Properties of American Beech in Tension and Compression Perpendicular to the Grain and their Relation to Drying

Eric L. Ellwood
Yale University
PROPERTIES OF AMERICAN BEECH
IN TENSION AND COMPRESSION
PERPENDICULAR TO THE GRAIN AND
THEIR RELATION TO DRYING

BY
ERIC L. ELLWOOD
Sheffield Fellow, Yale University and
Senior Research Officer, Commonwealth Scientific
and Industrial Research Organization,
Melbourne, Australia

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## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>STATUS OF MECHANICAL PROPERTIES IN RELATION TO DRYING BEHAVIOR</td>
<td>9</td>
</tr>
<tr>
<td>EXPERIMENTAL MATERIAL</td>
<td>13</td>
</tr>
<tr>
<td>TENSION TESTING</td>
<td>14</td>
</tr>
<tr>
<td>Preparation of sample material</td>
<td>14</td>
</tr>
<tr>
<td>Preparation and form of test specimens</td>
<td>15</td>
</tr>
<tr>
<td>Test conditions</td>
<td>17</td>
</tr>
<tr>
<td>Experimental equipment</td>
<td>17</td>
</tr>
<tr>
<td>Testing chamber</td>
<td>17</td>
</tr>
<tr>
<td>Control</td>
<td>19</td>
</tr>
<tr>
<td>Strain measuring device</td>
<td>20</td>
</tr>
<tr>
<td>Clip gauge sensitivity and calibration</td>
<td>23</td>
</tr>
<tr>
<td>Testing procedure</td>
<td>24</td>
</tr>
<tr>
<td>Statistical design</td>
<td>26</td>
</tr>
<tr>
<td>Results</td>
<td>26</td>
</tr>
<tr>
<td>Discussion of results</td>
<td>31</td>
</tr>
<tr>
<td>COMPRESSION TESTING</td>
<td>37</td>
</tr>
<tr>
<td>Preparation of sample material</td>
<td>37</td>
</tr>
<tr>
<td>Preparation and form of test specimens</td>
<td>37</td>
</tr>
<tr>
<td>Test conditions</td>
<td>38</td>
</tr>
<tr>
<td>Experimental equipment</td>
<td>38</td>
</tr>
<tr>
<td>Testing procedure</td>
<td>40</td>
</tr>
<tr>
<td>Statistical design</td>
<td>41</td>
</tr>
<tr>
<td>Results</td>
<td>41</td>
</tr>
<tr>
<td>Discussion of results</td>
<td>42</td>
</tr>
<tr>
<td>COMPARISON OF RESULTS OF TENSION AND COMPRESSION TESTS</td>
<td>48</td>
</tr>
<tr>
<td>Maximum stress in tension versus stress at 2.5 percent strain in compression</td>
<td>48</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>50</td>
</tr>
<tr>
<td>Fiber stress at proportional limit</td>
<td>54</td>
</tr>
<tr>
<td>Strain at proportional limit</td>
<td>55</td>
</tr>
<tr>
<td>GENERAL CONCLUSIONS ON RELATION BETWEEN TENSILE AND COMRESSIVE STRENGTH AND ELASTIC PROPERTIES</td>
<td>56</td>
</tr>
<tr>
<td>THE RELATION OF SHRINKAGE TO DRYING STRESSES</td>
<td>58</td>
</tr>
</tbody>
</table>
PROPERTIES OF AMERICAN BEECH

RELATION OF COMpressive AND TENSILE PROPERTIES PERPENDICULAR TO THE GRAIN TO DRYING PROBLEMS

Development of set and checking 60
Modification by duration of loading 69
  Loading repetitions 69
  Constant load 70

RECOMMENDATIONS FOR FURTHER STUDY 75

SUMMARY 77

REFERENCES CITED 81

ILLUSTRATIONS

Figure  Page
1. Changes in moisture content, shrinkage, and stresses in different zones of a 2- by to-in. flat-sawn sweetgum heartwood plank during drying. 5
2. Form and dimensions of tension and compression test specimens. 16
3. Effect of temperature on mechanical properties of beech in tension perpendicular to the grain. 29
4. Effect of moisture content on mechanical properties of beech in tension perpendicular to the grain. 30
5. Effect of temperature on mechanical properties of beech in compression perpendicular to the grain. 45
6. Effect of moisture content on mechanical properties of beech in compression perpendicular to the grain. 46
7. Effect of temperature and moisture content on compressive stress at a strain equal to that of maximum tensile strain under the same test environment. 51
8. Diagrammatic representation of a hypothetical drying board. 61
9. Calculated total strains occurring in the outside layers and center of a 2- by 10-in. flat-sawn heartwood plank of sweetgum during drying. 66
to. Effect of repetition of load in tension perpendicular to the grain on the modulus of elasticity and strain behavior of American beech at 6 percent moisture content and 80° F. 71
11. Creep curves for American beech when placed under a constant load in compression or tension above the proportional limit at various temperatures and moisture contents. 72
CONTENTS

Plate

I. Arrangement for testing in tension perpendicular to the grain. 85
II. Construction of portable testing chamber used in tests. 87
III. Construction of clip gauge and its attachment to the tension test specimen. 89
IV. Test arrangement of compression specimen fitted with compressometer and clip gauge. 91

TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Kiln schedule used for drying test specimens.</td>
<td>14</td>
</tr>
<tr>
<td>2. Nominal test conditions employed.</td>
<td>17</td>
</tr>
<tr>
<td>3. Saturated salt solutions used at various temperatures to obtain controlled specimen moisture contents during testing in tension and compression.</td>
<td>20</td>
</tr>
<tr>
<td>4. Effect of temperature and moisture content on properties of American beech in tension perpendicular to the grain in the tangential direction.</td>
<td>27</td>
</tr>
<tr>
<td>5. Variation of tension properties perpendicular to the grain of six logs of American beech.</td>
<td>28</td>
</tr>
<tr>
<td>6. Regression equations for the influence of temperature at various moisture contents on the tension properties of American beech perpendicular to the grain in the temperature range of 80 to 160°F.</td>
<td>31</td>
</tr>
<tr>
<td>7. Comparison of temperature effect on strength and elastic properties in tension perpendicular to the grain for several species in the green condition in the temperature range of 80 to 160°F.</td>
<td>32</td>
</tr>
<tr>
<td>8. Influence of test method on strength values in compression perpendicular to the grain.</td>
<td>39</td>
</tr>
<tr>
<td>9. Effect of temperature and moisture content on properties of American beech in compression perpendicular to the grain in the tangential direction.</td>
<td>43</td>
</tr>
<tr>
<td>10. Regression equations for the influence of temperature at the various moisture contents on the compression properties of American beech perpendicular to the grain in the temperature range of 80 to 160°F.</td>
<td>44</td>
</tr>
<tr>
<td>11. Variation of compression properties perpendicular to the grain of six logs of American beech.</td>
<td>44</td>
</tr>
<tr>
<td>12. Effect of temperature and moisture content on compressive stress perpendicular to the grain of American beech at a strain equivalent to maximum unit strain in tension under the same testing environment.</td>
<td>50</td>
</tr>
</tbody>
</table>
PROPERTIES OF AMERICAN BEECH

Table 13. Comparison of temperature effects at various moisture contents on modulus of elasticity of American beech in tension and compression perpendicular to the grain in the tangential direction within the temperature range from 80 to 160°F. 52

Table 14. Comparison of temperature effects at various moisture contents on fiber stress at proportional limit of American beech in tension and compression perpendicular to the grain in the tangential direction within the temperature range from 80 to 160°F. 55

Table 15. Calculated stresses and strains occurring in a hypothetical American beech board in the early stages of drying. 64
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PROPERTIES OF AMERICAN BEECH IN TENSION AND COMPRESSION PERPENDICULAR TO THE GRAIN AND THEIR RELATION TO DRYING

INTRODUCTION

ALTHOUGH a full discussion of the developments in drying theory, applied to wood, is outside the scope of this bulletin, the salient points leading to the present status of the theory, as it pertains to drying degrade, will be critically reviewed.

The beginning of kiln drying and the origin of wood drying theory are uncertain. However, the artificial drying of wood was not adopted on a wide-spread commercial scale until the twentieth century. Modern forced-draft, temperature- and humidity-controlled kilns were developed from heated rooms or hot boxes as the drying process became better understood.

In the United States, the development of a comprehensive and workable theory of kiln drying for wood must be largely credited to H. D. Tiemann (32). Tiemann's concepts, which were published in some detail in 1917, are the basis of modern drying theory. His theory includes an appreciation of the nature of wood-liquid relations and of the development of stresses in drying wood as a function of shrinkage, set, structure, permeability, and moisture gradients. He also recognized that high temperature and/or moisture content result in a loss of cohesive strength in the wood and also exert a plasticizing effect.

The ideal kiln schedule is one which will enable the stock to be dried economically for its end use in the shortest possible time with the least possible defect. In order to achieve the optimum kiln schedule for a species, a range of initial drying conditions is tried, and selection is made of the combination which affords the least degrade commensurate with the fastest drying time. The extent of the changes within the kiln schedule and their frequency are also determined by the occurrence, or absence, of drying defects. The change points are determined to a large degree by the presence or absence of drying defects and the stress condition of the lumber. This work is facilitated by a knowledge of the moisture content distribution and stress condition within the drying lumber.

On the basis of the above approach, kiln schedules were gradually de-

3 Italic numbers in parentheses refer to references cited at the end of this paper.
developed for American species. However, at best, kiln schedule development was still largely a trial and error technique. With this method it was unlikely that absolute optimum drying conditions could be obtained, considering the large number of possible combinations of temperature, relative humidity, moisture content, and time for a particular class of lumber, even allowing for the fact that the development of stresses was known in a qualitative way. The big deficiency in the drying process is the absence of criteria for determining the development of defects such as checking, both surface and internal, although the degree of casehardening may be effectively anticipated.

In addition, kiln schedules for commercial use with a particular class of lumber now recommended by various laboratories are based on the average moisture content of the drying board. This procedure was adopted for practical reasons, and is a source of error within itself, as by no means is there necessarily always close agreement between the stress condition within the drying board and its average moisture content.

Further, the establishment of optimum kiln schedules was handicapped by limitations of kiln design, particularly with respect to uniform heat distribution and adequate circulation.

The technical approach to the drying problem has been concentrated chiefly upon factors affecting the rate of drying, for example, the application of the Fourier heat equation (21) and its modifications to moisture diffusion, and the effects of heat, moisture content, and structure of wood upon drying rate (24, 27). Also, the majority of the work has been carried out on softwoods, probably owing to the fact that they constituted the bulk of the lumber dried and that they were simpler to study than the hardwoods. Considerable information has been collected in the field of drying rates and factors influencing moisture movement (27), but less advance has been made with respect to drying factors that may influence degrade in the form of checking.

The advent of World War I afforded a stimulus to the theory and practice of lumber drying when sudden large demands were made on stocks of dried lumber. This stage was marked by an improvement in dry kiln design and revision of some of the earlier kiln schedules.

Some fifteen years ago, the United States Forest Products Laboratory, realizing a growing need for a closer examination of the stress conditions in a drying board, particularly with respect to hardwoods, commenced a series of investigations on this problem.
In 1940 Peck (22), working on 2-in. thick black gum sapwood, published the results of a new approach to the study of the development of stress in a drying plank. His method, which hereinafter will be called the strip technique of stress analysis, was a development of Tiemann's slotted section method in which the curvature of the prongs indicated the presence or absence of drying stresses and their nature. Peck marked off strips or zones which extended across the width of the drying plank and were approximately 1/15 of its thickness. These strips were measured in length while in situ, and then were cut out of the plank and remeasured, care being taken to prevent moisture loss between measurements. The process was repeated at successive stages during the progress of drying, care being taken to prevent moisture loss before remeasurement upon removal from the plank. The change in dimension of the strip after cutting from the plank was taken as a measure of the nature and magnitude of the current drying stress. This relationship was based upon the assumption that stress is approximately proportional to dimensional change. Thus, if the dimension of a strip after sawing from a board or plank was less than its dimension before removal, a tensile stress was indicated; conversely, if the strip increased in length on cutting, a compressive stress was indicated.

