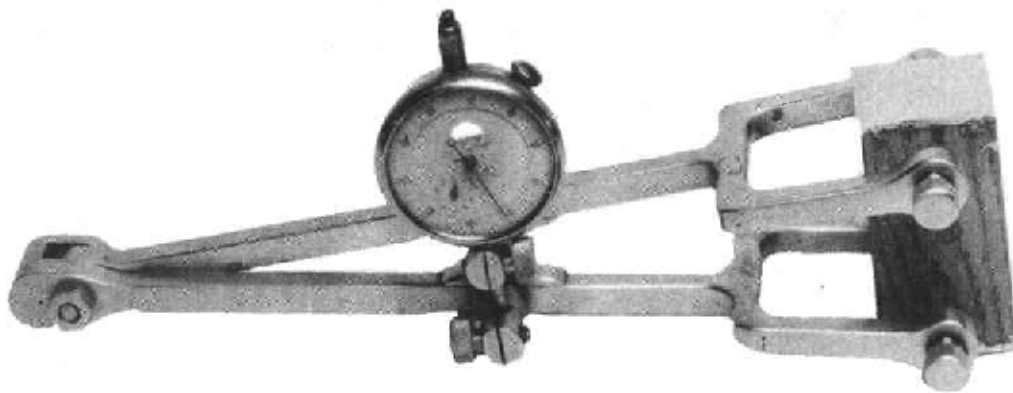
Z M 105 252

Figure 26.--Endwise-compressibility specimen with strain gage attached.

Figure 27.--Distribution of compressive strain in a bent stick.
The mean measurements for 11 sticks are shown.

Z M 65277 F