Peck assumed that the magnitude of dimensional change was an indication of the magnitude of existing stress. The present author (4), in preliminary studies on a stress analysis of drying beech, has subsequently established that the method does not afford an accurate indication of the magnitude of stress existing in a board within the temperature range of normal kiln drying schedules, as the magnitude of dimensional change appears to be similar, irrespective of the severity of the kiln drying schedule applied. However, a greater dimensional change of the strip was observed under low-temperature air-drying conditions, specifically at 60°F. The value of the strip technique appears to be that it gives information concerning the type of current stress occurring in a particular zone at any particular stage of drying, and also that it may indicate the approximate time of maximum stress development within the strip measured.

Peck's work showed that the maximum stress in tension of the surface zone, as indicated by dimensional change of the strips, occurred relatively early in the drying process. Further, a severe reduction in relative humidity at this stage did not throw the surface zones into greater tension, but instead the tension stresses began to subside. The severe reduction in relative humidity, just after the stage of maximum surface tensile stress had been
reached, did not cause surface checking, as the surface zones were coming into compression. Neither did subsequent internal checking occur. The beneficial effects of this early substantial decrease in relative humidity are three-fold, in that it considerably reduces the total drying time, simplifies the schedule, and reduces the time that the relatively wet inner layers are held under compression at comparatively high temperatures. On the basis that internal checking occurs on heating, to a substantial degree, the wetter inner parts of the wood, the temperature was not increased until the center of the stock had fallen below the fiber-saturation point. Once this critical point was reached, the temperature was raised considerably above that used in earlier recommendations. The result was a fast drying schedule with no appreciable increase in drying degrade when compared to the slower drying schedule previously used.

In 1944, Smith (25) developed very fast drying schedules for aspen crating and boxing, using the strip technique of stress analysis, and in 1946 Torgeson (33) published the results of work on accelerated kiln drying schedules for 1- and 2-in. thick black gum heartwood, using the same approach. Also in 1946, the results were published of a strip technique of stress analysis for 2-in. thick sweetgum heartwood (8), and these were discussed in more detail by Rietz (23) in 1950. Figure 1 shows the stress development obtained by the strip technique of stress analysis in a 2-in. thick plank of flat-sawn sweetgum during kiln drying. Current moisture contents and final shrinkage of the strips to the oven-dry condition are also shown. A study of these curves shows that, very early in the drying process, the outer layers of the plank (Nos. 1 and 10) reached their maximum tensile stress and began to subside. Lowering the relative humidity at this stage apparently did not produce any further tensile stress in the outer layers, but the layers adjacent to the surface rapidly developed their maximum tensile stress after a short period under compression. At the same time, the inner layers were thrown into even greater compression, apparently reaching maximum compression on approximately the tenth day. Reference to the tangential shrinkage values for the tenth day shows a large difference in final shrinkage between the outer and inner layers. The outer layers had apparently been stressed beyond their proportional limit, and had developed "set," which reduced their total shrinkage. The increasing shrinkage of the inner layers, which is apparent on the tenth day, indicates that the majority of the inner layers had exceeded the proportional limit in compression and had developed a compression set.
FIGURE 1. Changes in moisture content, shrinkage, and stresses in different zones of a 2- by 10-in. flat-sawn sweetgum heartwood plank during drying. (U.S. Forest Products Laboratory)
PROPERTIES OF AMERICAN BEECH

Apart from the surface layers, which are immediately thrown into tension and then commence to undergo compression, each successive layer in depth undergoes a period of compression and then one of tension. The degree of apparent compression of each strip is proportional to its depth from the surface, and the subsequent degree of tension seems to be inversely proportional to the depth of the strip in the stock. Rietz has interpreted the fact that the inner layers do not show as great a tensile strain as the outer layers to indicate that if surface checking had not occurred, then internal checking would not occur, as the tensile forces in the inner layers were less than those which produced casehardening. Internal checking under these conditions, then, would not be expected to develop unless the strength of the inner layers in tension perpendicular to the grain had been reduced by heating.

It must be pointed out, however, that the inner layers had undergone a considerable compression at relatively high moisture content before they were brought into tension, and therefore it is probable that their strain behavior under tension may have been modified by their previous treatment. It is therefore contended that the strains shown by the inner layers when they were subjected to tensile stress may not bear the same relation to stress as do the strains of the outer layers.

It is interesting to note that, with the possible exceptions of strips 2 and 9, the inner layers all attained their maximum compression set at a considerably later stage than that at which they showed their maximum compressive strain. For example, the innermost layers (Nos. 5 and 6) attained their maximum compressive strain on approximately the tenth day of drying, yet attained their maximum compression set on the 27th day. On the 27th day the innermost layers were showing increasing tensile strain, although these layers had a moisture content of approximately 55 per cent at this stage. The difference in time between the attainment of maximum compressive strain and maximum compression set of the inner layers may be explained in part by the occurrence of creep under a sustained load above the proportional limit. However, if tensile strain is to be interpreted as indicative of a tensile stress, then it is not apparent how the maximum compression set could be obtained when the layer was showing a tensile stress. The above behavior indicates the fallibility of interpreting strain readings obtained from excised layers as indicative of the appropriate stress without regard for the set attained by the layers over the course of the drying period.

Applying the strip technique of stress analysis to the kiln drying of
5/4-in. northern red oak, Rietz (23) states that the drying time was reduced from 45 days, which time was necessary when it was dried under the conditions recommended in Technical Note No. 175 (7), to 28 days, and the stock was then more check-free than material dried under the slower schedule.

In work at present under way at the Oregon Forest Products Laboratory, the strip technique of stress analysis is being applied to the development of kiln schedules for softwoods, namely western hemlock and Douglas fir. Espenas (in private correspondence with the author) has stated that thermal effects may have a considerable influence on strip dimensional changes. This work showed a marked difference in the stress development of softwoods, when compared to hardwoods, with respect to the time at which stress reversal took place. In general, the surface strips remained in tension until a comparatively late stage of drying had been reached, namely until the average moisture content had been reduced to 20 per cent. This stress behavior does not appear to be affected by the initial moisture content of the boards or by the presence of wet spots within the drying lumber. The above stress behavior is confirmed to a certain extent by the claim of some softwood operators that checking does not occur until a late stage in the drying, and also by the fact that checks do not close until a moisture content of 8 or 10 per cent is reached.

The behavior described above points to the fact that differences in moisture content, moisture distribution, and permeability cannot be used to explain satisfactorily the difference between softwoods and hardwoods in their stress behavior and consequent check formation. The approach to these problems appears to be an analysis of stress formation in the drying board, based on a knowledge of the mechanical and elastic properties of wood under kiln-drying temperatures and moisture contents.

As the strip technique of stress analysis is cumbersome, the United States Forest Products Laboratory bases the relative humidity change points in their recommended schedules on the average moisture content of the board. An empirical formula was derived by establishing the board moisture content at the time of maximum surface tensile stress. This formula states that the relative humidity should be reduced when $E$, which is obtained from the formula

$$E = \frac{\text{current moisture content} - \text{E.M.C.}^2}{\text{original moisture content} - \text{E.M.C.}},$$

$^4$E.M.C. refers to the equilibrium moisture content associated with the particular drying atmosphere.
reaches a value of 0.7 (8). However, this formula cannot, in general, be adopted for the more refractory species, as it is not known how thick the set outer zone should be before the relative humidity is lowered. In the opinion of the Forest Products Laboratory (8), the E value appropriate to a drop in the relative humidity should be considerably lower for refractory species, and the drop in relative humidity should not be sudden.

Rietz (23) has stated that, although it has not yet been demonstrated that the majority of hardwoods follow the stress pattern as indicated for sweetgum and black gum herein described, the strip technique method has been applied to develop new schedules for black walnut, laurel, madrona, tanoak, and chinquapin. The influence of the stress technique approach is apparent in the new kiln schedules published in 1951 by the United States Forest Products Laboratory (34).
STATUS OF MECHANICAL PROPERTIES IN RELATION TO DRYING BEHAVIOR

FROM the previous discussion it is apparent that a more complete investigation is required of the effect of temperature and moisture content on the strength and elastic properties perpendicular to the grain of wood. These data will provide information as to the critical temperatures at which surface and internal checking occur, and should afford information as to the time in a kiln drying schedule when the dry-bulb temperature can be increased to obtain faster drying. Further, a comparative study of the relative changes in strength and elastic properties of wood in both tension and compression will clarify the position as to the actual drying stresses existing within the board, and will enable a better evaluation of the strip technique of stress analysis to be made. In addition, such a study should provide an explanation of the fact that the shrinkage of wood varies with its drying conditions.

Although the importance of strength and elastic properties of wood, perpendicular to the grain, has been recognized, comparatively little work has been done in this field as it relates to drying.

In 1931, Greenhill (12, 13) carried out the first work on the effect of temperature and moisture content on the strength and elastic properties of wood perpendicular to the grain. In this work the experimental difficulties encountered were substantial, with the result that considerable judgment had to be exercised in the derivation of a portion of the results, particularly those carried out at the higher temperatures.

Greenhill's investigation was made on American beech, and was restricted to an examination of tensile strength and elastic properties. Testing was carried out over saturated salt solutions which were heated to the appropriate temperature to obtain the desired equilibrium moisture content at the temperature of test. In the green condition, the maximum stress that could be resisted by the wood at 180°F was 55 per cent less than that at room temperature, while at 5 per cent moisture content the maximum stress at 180°F was 19 per cent less than that at room temperature. The curve of maximum stress plotted against temperature was sigmoid for material in the green condition, with the maximum rate of loss of strength occurring between 100 and 155°F. The behavior of modulus of elasticity was similar in nature to that of maximum stress.

Perhaps the most significant results put forward by Greenhill were
those which showed that, although the overall differences were small, the maximum deformation just before failure was obtained at a temperature of approximately 124°F.

It was subsequently proposed that the optimum drying temperature of beech should therefore be 124°F., as the tensile stress in the drying board could be accommodated by stretching rather than relieved by checking. The validity of this hypothesis is critical in the further development of the drying theory. In actual fact, it has never been demonstrated that the optimum drying temperature of beech is 124°F. from the aspect of the drying degrade developed.

Kollmann (18), in 1950, published results of an investigation carried out in Sweden to determine the causes of injury in the drying of green oak. To determine the influence of temperature on the tensile strength of oak, tests were made in which a high frequency alternating electric field was used to obtain the temperature at test. To reduce radiation and moisture loss from the specimen, the wide faces of the specimen were covered with strips of wood at the same moisture content. In these tests, the relationship of maximum tensile stress to temperature was rectilinear, strength decreasing with increasing temperature. Kollmann concluded from the results of these investigations that there was no indication of greater deformation at any particular temperature. In this experiment, however, the strain was measured by movement of the crosshead in the testing machine, and no attempt was made to estimate or correct for movement in the tension grips. The evidence put forward by Kollmann therefore cannot be accepted as conclusive.

Evidence advanced by Barnard-Brown and Kingston (1), on the tension testing of two eucalypt species and myrtle beech, suggests that the deformation at failure increases with temperature, but the results are not considered to be conclusive by the authors, owing to the limited amount of material tested.

The unsatisfactory present state of knowledge on the vital point of strain behavior of wood in a direction perpendicular to the grain indicates the desirability of further work on this subject.

Kollmann, in his approach to the application of strength and elastic properties of wood to its drying defects, considered the probable forces that lead to the formation of internal checks in European oak. He postulated that the two major strength properties concerned with the formation of checks were tension perpendicular to the grain and shear parallel
to the grain in a radial plane. He therefore carried out tests on un­
seasoned oak, over a wide range of temperatures, on the shear strength
parallel to the grain in the radial plane, in addition to the tensile tests.
These values of tensile and shear strength were plotted together on
the same axis against temperature. On the basis of determining the tem­
perature at which the shear strength decreased markedly relative to the
tensile strength, he advanced a critical temperature which should not be
exceeded in the drying of oak.
In conjunction with the strength testing of oak, Kollmann also meas­
ured the total volume of internal checks developed over a range of drying
temperatures, and plotted these values against temperature. The rela­
tionship was linear, and extrapolation of the curve to zero coincided with
a temperature of 35°C., which is in fact close to the initial temperature
of 40.5°C. recommended by the British Forest Products Laboratory (10)
for the drying of green oak. While this finding affords some basis for the
drying temperature proposed by the British laboratory, it does not clarify
the fundamental causes of the checking.
There is also reason to believe that the factors involved in the produc­
tion of surface checks are different from those responsible for internal
checking. Instance of this is given by Kollmann, who states that the oak
tended to have more apparent surface checking at the lower tempera­
tures of drying. Also, the present author, in preliminary studies of drying
stresses in beech (4), observed that considerable surface checking oc­
curred in some boards at drying temperatures as low as 50°F., and was
not so apparent at 130°F. Further, it has been observed by Gadd and
Hudson (II), in the course of vapor drying experiments, that certain
species, when vapor dried at elevated temperatures, show little or no
surface checking in comparison with their behavior under air drying
conditions, although internal checking may be quite severe. The above
finding points to the effects of the mutual interaction between tensile and
compressive stresses within the drying board.
It is probable that the relation between the strengths in compression
and tension with changing temperature and moisture content will be
found to vary with the species. In this connection, Stamm and Lough­
borough (26), in discussing the shrinking and swelling of wood, cited
the case of white pine which showed the same shrinkage over a range of
drying temperatures from winter air temperatures to 170°F. On the
other hand, white oak shows a large increase in total shrinkage with in-
Increasing temperature of drying. Stamm and Loughborough conclude from this behavior that, in the case of white pine, the ratios of tensile to compressive strength values are approximately equal under the various conditions. But in white oak the strength in compression perpendicular to the grain must decrease relatively faster than the tensile strength, thus leading to greater compression shrinkage or collapse. Stamm and Loughborough also showed that species in which the ratio of compressive to tensile strength perpendicular to the grain (stress at proportional limit in compression and maximum stress in tension, taken from reference 20) was high, tended to show less shrinkage than would be expected from the specific gravity-volumetric shrinkage relationship. It should be pointed out that it is not a strictly correct procedure to compare strength in tension and compression from standard ASTM tests, as the basis for determination of these strengths is entirely different.

On the basis of these observations, it might be expected that, holding all other variables constant, species which show a low ratio of compressive to tensile strength perpendicular to the grain would have less tendency to surface checking than other species having a high ratio. Consequently, such species (assuming that liquid tension collapse does not occur) could in general be dried at the higher kiln drying temperatures with development of only a little surface checking. On examination of some 28 hardwood species, for which strength properties perpendicular to the grain and recommended kiln schedules were available, the present author found a trend toward the use of higher kiln temperatures with decreasing compressive-tensile strength perpendicular to the grain ratios. However, there was a considerable scatter of values about the trend, and also the specific gravity of the species decreased with the decrease in compressive-tensile strength ratio. Therefore the factors pertinent to shrinkage and permeability could not be separated from mechanical effects.

In order to explore more fully the critical conditions in drying with respect to the development of drying defects, particularly surface checking, the following study was undertaken to investigate the variation with temperature and moisture content of tensile and compressive properties perpendicular to the grain in a tangential direction. It was considered that a species such as American beech, which is susceptible to surface checking but is not normally subject to failure through internal checking or liquid tension collapse, would provide ideal material for an investigation of the relationship of strength and elastic properties to drying defects.
EXPERIMENTAL MATERIAL

SIX beech logs from various localities provided the material for this study. It was considered that variability within the species may have a determining influence on any practical recommendations arising from such a study. Although one log from each of a number of localities cannot, by any means, be considered as an adequate representative sample of the area, this system of sampling is more likely to approach the variability of the species than material from a single locality.

According to the variability values published by Markwardt and Wilson (20), the approximate probable variation of the observed average from the true average of a species when based on six trees is as follows:

- Tension perpendicular to the grain
  - Maximum stress : 5 per cent
- Compression perpendicular to the grain
  - Fiber stress at proportional limit : 6 per cent

The localities from which the logs were obtained were:

- Ager County, Michigan; White Mountain Forest, New Hampshire;
- Allegheny National Forest, Pennsylvania; Russ Forest, Michigan;
- Susquehannock State Forest, Pennsylvania; State Forest, Indiana.

All the logs were 8-ft. butt logs, and were delivered, with bark attached and end coated, within three weeks of felling. The small end diameters varied from 19 to 26 in. outside the bark. The ages of the trees, as determined from ring counts, varied from 105 to 260 years. All the logs were apparently sound when received, although some variation in heartwood color with distance from the pith was apparent in some of the logs. Considerable variation in the width of the sapwood was also evident, the variation being from 2½ to 4 in.

On arrival at the mill, all logs were sawn around the log to remove the sapwood, and then 1 ¼-in. thick heartwood boards were sawn from the four faces of the log so that maximum width boards of truly flat-sawn heartwood were obtained. Efforts were made to obtain board widths of at least 7 in. with minimum curvature of the growth rings.

All the boards from which the test specimens were later prepared were designated according to the log number and position in the log. The boards were then stored in damp sawdust treated with sodium pentachlorophenate until required.
TENSION TESTING
Preparation of Sample Material

One 1 1/4-in. thick heartwood board from each log, cut from the outer portion of the heartwood, was selected at random with respect to the four sides of the log flitch. Each board was then marked into four sections, and each section was designated by random procedure to provide material for each of the four test moisture contents. The sections from each board which were assigned for testing in the green condition were stored until required under damp sawdust treated with sodium pentachlorophenate to preclude stain and decay.

The remaining portions of each board were kiln dried under very mild conditions to the approximate moisture content at which they would be tested. The kiln schedule used is shown in Table 1. Thus, when the charge reached approximately 18 per cent moisture content, the material for testing at that moisture content was removed, and the same was done for the 12 and 6 per cent material. The specimens were dried in board dimensions as it was found that warping developed when the specimens were dried in test size. The presence of warp was undesirable, as stress concentrations would undoubtedly occur in the tension testing of cupped material. By drying in

<table>
<thead>
<tr>
<th>Moisture content at change points</th>
<th>Dry-bulb temperature (°F.)</th>
<th>Wet-bulb depression (°F.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green condition—40 per cent</td>
<td>110</td>
<td>3</td>
</tr>
<tr>
<td>40 per cent—25 per cent</td>
<td>110</td>
<td>5</td>
</tr>
<tr>
<td>25 per cent—15 per cent</td>
<td>120</td>
<td>10</td>
</tr>
<tr>
<td>15 per cent—6 per cent</td>
<td>120</td>
<td>25</td>
</tr>
</tbody>
</table>

board form, any distortion that developed was dressed out from the oversized boards before final shaping was done. In addition, as drying checks (if present) develop in the surface zones of beech rather than in the interior zones, there would be little likelihood of drying checks being present in the actual test specimen, as the surface zones were removed in the shaping operation.
TENSION TESTING

Specimens were cut from the board sections and then shaped for test. Test specimens were numbered consecutively on cutting from each board section, and allocated in random order to each temperature of test at the moisture content appropriate to the board section. Until required for test, the groups of specimens for the different test conditions were maintained at 6, 12, or 18 per cent moisture content at room temperature in sealed jars over saturated salt solutions which provided appropriate equilibrium moisture content conditions.

PREPARATION AND FORM OF TEST SPECIMENS

Specimens for testing in tension perpendicular to the grain were obtained by first thicknessing the boards accurately to 1 inch. Strips, which were \( \frac{1}{3} \) in. along the grain, were then cut across the full width of the boards with a smooth-cutting, tungsten-carbide tipped saw. The form of the test specimen was then marked on each strip with a template and the specimen cut approximately to shape with a fine bandsaw. Final shaping was carried out with a vertically mounted drum sander, to which a jig was fitted to allow the sander to shape the specimen accurately.

Although only limited information was available on the behavior of the non-standard tension test specimens, experiments carried out elsewhere on tension parallel to the grain have shown that higher unit stress values are obtained with a specimen having a relatively small area of cross section in the test zone gradually increasing to relatively large dimensions at the supported ends, and with a reasonably long distance between the friction grips. Although these factors had been determined for testing in tension parallel to the grain, they were kept in mind in the development of the tension perpendicular to the grain specimen dimensions for the present work.

The final shape of specimen adopted for the present experiment had a central 12-in. length which measured \( \frac{1}{3} \) by \( \frac{1}{2} \) in. in cross section. The 2-in. central portion of the specimen was expanded out to a 1 by \( \frac{1}{3} \)-in. cross section at the ends, the gradual transition being accomplished by means of a 2 3/4-in. radius of curvature. During test, the extended arms of the specimen were held in self-aligning Templin grips. The form of the tension specimen is shown in Figure 2.

The type of specimen described above was adopted in place of the standard American Society for Testing Materials specimen chiefly because it was more suitable for making strain readings, and also to avoid objectionable
stress concentrations which might result in apparent tensile strength values considerably lower than the true values. Coker (2) determined by photoelastic methods that the stress in tension of isotropic materials is not uniformly distributed over the section of such a test specimen, but falls off from a high tensile stress at the loaded edges of the section to a uniform com-
TENSION TESTING

pressive stress at the center. No doubt similar variations occur in wood specimens of the ASTM type. It is mainly as a result of Coker's work that the tension perpendicular to the grain test has been eliminated from the British specifications (6). Further, it was observed by Keylworth (15) that the necked-down specimen of the type used in this experiment would show tensile strength values more closely approaching the true value than would the standard ASTM specimen.

TEST CONDITIONS

Tension specimens from each of the six logs were tested, in duplicate, under five levels of temperature in combination with four levels of moisture content, as shown in Table 2. Thus, 12 specimens were tested at each of the 20 combinations of temperature and moisture content.

<table>
<thead>
<tr>
<th>Nominal temperature at test (°F.)</th>
<th>Nominal moisture content at test (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>6  12  18  green</td>
</tr>
<tr>
<td>100</td>
<td>6  12  18  green</td>
</tr>
<tr>
<td>120</td>
<td>6  12  18  green</td>
</tr>
<tr>
<td>140</td>
<td>6  12  18  green</td>
</tr>
<tr>
<td>160</td>
<td>6  12  18  green</td>
</tr>
</tbody>
</table>

EXPERIMENTAL EQUIPMENT

Testing Chamber

A primary consideration was that the testing machine could not be withdrawn from use on other work for long periods of time. Therefore, to control the temperature and moisture content of the specimens during test, a portable temperature- and humidity-controlled chamber was constructed. The chamber was designed to be mounted on the crosshead of a Baldwin-Southwark universal testing machine (see Plate I), so that the chamber enclosed the central portion of the specimen but not the friction grips which held it. With this arrangement it was not necessary to heat the friction
grips to test temperature, and condensation troubles at high humidities were also minimized.

The chamber consisted essentially of two sections, as shown in Plate I, namely, the heating and humidifying compartment (A) and the test compartment (B).

The heating compartment contained a 150-watt strip heater mounted between the floor of the compartment and a darkened non-reflecting false floor which was open at either end. A 7-in. fan was mounted in a vertical position on the wall to provide circulation through to the test compartment. Humidification was obtained by means of a tray of the appropriate saturated salt solution resting on the false floor above the strip heater. A small hinged door was provided in this compartment, closing tightly on to a rubber strip thus providing a seal against vapor transmission. The detailed construction of the chamber is shown in Plate II.

The test compartment was designed to provide for free movement of the friction grips, and yet to maintain good thermal and vapor insulation. To achieve this, a small hole was cut in the bottom of the test compartment, only large enough to allow the tension specimen to project into the compartment. When the specimen was in place, this hole was then packed with glass wool. The upper portion of the test compartment was constructed with a flexible section which provided heat insulation and a vapor seal, yet permitted elongation of the specimen without hindrance. This was achieved by packing glass wool and aluminum foil between two sheets of rubber damask. The lower sheet of rubber was incised in the center so that it closed tightly around the upper portion of the test specimen, which projected through it to the friction grip. The upper sheet of rubber damask was cut out to allow the friction grip to extend into the flexible top, so that the specimen could be gripped. The load applied to the specimen during test by this flexible cover was insignificant, as shown by machine tests, and free alignment of the grips was not hindered. The test compartment was provided with a small door which closed tightly on to an insulating rubber strip. For observation of the specimen during test, a window was built into this door. In order to reduce heat losses from the window, three plates of lucite were used, with an air space between each plate.

To reduce heat and vapor losses to a minimum, the interior plywood walls of the chamber were packed with rock wool 3/4-in. thick, and an additional layer of aluminum foil was applied over the rock wool before the exterior plywood surface was attached.
Control

Temperature control in the chamber was obtained by means of a bi-metallic on-off thermoregulator which was placed in the test compartment in the vicinity of the test specimen. It was found that optimum temperature control was obtained when the strip heater was heating 75 per cent of the time. In order to provide this condition at the various temperatures used, a variable resistance was placed in series with the strip heater so that the heat dissipation of the heater could be varied. A condenser was provided at the thermoregulator to suppress sparking at the contacts, and an indicator light placed in the circuit. Under these conditions the degree of control obtained, as determined from shielded thermocouples, was $\pm 1.5^\circ F$.

To obtain the desired moisture content at each temperature of test, saturated solutions of various salts were used. Saturated solutions of salts, as distinct from unsaturated solutions, have the desirable property of being self-regulating, to a constant value, of the water vapor pressure above their surface, provided that excess solute is present. The advantages of a theoretically greater possible range of humidities with the use of unsaturated solutions are outweighed by difficulties with change in concentration as a result of evaporation from the salt solution or absorption of water from the specimens.

A survey was therefore made of salts which would provide the desired equilibrium moisture content at each temperature of test. A further selection was then made on the basis of availability, cost, and variation of solubility with temperature. Final selection was made from a test of the salt under operating conditions in the testing chamber. Equilibrium moisture content values for the salts so used were determined from wet- and dry-thermocouple readings in the chamber near the test specimen. Under actual test conditions it was found that several of the salt solutions could be used over a range of temperatures to produce approximately the same equilibrium moisture content of the specimen. This behavior deviated from theoretical values under ideal conditions, and the variation is probably due to the fact that the test chamber was not a closed system. Table 3 shows the salt solutions used for the various test conditions. A check on the validity of the equilibrium moisture content determination, as derived from thermocouple readings, was made under a number of combinations of temperature and humidity by determining the equilibrium moisture content of "dummy" tension specimens placed in the chamber. In no instance did the actual equilibrium moisture content, determined by weighing, vary more than
TABLE 3. SATURATED SOLUTIONS USED AT VARIOUS TEMPERATURES TO OBTAIN
CONTROLLED SPECIMEN MOISTURE CONTENTS DURING TESTING IN
TENSION AND COMPRESSION

<table>
<thead>
<tr>
<th>Nominal temperature at test (°F.)</th>
<th>Nominal moisture content at test (per cent)</th>
<th>Saturated solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>6</td>
<td>KC₆H₈O₇</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>NaNO₂</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>KBr</td>
</tr>
<tr>
<td>green</td>
<td></td>
<td>water</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>KC₆H₈O₇</td>
</tr>
<tr>
<td></td>
<td>12</td>
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<td></td>
<td>18</td>
<td>KBr</td>
</tr>
<tr>
<td>green</td>
<td></td>
<td>water</td>
</tr>
<tr>
<td>120</td>
<td>6</td>
<td>KC₆H₈O₇</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>NaNO₂</td>
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<tr>
<td></td>
<td>18</td>
<td>KBr</td>
</tr>
<tr>
<td>green</td>
<td></td>
<td>water</td>
</tr>
<tr>
<td>140</td>
<td>6</td>
<td>KC₆H₈O₇</td>
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<tr>
<td></td>
<td>12</td>
<td>NaNO₂</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>KBr</td>
</tr>
<tr>
<td>green</td>
<td></td>
<td>water</td>
</tr>
<tr>
<td>160</td>
<td>6</td>
<td>KC₆H₈O₇</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>KBr</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>water</td>
</tr>
<tr>
<td>green</td>
<td></td>
<td>water</td>
</tr>
</tbody>
</table>

1.5 per cent moisture content from the calculated equilibrium moisture content.

Strain Measuring Device

In preliminary work carried out on the strain measurement of specimens tested in tension perpendicular to the grain, under a range of combinations of temperature and moisture content (4), Baldwin SR-4 electric strain gauges were attached directly to the surface of each specimen. The strain was followed manually through the test to failure of the specimens by means of a Baldwin SR-4 type K portable strain indicator.

Considerable difficulty was encountered in attempting to attach the strain gauges directly to the surface of the green specimens, particularly for testing
TENSION TESTING

at the higher temperatures. This fact, in association with the high cost which would be entailed in the use of a separate gauge for each of a large number of specimens, indicated the desirability of adopting a different technique for strain measurement.

The principle eventually adopted was that of the bending beam or clip gauge, with which repeated use of an electric strain gauge is possible. In this device, a bent metal beam, with electric strain gauges attached to the convex and concave surfaces, is clipped between the "ears" of an extensometer. The spring of the clip holds it in position in the extensometer. When the specimen is subjected to tensile strain the ends of the extensometer move apart and the beam curvature decreases. As a result, the gauge on the convex surface is subjected to compression, while that on the concave face is subjected to tension.

With the gauge from the convex face of the beam attached to the compensating gauge terminals of the strain indicator, and the gauge on the concave face attached to the active gauge terminals, strain readings may be made on the indicator dial of the instrument. As the readings of strain obtained on the dial are not a direct measure of the actual elongation of the specimen between the gauge points of the extensometer, the clip gauge must be calibrated to transform the readings into direct unit strain. Temperature of test is automatically compensated for, as both gauges are under the same environmental conditions.

As it was not possible to obtain from a commercial source either an extensometer suitable for the specimen to be tested or a clip gauge assembly, it was necessary to construct these units. In this regard, considerable valuable advice on the construction of a clip gauge was obtained from the United States Forest Products Laboratory, where clip gauges had been constructed and were in use for strain measurement in wood under similar test conditions.

The extensometer was constructed from aluminum alloy to minimize the weight which would be applied to the specimen. It consisted of two U-shaped collars which were attached to the specimen by means of two diametrically opposed screws in each collar which were screwed firmly against the surface of the specimen. The collars were constructed to accommodate specimens up to cross sections slightly in excess of 1/2 by 1/2 in. They were also provided with removable stops on the inside of the collar to aid in centering different sizes of specimens, and to prevent any tendency of the collar to rotate around the screw axis under the pressure of the clip
gauge. The collar centers were 1 in. apart, providing for a strain measurement over 1 in. of the specimen.

In adjusting the extensometer on the specimen, two adjustable slotted metal strips connecting the two arms of each collar were set flush with the edges of the collars to give exactly 1 in. between the screws. From each collar projected a metal lug which contained on its inner face a smooth hemispherical recession in which to seat the arms of the clip gauge.

In the construction of the clip gauge, a compromise was of necessity adopted between the geometrical configuration of the clip which would give the greatest sensitivity, and the force which the clip would apply to the arms of the extensometer when sprung into position. The form of the clip gauge finally chosen was as follows: A strip of phosphor bronze 0.025-in. thick, 5/16-in. wide, and 2-in. long was bent to a 4-in. radius of curvature. At each end of the phosphor bronze strip was fastened a brass rod 3/4-in. long and 5132-in. in diameter, which extended towards the axis of curvature of the strip. To the outer end of each of these brass rods was attached a brass rod 11/32-in. long and 1/32-in. in diameter, extending outward. The short brass rods were smoothly rounded on the ends. When the clip was unstressed, the rounded ends of the rods were approximately 3/14 in. apart, and when in use, that is, compressed between the "ears" of the extensometer, they were 1 1/4 in. apart.

Two electric strain gauges, Baldwin type AB-3, were attached to the concave and convex faces of the phosphor bronze strip in the unstressed condition with Armstrong's epoxide thermosetting resin Type A 4.

The strain gauge on the convex side of the clip was connected to the compensating gauge terminals, and the gauge on the concave face connected to the active gauge terminals.

In use, the extensometer was attached to the specimen and the arms of the clip gauge seated in the "ears" of the extensometer, where the clip was held by the spring of the stressed phosphor bronze strip. At failure of the specimen, the clip was unseated from the extensometer "ears" and held

Prior to gluing on the strain gauges, the phosphor bronze surface was degreased by immersing the strip in a solution of 10 per cent sodium metasilicate for 10 minutes at 140°F. and rinsed in running water. The surface was brightened by immersing the strip for 2 minutes in 85 per cent phosphoric acid, then rinsing and drying.

This thermosetting, room-temperature curing resin is recommended for use with synthetic resin type strain gauges, as it is claimed that, besides having a high resistance to heat and moisture, the resin does not shrink or swell upon curing as it contains no volatile solvent. Also, as a result, it is claimed that the strength of bond is independent of the glue-line thickness.

22
suspended by the indicator wires which were coiled towards the ends to prevent sudden shocks to the gauges.

The clip gauge arrangement is shown in Plate III.

As the clip gauge assembly was used under a variety of humidities (up to 100 per cent relative humidity), complete sealing of the unit was highly important to prevent electrical leaks and stray influences. To this end, a careful application of Dow Corning 935 silicone resin sealer was made to the clip and all exposed leads from the strain gauges to the indicator.

**Clip Gauge Sensitivity and Calibration**

Loss of sensitivity is incurred when the clip gauge is substituted for the direct application of a gauge on the specimen. Using the Baldwin SR-4 type K portable strain indicator in association with a strain gauge attached directly to the specimen, readings to the nearest 10 micro-inches⁵ are possible at the speed of testing used (0.0033 in. per in. of specimen length per min.). However, to follow accurately the strain of the specimen, considerable manual manipulation of the indicator is involved, including the use of a range-extender switch, owing to the considerable deflection of the indicator needle for relatively small strain increments.

Using the clip gauge described above, a reading of one division on the indicator scale, which is 10 micro-inches, corresponds approximately to 0.0002 in. movement between the extended rods of the clip gauge. By reading to 0.2 of a division on the indicator scale, readings to approximately 0.00004 in. can be obtained. In addition, only one setting of the range-extender switch is required, as the total strain can be accommodated within the range of the rotating scale of the instrument.

As the sensitivity of the clip is directly proportional to the thickness of the phosphor bronze strip, and inversely proportional to the length of the rods extending from its ends, the sensitivity can be increased by suitably altering these dimensions.⁶ However, shortening the arm length and increasing the thickness of the phosphor bronze strip both increase the pressure exerted by the clip on the "ears" of the extensometer. High pressure against the extensometer was undesirable, as it caused pre-stressing of the specimen before loading, and required very tight screw pressure of the extensometer to prevent slippage of the extensometer on the specimen.

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⁵ 1 micro-inch = 0.000001 in.

- When the strain gauges are attached to the phosphor bronze strip, the thickness of the glue line adds to the effective thickness of the bending beam.
PROPERTIES OF AMERICAN BEECH

With the clip gauge dimensions adopted, the force exerted by the clip on the extensometer was less than 0.5 lb.

To calibrate the clip gauge, strain gauges were attached directly to the surface of several specimens and, under room conditions, a series of readings was taken within the proportional limit of the specimens. The load was then removed, the extensometer and clip gauge attached, and clip gauge readings taken up to the same load. This procedure was carried out a number of times, with alternate readings of the directly attached strain gauge and the clip gauge, and a conversion factor was thus obtained to convert dial readings to unit strain.

Over the range of strains measured on the test specimens, the relationship of the strain measurements obtained by means of the clip gauge and those obtained by the directly attached gauge was linear, so that the correction factor required to convert indicator readings to actual unit strain occurring in the specimen was constant over the range of strains used.\(^7\)

During the course of the work several clips were made up, and the conversion factors obtained varied from 21.0 to 29.0. The conversion factors for the clips were rechecked several times during the course of the testing.

TESTING PROCEDURE

Owing to the time taken for bringing the test chamber to the desired conditions, the time necessary for stabilization of specimen temperature and moisture content, and the availability of the testing machine for this work, the experiment was set up to provide for three hours of actual testing each day, in which time six specimens could be tested.

In order to randomize error in experimentation, the experimental material was divided into groups of six specimens, each group containing one specimen from each log, so that one replicate of the material was tested at a time. The order of using the testing conditions, that is, of the twenty combinations of temperature and moisture content, each to be set up twice, was also randomized.

The sequence of events in testing was as follows. A specimen was taken from the sealed salt solution container where it had been at a predeter-

\(^7\) When the clip gauge extensometer assembly was used, it was found that more early strain readings must be discarded before the strain readings stabilize than was the case with the strain gauge attached directly to the wood.
mined moisture content at room temperature, and placed in a small conditioning cabinet in which the temperature and humidity conditions were the same as those required for testing. After the specimen had been conditioned in the cabinet for 2 hours, it was transferred rapidly to the testing chamber on the Baldwin machine. The specimen was fitted into the grips of the machine, and the extensometer and clip gauge attached. When the conditions of the testing chamber had again stabilized (after approximately 5 minutes), and the specimen was also in a stable condition as shown by zero drift of the strain gauge readings with no load applied, the test was commenced.

Load increments, ranging from 2 to 10 lb., appropriate to the strength at test conditions were determined previously, so that a minimum of 10 to 15 load-strain readings could be taken up to the proportional limit. The sensitivity of the testing machine was 0.2 lb. on the lowest loading range. The rate of loading was controlled to 0.0033 in. of strain, per in. of specimen between the friction grips, per min. Owing to the shorter length of the specimens from logs nos. 5 and 6, as a result of the smaller board widths available, the distance between the friction grips was slightly less than 4 1/2 in. The rate of loading for specimens from these two logs was therefore adjusted to give the same rate of strain per unit length as in the case of the longer specimens. In this regard, it was considered that small variations in the rate of loading would not appreciably influence the results. In timber testing under ASTM methods, the allowable tolerance in rate of loading is limited to \( \pm 25 \) per cent of the required rate in order to keep variation in test results from this cause to within approximately 1 per cent (31). The strain was recorded to failure by following the strain manually with the strain gauge indicator.

After failure, the specimen was removed from the grips, the cross-sectional dimensions of the necked-down portion measured with a machinists' micrometer to 0.001 in., and the test zone weighed and oven dried to determine the actual moisture content at test. The specific gravities of the test specimens were determined (oven-dry weight, oven-dry volume basis), using a Breuil mercury volume meter to determine the volumes.

All specimens which failed in parts other than the necked-down portion of the specimen were discarded.

Stress-strain curves were drawn for all specimens, and maximum stress, modulus of elasticity, and fiber stress at proportional limit were computed.
PROPERTIES OF AMERICAN BEECH

Statistical Design

The experiment was designed as a 2 x 4 x 5 x 6 randomized block factorial. Replications were pooled and significance levels at 1 per cent and 5 per cent obtained by means of the F test. In general, third order interactions were not significant, and were generally pooled to obtain an error term.

In analyzing the effect of moisture content on strength and elastic properties at the various moisture contents, statistical analysis was only applied to the 6, 12, and 18 per cent moisture content material, as the true interval between 18 per cent and the effective fiber saturation point was unknown.

No account was taken in the statistical analysis of the deviation of specimen moisture contents from the nominal values.

Results

In general, good control of moisture content was obtained by using the technique of periodically checking the weight of the specimens during the conditioning period. The maximum deviation of any group of specimens from the control moisture content was 0.8 per cent. The greatest difficulty encountered was in stabilizing the specimens at 18 per cent moisture content at the higher temperatures.

On the whole, the clip gauge behaved satisfactorily, although some trouble was experienced because of breakage of the fine lead wires during handling. Special attention in waterproofing the lead wires was also necessary to prevent electrical short circuits at the higher humidities.

Although the temperature tended to fall slightly below the control point when the specimen was introduced into the testing chamber, temperature variations were restricted to ± 2°F. about the control point during actual test.

Experimental data obtained for the effects of temperature and moisture content on the tensile strength and elastic properties are given in Table 4. The mean values of all properties determined are shown for each log in Table 5. Regression curves for the effect of temperature on strength and elastic properties for the nominal 6, 12, 18 per cent, and green moisture contents are shown in Figures 3A, B, and C. Table 6 shows the regression equations of temperature upon strength and elasticity at the four nominal moisture contents tested. Figures 4A, B, and C show the effect of moisture
<table>
<thead>
<tr>
<th>Nominal temp. (°F.)</th>
<th>Nominal moisture content (per cent)</th>
<th>Actual moisture content (per cent)</th>
<th>Stress at maximum load (lb. per sq. in.)</th>
<th>Proportional limit stress (lb. per sq. in.)</th>
<th>Modulus of elasticity (100 lb. per sq. in.)</th>
<th>Strain at maximum load (in. per in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>6</td>
<td>5.5</td>
<td>1523</td>
<td>1078</td>
<td>1916</td>
<td>0.0100</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>12.2</td>
<td>1289</td>
<td>741</td>
<td>1347</td>
<td>0.0155</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>17.7</td>
<td>1040</td>
<td>569</td>
<td>1011</td>
<td>0.0179</td>
</tr>
<tr>
<td></td>
<td>green</td>
<td>89.4</td>
<td>782</td>
<td>395</td>
<td>799</td>
<td>0.0183</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>5.9</td>
<td>1475</td>
<td>952</td>
<td>1628</td>
<td>0.0113</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>12.0</td>
<td>1166</td>
<td>637</td>
<td>1109</td>
<td>0.0214</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>18.5</td>
<td>863</td>
<td>472</td>
<td>752</td>
<td>0.0209</td>
</tr>
<tr>
<td></td>
<td>green</td>
<td>89.3</td>
<td>666</td>
<td>330</td>
<td>620</td>
<td>0.0213</td>
</tr>
<tr>
<td>120</td>
<td>6</td>
<td>5.8</td>
<td>1411</td>
<td>873</td>
<td>1481</td>
<td>0.0125</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>12.2</td>
<td>1061</td>
<td>525</td>
<td>970</td>
<td>0.0220</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>18.8</td>
<td>737</td>
<td>375</td>
<td>634</td>
<td>0.0224</td>
</tr>
<tr>
<td></td>
<td>green</td>
<td>85.6</td>
<td>522</td>
<td>246</td>
<td>454</td>
<td>0.0225</td>
</tr>
<tr>
<td>140</td>
<td>6</td>
<td>5.6</td>
<td>1321</td>
<td>726</td>
<td>1350</td>
<td>0.0147</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>11.9</td>
<td>987</td>
<td>465</td>
<td>825</td>
<td>0.0268</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>17.9</td>
<td>618</td>
<td>262</td>
<td>450</td>
<td>0.0257</td>
</tr>
<tr>
<td></td>
<td>green</td>
<td>81.4</td>
<td>418</td>
<td>225</td>
<td>356</td>
<td>0.0231</td>
</tr>
<tr>
<td>160</td>
<td>6</td>
<td>6.0</td>
<td>1177</td>
<td>746</td>
<td>1190</td>
<td>0.0134</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>11.5</td>
<td>932</td>
<td>402</td>
<td>749</td>
<td>0.0227</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>18.3</td>
<td>552</td>
<td>236</td>
<td>360</td>
<td>0.0261</td>
</tr>
<tr>
<td></td>
<td>green</td>
<td>81.9</td>
<td>350</td>
<td>162</td>
<td>263</td>
<td>0.0229</td>
</tr>
</tbody>
</table>
TABLE 5. VARIATION OF TENSION PROPERTIES PERPENDICULAR TO
THE GRAIN OF SIX LOGS OF AMERICAN BEECH.
(MEANS OF VALUES FOR ALL TESTS.)

<table>
<thead>
<tr>
<th>Log no.</th>
<th>Mean specific gravity*</th>
<th>Maximum stress (lb. per sq. in.)</th>
<th>Proportional limit stress (lb. per sq. in.)</th>
<th>Modulus of elasticity (100 lb. per sq. in.)</th>
<th>Maximum strain (in. per in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.70</td>
<td>949</td>
<td>522</td>
<td>880</td>
<td>0.0203</td>
</tr>
<tr>
<td>2</td>
<td>0.73</td>
<td>957</td>
<td>507</td>
<td>911</td>
<td>0.0206</td>
</tr>
<tr>
<td>3</td>
<td>0.73</td>
<td>923</td>
<td>523</td>
<td>950</td>
<td>0.0171</td>
</tr>
<tr>
<td>4</td>
<td>0.73</td>
<td>1017</td>
<td>527</td>
<td>917</td>
<td>0.0225</td>
</tr>
<tr>
<td>5</td>
<td>0.72</td>
<td>930</td>
<td>513</td>
<td>898</td>
<td>0.0197</td>
</tr>
<tr>
<td>6</td>
<td>0.71</td>
<td>899</td>
<td>531</td>
<td>915</td>
<td>0.0174</td>
</tr>
</tbody>
</table>

* Specific gravity based on oven-dry weight and volume.
Figure 3. Effect of temperature on mechanical properties of beech in tension perpendicular to the grain. A.B.C. Mathematically fitted curves at nominal moisture contents of test. D. Freehand curve at nominal moisture contents of test.
Figure 4. Effect of moisture content on mechanical properties of beech in tension perpendicular to the grain. Freehand curves at actual moisture contents. (Values taken from fitted curves in Figure 3.)
## TENSION TESTING

### TABLE 6. REGRESSION EQUATIONS FOR THE INFLUENCE OF TEMPERATURE AT VARIOUS MOISTURE CONTENTS ON THE TENSILE PROPERTIES OF AMERICAN BEECH PERPENDICULAR TO THE GRAIN IN THE TEMPERATURE RANGE OF 80 TO 160°F.

<table>
<thead>
<tr>
<th>Property</th>
<th>Moisture content (per cent)</th>
<th>Regression equation of property on temperature</th>
<th>Significance of temperature effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at maximum load</td>
<td>6</td>
<td>$y = 1888.20 - 4.225x$</td>
<td>L*</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>$y = 1622.28 - 4.460x$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>$y = 1494.48 - 6.101x$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>green</td>
<td>$y = 1215.45 - 5.564x$</td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>6</td>
<td>$y = 3210.64 - 20.290x + 0.0485x^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>$y = 2659.02 - 21.002x + 0.0567x^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>$y = 2263.15 - 19.657x + 0.0485x^2$</td>
<td><em>L</em> Q*</td>
</tr>
<tr>
<td></td>
<td>green</td>
<td>$y = 1881.74 - 16.950x + 0.0428x^2$</td>
<td></td>
</tr>
<tr>
<td>Proportional limit stress</td>
<td>6</td>
<td>$y = 1949.97 - 14.002x + 0.0398x^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>$y = 1394.76 - 10.082x + 0.0243x^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>$y = 1215.70 - 9.802x + 0.0225x^2$</td>
<td><em>L</em> Q*</td>
</tr>
<tr>
<td></td>
<td>green</td>
<td>$y = 783.04 - 5.820x + 0.0122x^2$</td>
<td></td>
</tr>
</tbody>
</table>

L = Linear component  
Q = Quadratic component  
* = Significant at the 1 per cent level  
x = Temperature (°F.)  
y = Computed property value in lb. per sq. in. for stress at maximum load and proportional limit stress, and 100 lb. per sq. in. for modulus of elasticity.

content upon the strength and elastic properties for the temperatures of 80, 100, 120, 140, and 160°F. The latter curves were obtained by drawing freehand lines through the strength values obtained from the fitted curves in Figures 3A, B, and C, plotted against actual moisture content at test. These curves were extrapolated to the strength in the green condition.

Figure 3D shows the effect of temperature on strain at failure for the nominal moisture contents of 6, 12, and 18 per cent, and for the green condition. The relationship is represented by freehand curves.

The mean specific gravity of the material tested was 0.72.

### DISCUSSION OF RESULTS

Maximum stress in tension showed a highly significant\(^8\) linear trend with

\(^8\)The term “highly significant” denotes a difference or trend which is statistically significant at the 1 per cent level. The term “significant” applies at the 5 per cent level.


<table>
<thead>
<tr>
<th>Source of data</th>
<th>Species</th>
<th>Maximum stress</th>
<th>Modulus of elasticity</th>
<th>Proportional limit stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present work</td>
<td>American beech</td>
<td>0.71</td>
<td>0.84*</td>
<td>0.72*</td>
</tr>
<tr>
<td>Reference (13)</td>
<td>American beech</td>
<td>0.56*</td>
<td>0.66*</td>
<td>0.62*</td>
</tr>
<tr>
<td></td>
<td>European oak</td>
<td>0.57</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Myrtle beech</td>
<td>0.73 +</td>
<td>0.99 +</td>
<td>0.65 +*</td>
</tr>
<tr>
<td></td>
<td>Alpine ash</td>
<td>0.63 +</td>
<td>0.95 +</td>
<td>0.58 +</td>
</tr>
<tr>
<td></td>
<td>Mountain ash</td>
<td>0.59 +</td>
<td>0.59 +</td>
<td>0.55 +*</td>
</tr>
</tbody>
</table>

* Non linear components included  
+ Approximate values
TENSION TESTING

temperature for all moisture contents, the strength decreasing with increasing temperature. This is in contrast to a sigmoid relationship found in earlier tests on this species. The present results conform with the trend found by Kollmann for unseasoned oak, and by Barnard-Brown and Kingston for three Australian species.

A highly significant difference of temperature effect on maximum stress with moisture content was found. The temperature coefficient was greatest at 18 per cent moisture content (see Table 6 and Figure 3A).

Table 7 shows a comparison of the limited data available on the effect of temperature upon maximum tensile stress perpendicular to the grain. It can be seen that there is a considerable variation in temperature effect between species. A greater strength decrease with temperature than has been published previously was found for beech in this experiment.

Up to 18 per cent moisture content, the effect of moisture content on maximum tensile stress showed a highly significant linear relationship (see Figure 4A). The moisture content effect increased with increasing temperature. The curve for each temperature group was extrapolated to the green strength at that temperature.

It should be noted that the moisture content-maximum stress in tension relationship departs from the usual exponential law generally assumed to hold for wood properties at room temperature (36). In this connection, Sulzberger (30) found that the crushing strength parallel to the grain also departed from the exponential law, and that the actual relationship depended upon the temperature of test.

It is interesting to note that both the 12 per cent moisture content and green specimens tested at room temperature in this investigation, when corrected for specific gravity, showed higher values than those given by the ASTM method of testing (20) for which comparable data are available. A closer approach to the true tensile strength by use of the test specimen employed in this study is therefore obtained, probably as a result of reduced stress concentrations in the specimen.

The effect of temperature upon modulus of elasticity showed highly significant linear and quadratic components (see Table 6 and Figure 3B), although the quadratic component was very small in comparison with the linear component. This trend differs from the sigmoid relationship between modulus of elasticity and temperature previously published for this species.

• Direct proportionality between specific gravity and tensile strength was assumed, in the absence of data on the precise relationship between these two properties.
and tends to be more similar to the linear relation found from limited tests in the green condition for three Australian species. It can be seen from Table 7 that the percentage reduction with temperature in modulus of elasticity of unseasoned beech is considerably greater than values previously published. The linear temperature coefficients for the 6, 12, and 18 per cent moisture content series were significantly greater than the linear temperature coefficient for the green series.

In the moisture content range of 6 to 18 per cent, modulus of elasticity showed a highly significant linear and quadratic decrease with increasing moisture content. The relationship was extrapolated to green values as shown in Figure 4B. The decrease in modulus of elasticity with increasing moisture content appears independent of the temperature within the temperature range tested.

Reduction of fiber stress at proportional limit with increasing temperature is largely accounted for by a linear component, but, as in the case of modulus of elasticity, a relatively small quadratic component was highly significant. Again, the linear temperature coefficients for the 6, 12, and 18 per cent moisture content series were not significantly different, and were greater than the temperature coefficient for the green material (see Figure 3C).

Within the moisture content range of 6 to 18 per cent, the reduction of fiber stress at proportional limit with increasing moisture content is accounted for by highly significant linear and quadratic components. The effect of moisture content upon the fiber stress at proportional limit was not markedly influenced by the temperature of test (see Figure 4C).

The extrapolation of the curves for maximum stress, modulus of elasticity, and fiber stress at proportional limit, plotted against moisture content, shows that fiber saturation point (or intersection point) decreases with increasing temperature of test. This behavior is in conformity with other observations (37) and justifies the extrapolation.

Considering strain relationships, the strain at proportional limit showed large variations between logs, and revealed no trend with temperature or moisture content of test. The mean strain at proportional limit was 0.00579 in. per in., and varied from 0.00357 to 0.00840 in. per in., depending on the material.

Maximum tensile strain for the test material is shown in Figure 3D. No attempt was made to fit regression curves, as many interactions were highly significant. Specimens at all moisture contents showed a highly sig-
significant linear increase in maximum strain with increasing temperature of
test, but significant curvilinear effects were also present. There was no trend
to indicate a maximum in deformation at failure in the vicinity of 124°F.,
as found by Greenhill, although some moisture content groups showed a
slight decrease in strain at 160°F.

Maximum strain at 6 per cent moisture content was considerably less than
that at all other moisture contents at all temperatures. At 80°F., the 6, 12,
and 18 per cent, and green moisture content results fell into a series of
successively higher maximum strain values. At higher temperatures, the
difference in maximum strain between the 12 and 18 per cent moisture con­
tent and green groups was not large, indicating a very similar maximum
strain at these moisture contents between 100 and 160°F.

With respect to the effect of the material on strength and elastic behavior
in tension perpendicular to the grain, material from logs 4 and 6 showed
highly significant differences from the remainder of the material in their be­
havior in maximum stress. Logs 3, 4, and 6 were significantly different from
the others in their maximum strain behavior. Material from log 4 showed
the highest maximum stress in the series and also the greatest strain at
failure, while material from log 6 showed the lowest maximum stress of
the series, and was equal lowest with log 3 in maximum strain. Considera­
tion of Table 5 shows a general trend toward increased maximum strain
with increased maximum stress within the range of material used. This in­
dicates that maximum extensibility increases with the strength, at least
within the range of material tested. The variation between the different
logs cannot be explained completely in terms of specific gravity.

With respect to interactions not previously considered, maximum stress
proved less sensitive than the other three tensile properties. The interaction
of source of material by moisture content was highly significant in all of the
four properties concerned, indicating that decrease in value of the property
with increasing moisture content varied considerably with each log. The
interaction, log by temperature, was highly significant in the cases of
modulus of elasticity and maximum strain, indicating a variation of the
temperature effect with the logs used.

In general, considerable differences are apparent between earlier work and
the present investigation in the effects of temperature and moisture content
on the tensile strength and elastic properties of beech. It is considered that
these discrepancies are due largely to insufficient moisture content control
of the specimen in the earlier investigation, as the facilities available for such
control have since been much improved. Considerable judgment was therefore apparently exercised in locating curves in the earlier work, with the result that some trends were shown which are now known to be untenable, for example, the absence of a temperature effect on the strength of oven-dry wood.

It is not yet possible to state whether other species of wood react similarly to beech with respect to the effect of temperature and moisture content, but some differences are apparent in the very limited data available.
COMPRESSION TESTING

PREPARATION OF SAMPLE MATERIAL

For compression testing, essentially the same procedure was adopted as was described under the preparation of material for tension testing. One flat-sawn heartwood board, free of defect, and with minimum curvature of the growth rings, was selected from each of the six logs. The compression material was therefore side-matched with that used for the tension tests. Each board was marked into four sections, each section being allocated for testing at one of the four moisture contents of the testing series. The green sections were stored under damp sawdust, and the remainder of the material was kiln dried under the mild conditions given in Table 1. Sections from each board were taken at random when the material reached the appropriate moisture content, and stored in sealed plastic bags until machined to final dimensions.

After the various sections had been conditioned to their approximate moisture contents of test, they were planed to 1/2-in. thickness, and a 2-in. wide strip with the least possible curvature of the growth rings was cut along the grain. The cuts were made on a smooth-cutting carbide-tipped saw to produce truly squared sides. Specimens 1/2-in. along the grain were then cut from each section and allocated by random procedure for testing at each of the five temperatures of test. The specimens were then kept for several weeks at room temperature in sealed jars over saturated salt solutions which provided the appropriate equilibrium moisture content conditions. The green specimens were stored under damp sawdust treated with sodium pentachlorophenate until required for test.

PREPARATION AND FORM OF TEST SPECIMENS

The compression test specimen consisted of a short column 2 in. long in the tangential plane of the growth rings, and with a 1/2-in. square bearing area. The form and dimensions of the specimen are shown in Figure 2.

In actual test, the specimen was loaded over the entire face of the 1/2-in. square ends so that compression was applied perpendicular to the grain in the tangential plane of growth. This form of specimen was adopted in preference to the standard ASTM specimen because the standard test does not give true values for compression properties owing to the fact that the load is applied through a metal bearing plate which, in effect, is driven
PROPERTIES OF AMERICAN BEECH

into the specimen. It has been stated that, as a result of the edge effects of the bearing plate, the recorded modulus of elasticity is higher than when the specimen is loaded over an entire face (17). It is also to be expected that localized crushing would occur in the vicinity of the bearing plate. Several trials were therefore carried out on matched material with different types of loading, strain measurement, and size of specimen. The results of these tests, based on two specimens for each type of test, are listed in Table 8.

It is seen that loading the specimen over the entire face resulted in a considerable decrease in strain at proportional limit, while fiber stress at proportional limit also decreased markedly. Elimination of end effects by restricting the strain measurement to the central portion of the depth of the specimen resulted in a further apparent decrease in the strain at proportional limit with a corresponding increase in stiffness, while the fiber stress at proportional limit remained relatively constant.

Reduction of specimen dimensions from $2 \times 2 \times 2$ in. to $1/2 \times 1/2 \times 2$ in. did not significantly influence the derived properties.

The specimen of dimensions $1/2 \times 1/2 \times 2$ in. was adopted, as the use of a comparatively small size of specimen afforded considerable advantage in facilitating the attainment of the required specimen moisture content and temperature. It was also considered that, by taking strain measurements in the central portion of the test specimen, strength values more closely representative of the true values would be obtained, as end effects are eliminated.

Table 8 shows, incidentally, the arbitrary nature of the standard testing procedures.

TEST CONDITIONS

The experiment was set up in the same way as that for tension testing, with five levels of temperature and four levels of moisture content, as shown in Table 2. As in the case of the tension testing, compression testing was carried out in duplicate. Thus, 12 specimens were tested at each of the 20 combinations of temperature and moisture content.

EXPERIMENTAL EQUIPMENT

To accommodate the compression specimens, the testing chamber used for tension testing was set on the platen of a Baldwin-Southwark testing machine, with the test compartment aligned under the crosshead of the machine. A heavy metal platform was placed under the test compartment, and a block
<table>
<thead>
<tr>
<th>Load application</th>
<th>Specimen size</th>
<th>Strain measurement</th>
<th>Modulus of elasticity (lb. per sq. in.)</th>
<th>Proportional limit stress (lb. per sq. in.)</th>
<th>Unit strain at proportional limit (in. per in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard ASTM</td>
<td>Standard ASTM 2 x 2 x 6 in.</td>
<td>Standard ASTM</td>
<td>--</td>
<td>520</td>
<td>0.0203</td>
</tr>
<tr>
<td>Over entire face of specimen</td>
<td>2 x 2 x 2 in.</td>
<td>Standard ASTM</td>
<td>45,850</td>
<td>335</td>
<td>0.0073</td>
</tr>
<tr>
<td>Over entire face of specimen</td>
<td>1 x 1 x 2 in.</td>
<td>Standard ASTM</td>
<td>47,200</td>
<td>349</td>
<td>0.0073</td>
</tr>
<tr>
<td>Over entire face of specimen</td>
<td>3/4 x 3/4 x 2 in.</td>
<td>Standard ASTM</td>
<td>46,900</td>
<td>333</td>
<td>0.0071</td>
</tr>
<tr>
<td>Over entire face of specimen</td>
<td>1/2 x 1/2 x 2 in.</td>
<td>Standard ASTM</td>
<td>43,500</td>
<td>326</td>
<td>0.0078</td>
</tr>
<tr>
<td>Over entire face of specimen</td>
<td>1/2 x 1/2 x 2 in.</td>
<td>Strain measured only in center inch of specimen</td>
<td>54,500</td>
<td>324</td>
<td>0.00595</td>
</tr>
</tbody>
</table>

Table 8. Influence of test method on strength values in compression perpendicular to the grain.
of lignum vitae, 1 in. square and 1 1/2 in. long, was placed on the platform and fitted into the test compartment. The block of lignum vitae provided the base on which the specimen was supported. The flexible top of the test compartment was modified to suspend another block of lignum vitae through which the load was applied to the specimen by means of a suspended self-aligning spherical bearing block. In this manner, the compression specimens were completely enclosed in the test compartment of the testing chamber and did not contact any metal bearing blocks through which substantial heat losses might occur. This is shown in Plate IV. As a further precaution against heat losses from the compression specimens during test, the lignum vitae bearing blocks were brought to test temperature prior to testing. During the test, the lignum vitae blocks remained close to test temperature by virtue of the fact that the greater portion of their bulk was exposed to the test conditions within the test compartment.

The extensometer (now a compressometer) and clip gauge arrangement used in the tension testing were applied to obtain strain readings in compression. The compressometer was modified so that the gauge points could be fitted on the central vertical axis of the specimen. The leads from the clip gauge to the strain gauge indicator were also reversed. By attaching the leads from the gauge on the convex face to the active gauge terminal, and the leads of the gauge on the concave face to the compensating gauge terminals of the strain indicator, forward readings of strain on the indicator dial were maintained.

TESTING PROCEDURE

As was the case with tension testing, only a small number of samples could be tested at a time because of the comparatively long time required to test each specimen, and the time needed for conditioning to test requirements. Consequently, the experiment was set up to test one replicate at a time of each of the 20 test conditions. This procedure required that the apparatus be set up 40 times, and the order of testing conditions was randomized.

Samples were first placed in a conditioning chamber which had previously been brought to the temperature and relative humidity required for the test, and left there for approximately 3 hours until they had reached test conditions. A close check on the moisture content of the specimens was kept by weighing during this period. The samples were then transferred rapidly to the testing chamber, the compressometer fitted, and 5 minutes allowed for stabilization before actual testing. Great care was taken to align the
specimens centrally with respect to the loading blocks, to produce optimum
uniformity of loading.

The testing speed was controlled to 0.0033 in. of strain, per in. of
specimen, per min., and load readings taken to 2.5 per cent of strain.
There is no real maximum stress value in compression perpendicular to
the grain, as continued application of pressure merely results in greater
flattening and distortion of the cells. It was therefore necessary to adopt
some arbitrary measure of strength in compression. In the ASTM test the
specimen is tested to 5 per cent strain. After exploratory tests had been
carried out, it was decided to adopt the stress value at 2.5 per cent strain,
as the value obtained at this point was not less than the maximum stress
in tension under the same conditions, and when greater strains were in­
volved there was some tendency for the specimen to bend.

After test, the cross section of the specimen was measured with a mi­
crometer. Specific gravities were sampled from each group of specimens
tested as a check on agreement of specific gravities with the matched tension
specimens.

Stress-strain curves were plotted for all specimens, and stress at 2.5 per
cent strain, modulus of elasticity, and fiber stress at proportional limit were
computed.

STATISTICAL DESIGN

The statistical design of the compression testing portion of the experi­
ment was essentially the same as that used for the tests, namely, a 2 x 4 x
5 x 6 randomized block factorial.

RESULTS

The sampling of specific gravities of the material tested in compression
showed no significant difference from the specific gravities of the material
tested in tension.

Satisfactory control of moisture content was obtained, although the
deviation from the nominal moisture content was in some cases greater than
that obtained in the tension testing. The mean maximum deviation from
the nominal value did not exceed 0.5 per cent moisture content for any test
condition. Where considerable deviation of moisture content from the
nominal was found, re-tests were carried out.

Great care was necessary to prevent bending of the specimen during
test. The specimens had to be aligned exactly on the lignum vitae bearing
blocks which themselves had previously been centered under the spherically-
seated metal bearing block carried on the crosshead of the testing machine.
The mean values at the various combinations of temperature and moisture content for stress at 2.5 per cent strain, modulus of elasticity, and fiber stress at proportional limit are shown in Table 9. Regression curves relating the compressive strength and elastic properties to temperature at the nominal moisture contents used are shown in Figures 5A, B, and C. Table 10 shows the regression equations for the effect of temperature on compressive properties at the nominal moisture contents of test. Freehand curves relating strength and elastic properties in compression to moisture content at the various temperatures of test are shown in Figures 6A, B, and C. In these curves the values were taken from the fitted regression curves in Figures 5A, B, and C. Table 11 shows the variation of the compressive properties evaluated with the logs used.

DISCUSSION OF RESULTS

The stress at 2.5 per cent strain showed a highly significant linear trend with temperature for all moisture contents (see Figure 5A).

A significant difference of temperature effect with moisture content was found, the temperature coefficient being least for the green material and greatest for the 6 and 12 per cent moisture content material (see Table 10). No data are available for comparison with the results obtained in this experiment.

Analysis of the effect of moisture content on strength up to 18 per cent moisture content showed a highly significant linear relationship. The moisture content effect was not markedly influenced by the temperature of test. Extrapolation of the curves to the green strength value shows that fiber saturation point (or intersection point) decreased with temperature of test (see Figure 6A). The moisture content-compressive strength perpendicular to the grain relationship departs from the usually accepted exponential law generally assumed to hold for wood properties at room temperature.

The effect of temperature upon modulus of elasticity showed a highly significant linear trend (see Figure 5B), although a variation, significant at the 5 per cent level, remained, which could not be accounted for by linear, quadratic, or cubic components. This linear relationship is similar to that previously found for three Australian species. The temperature coefficients for the 6, 12, and 18 per cent moisture content material were significantly greater than that for the green material, although on a percentage basis greatest loss of stiffness with temperature occurred in the green material.
<table>
<thead>
<tr>
<th>Nominal temp. °F.</th>
<th>Nominal moisture content (per cent)</th>
<th>Actual moisture content (per cent)</th>
<th>Stress at 2.5 per cent strain (lb. per sq. in.)</th>
<th>Proportional limit stress (lb. per sq. in.)</th>
<th>Modulus of elasticity (100 lb. per sq. in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>6</td>
<td>6.2</td>
<td>1773</td>
<td>1045</td>
<td>1781</td>
</tr>
<tr>
<td>12</td>
<td>12.2</td>
<td></td>
<td>1402</td>
<td>780</td>
<td>1337</td>
</tr>
<tr>
<td>18</td>
<td>17.9</td>
<td></td>
<td>989</td>
<td>583</td>
<td>1064</td>
</tr>
<tr>
<td>green</td>
<td>87.8</td>
<td></td>
<td>753</td>
<td>444</td>
<td>813</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>6.0</td>
<td>1688</td>
<td>930</td>
<td>1590</td>
</tr>
<tr>
<td>12</td>
<td>12.0</td>
<td></td>
<td>1254</td>
<td>674</td>
<td>1196</td>
</tr>
<tr>
<td>18</td>
<td>18.0</td>
<td></td>
<td>811</td>
<td>483</td>
<td>818</td>
</tr>
<tr>
<td>green</td>
<td>83.2</td>
<td></td>
<td>646</td>
<td>403</td>
<td>734</td>
</tr>
<tr>
<td>120</td>
<td>6</td>
<td>6.0</td>
<td>1545</td>
<td>867</td>
<td>1498</td>
</tr>
<tr>
<td>12</td>
<td>11.5</td>
<td></td>
<td>1099</td>
<td>633</td>
<td>1133</td>
</tr>
<tr>
<td>18</td>
<td>18.0</td>
<td></td>
<td>691</td>
<td>431</td>
<td>760</td>
</tr>
<tr>
<td>green</td>
<td>95.3</td>
<td></td>
<td>561</td>
<td>318</td>
<td>647</td>
</tr>
<tr>
<td>140</td>
<td>6</td>
<td>5.5</td>
<td>1459</td>
<td>802</td>
<td>1442</td>
</tr>
<tr>
<td>12</td>
<td>11.5</td>
<td></td>
<td>997</td>
<td>538</td>
<td>934</td>
</tr>
<tr>
<td>18</td>
<td>18.3</td>
<td></td>
<td>598</td>
<td>351</td>
<td>610</td>
</tr>
<tr>
<td>green</td>
<td>81.5</td>
<td></td>
<td>454</td>
<td>265</td>
<td>472</td>
</tr>
<tr>
<td>160</td>
<td>6</td>
<td>6.0</td>
<td>1249</td>
<td>696</td>
<td>1202</td>
</tr>
<tr>
<td>12</td>
<td>12.1</td>
<td></td>
<td>857</td>
<td>477</td>
<td>883</td>
</tr>
<tr>
<td>18</td>
<td>17.9</td>
<td></td>
<td>518</td>
<td>300</td>
<td>524</td>
</tr>
<tr>
<td>green</td>
<td>82.5</td>
<td></td>
<td>383</td>
<td>211</td>
<td>370</td>
</tr>
</tbody>
</table>
## PROPERTIES OF AMERICAN BEECH

### TABLE 10. REGRESSION EQUATIONS FOR THE INFLUENCE OF TEMPERATURE AT VARIOUS MOISTURE CONTENTS ON THE COMPRESSION PROPERTIES OF AMERICAN BEECH PERPENDICULAR TO THE GRAIN IN THE TEMPERATURE RANGE OF 80 TO 160°F.

<table>
<thead>
<tr>
<th>Property</th>
<th>Moisture content (per cent)</th>
<th>Regression equation of property on temperature</th>
<th>Significance of temperature effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at 2.5% strain</td>
<td>6</td>
<td>( y = 2308.50 - 6.381x )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>( y = 1931.58 - 6.748x )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 (green)</td>
<td>( y = 1418.27 - 5.798x )</td>
<td>( \text{L}^\ast )</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>6</td>
<td>( y = 2285.67 - 6.527x )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 (green)</td>
<td>( y = 1798.36 - 5.846x )</td>
<td>( \text{L}^\ast )</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>( y = 1526.83 - 6.431x )</td>
<td></td>
</tr>
<tr>
<td>Proportional limit stress</td>
<td>6</td>
<td>( y = 1362.32 - 4.125x )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 (green)</td>
<td>( y = 1065.52 - 3.710x )</td>
<td>( \text{L}^\ast )</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>( y = 847.68 - 3.488x )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( y = 690.72 - 3.022x )</td>
<td></td>
</tr>
</tbody>
</table>

\( \text{L} = \) Linear component  
\( \ast = \) Significant at the 1 per cent level  
\( x = \) Temperature (°F)  
\( y = \) Computed property value in lb. per sq. in. for stress at 2.5 per cent strain and proportional limit stress, and 100 lb. per sq. in. for modulus of elasticity.

### TABLE II. VARIATION OF COMPRESSION PROPERTIES PERPENDICULAR TO THE GRAIN OF SIX LOGS OF AMERICAN BEECH. (MEANS OF VALUES FOR ALL TESTS.)

<table>
<thead>
<tr>
<th>Log no.</th>
<th>Mean specific gravity</th>
<th>Stress at 2.5 per cent strain (lb. per sq. in.)</th>
<th>Proportional limit stress (lb. per sq. in.)</th>
<th>Modulus of elasticity (100 lb. per sq. in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.70</td>
<td>977</td>
<td>547</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>0.73</td>
<td>903</td>
<td>524</td>
<td>978</td>
</tr>
<tr>
<td>3</td>
<td>0.73</td>
<td>963</td>
<td>549</td>
<td>998</td>
</tr>
<tr>
<td>4</td>
<td>0.73</td>
<td>1060</td>
<td>604</td>
<td>1018</td>
</tr>
<tr>
<td>5</td>
<td>0.72</td>
<td>1010</td>
<td>573</td>
<td>975</td>
</tr>
<tr>
<td>6</td>
<td>0.71</td>
<td>1005</td>
<td>567</td>
<td>1010</td>
</tr>
</tbody>
</table>

44
FIGURE 5. Effect of temperature on mechanical properties of beech in compression perpendicular to the grain. Mathematically fitted curves at nominal moisture contents of test.
FIGURE 6. Effect of moisture content on mechanical properties of beech in compression perpendicular to the grain.
Freehand curves at actual moisture contents.
(Values taken from fitted curves in Figure 5.)
In the moisture content range of 6 to 15 per cent, the modulus of elasticity showed significant linear and quadratic relationships with moisture content at all temperatures of test (see Figure 6B). The curves were extrapolated to the green values of the material, and a decreasing fiber saturation point with temperature was obtained. The relationship of moisture content to modulus of elasticity was not particularly affected by temperature of test.

The effect of temperature on fiber stress at proportional limit showed a highly significant linear relationship for all moisture contents, but a quadratic component was significant only at the 5 per cent level. Rectilinear curves were fitted to the data, as shown in Figure 5C. The temperature coefficients decreased significantly with increasing moisture content, as shown in Table 10.

Fiber stress at proportional limit showed a highly significant linear and quadratic relationship with moisture content, as shown in Figure 6C. This relationship was not affected by the temperature of test.

With respect to the effect of the source of the material on compressive properties, it was found that material from logs 2 and 4 differed significantly from the remainder in their stress at 2.5 per cent strain and fiber stress at proportional limit. No significant difference between logs was found in modulus of elasticity. Table 11 shows the means of the compressive properties for all tests for material from each log, together with their respective specific gravities. The material from log 4 showed the highest stress at 2.5 per cent strain, and also the highest fiber stress at proportional limit of the series. Material from log 2, on the other hand, showed the lowest load at 2.5 per cent strain, and the lowest fiber stress at proportional limit of the series. Although differences between logs other than numbers 4 and 6 are not statistically significant, it is very evident that high loads at 2.5 per cent strain are associated with high fiber stress at proportional limit. The relationship of load at 2.5 per cent strain to modulus of elasticity is not so clear.

Considering interactions not previously discussed, the interaction of log by moisture content was highly significant for all compressive properties, which indicates a variable effect of moisture content on the properties according to the source of the material. Also, the interaction of log by temperature was highly significant in the case of modulus of elasticity, which indicates an influence due to the log on the effect of temperature on modulus of elasticity.
COMPARISON OF RESULTS OF TENSION AND COMPRESSION TESTS
MAXIMUM STRESS IN TENSION VERSUS STRESS AT 2.5 PER CENT STRAIN IN COMPRESSION

STRICTLY speaking, these two properties cannot be directly compared, as they represent two unlike quantities. In the case of maximum stress in tension, the value represents a marked discontinuity in the stress-strain relationship where the cohesion of the wood substance is overcome and failure occurs. In the case of load at 2.5 per cent strain, no actual failure occurs; the value representing a stress at an arbitrarily chosen strain. Further increase of the load would not produce actual failure, but rather a consolidation of the wood.

However, in so far as it was considered necessary to set up a criterion of the strength of wood in compression perpendicular to the grain which was considerably above the proportional limit, it was believed that this method would be satisfactory. For the purposes of this bulletin, the load at 2.5 per cent strain in compression should be regarded as a resistance obtained under static loading conditions at an arbitrarily selected strain.

With respect to tension, it was observed that the strain at failure increased with increasing moisture content, at least at room temperature, and the 6 per cent moisture content material showed consistently lower maximum strain values than the remainder of the material for all temperatures. The green material showed a lower maximum strain than the 12 and 18 per cent moisture content material at the higher test temperatures. Material at all moisture contents showed an increase in maximum strain with temperature. The mean maximum strains at failure for the 6, 12, and 18 per cent moisture content, and green material were 0.0124, 0.0216, 0.0226, and 0.0216 in. per in. respectively.

Consideration of the compression data shows that the stress values for the 6 per cent material were greater than those for the maximum stress in tension at the same moisture content, and tended to converge towards the maximum tension stress values with increase in temperature. For the 12 per cent moisture content material, the compressive stresses were also considerably greater than the maximum stresses in tension at the lower temperatures, but approximated the tensile strength at the higher temperatures. Loads in compression for the 18 per cent moisture content and green material showed an approximate correspondence with the tensile strengths at all temperatures.
The above relationship between tensile and compressive strengths may be explained on the basis of an approximate equivalence of maximum stress in tension and stress in compression at the same strain at which failure occurred in tension. This would explain the greater overall slope of the compressive strength-temperature curves when compared with the tensile strength-temperature curves. It would also explain the tendency for the two sets of curves to converge at the higher temperatures as a result of the maximum strain in tension increasing to a value approaching 0.025 in. per in., which is 2.5 per cent strain in compression. Also, it would be expected that the curves for tensile strength and compressive strength, plotted against temperature and moisture content, would be more nearly similar with increasing moisture content because of increasing maximum tensile strain, and, in fact, this is so.

To determine whether there was equivalence of maximum stress in tension and stress in compression at the same strain at which failure occurred in tension, stresses in compression were computed from the stress-strain curves of compression at the mean maximum strain value obtained in the tension tests under the same conditions of test. The compression stresses so obtained are shown in Table 12, and the results are shown graphically in Figures 7A and B.

It is seen from Tables 9 and 12 that very good agreement exists between maximum stress in tension and stress at the same maximum strain in compression for the 12 and 18 per cent moisture content and green material. The compressive stresses for the 6 per cent material are approximately 9 to 11.5 per cent below the corresponding stress in tension, but the effect of temperature on the properties at this moisture content is similar.

It is therefore concluded that, under static loading conditions, both moisture content (12 per cent and above) and temperature affect similarly strength in tension and strength in compression at maximum tensile strain. At 6 per cent moisture content, compressive strength appears to be less than maximum stress in tension for an equivalent strain, although the temperature effect on the strength in compression and tension is very similar. Compressive strength at strain values greater than that of the maximum tensile strain is considerably greater than maximum tensile stress in the case of the two lower moisture contents, and shows a greater decrease in strength with temperature.

Complete equivalence of compression and tension in the range of stress-strain relationships up to a strain equivalent to maximum tensile strain de-
## PROPERTIES OF AMERICAN BEECH

### TABLE 12. EFFECT OF TEMPERATURE AND MOISTURE CONTENT ON COMPRESSIVE STRESS PERPENDICULAR TO THE GRAIN OF AMERICAN BEECH AT A STRAIN EQUIVALENT TO MAXIMUM UNIT STRAIN IN TENSION UNDER THE SAME TESTING ENVIRONMENT

<table>
<thead>
<tr>
<th>Temperature (°F.)</th>
<th>Nominal moisture content (per cent)</th>
<th>Actual moisture content (per cent)</th>
<th>Unit strain at which compressive stress was computed (in. per in.)</th>
<th>Compressive stress at maximum strain in tension (lb. per sq. in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>6.2</td>
<td>0.0100</td>
<td>1380</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td><strong>12</strong> 18 green</td>
<td>12.2 17.9</td>
<td>0.0155 936</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td><strong>12</strong> 18 green</td>
<td>12.0 18.0</td>
<td>0.0214 1168</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td><strong>12</strong> 18 green</td>
<td>11.5 18.0</td>
<td>0.0220 1100</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td><strong>12</strong> 18 green</td>
<td>11.5 18.3</td>
<td>0.0268 997</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td><strong>12</strong> 18 green</td>
<td>12.1 17.9</td>
<td>0.0227 870</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>green</strong></td>
<td>82.5 87.8</td>
<td>0.0231 518</td>
<td></td>
</tr>
</tbody>
</table>

Depends upon agreement of modulus of elasticity and fiber stress at proportional limit. This will be discussed in the following sections.

### MODULUS OF ELASTICITY

From the behavior of wood in tension and compression parallel to the grain (3), it may be expected that the modulus of elasticity in tension and compression perpendicular to the grain would be the same for closely matched specimens under the same conditions of test. It is apparent that Hearmon, in a treatise on elasticity in wood and plywood (I4), considers that the elasticity perpendicular to the grain is a constant and should not vary whether tested in tension or compression. However, prior to the present
**Figure 7.** Effect of temperature and moisture content on compressive stress at a strain equal to that of maximum tensile strain under the same test environment.
PROPERTIES OF AMERICAN BEECH

TABLE 13. COMPARISON OF TEMPERATURE EFFECTS AT VARIOUS MOISTURE CONTENTS ON MODULUS OF ELASTICITY OF AMERICAN BEECH IN TENSION AND COMPRESSION PERPENDICULAR TO THE GRAIN IN THE TANGENTIAL DIRECTION WITHIN THE TEMPERATURE RANGE FROM 80 TO 160°F.

<table>
<thead>
<tr>
<th>Moisture content (per cent)</th>
<th>Average decrease of modulus of elasticity per degree F. rise in temperature, expressed as a percentage of its value at 80°F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tension perpendicular to grain</td>
</tr>
<tr>
<td>6</td>
<td>0.45</td>
</tr>
<tr>
<td>12</td>
<td>0.56</td>
</tr>
<tr>
<td>18</td>
<td>0.81</td>
</tr>
<tr>
<td>green</td>
<td>0.82</td>
</tr>
</tbody>
</table>

work, no published data are known to the author which establish experimentally a relationship between modulus of elasticity in tension and compression perpendicular to the grain. Comparison of the modulus of elasticity values obtained for tension and compression in this experiment shows that, in the case of tension, a curvilinear relationship was obtained with temperature, whereas for compression a rectilinear relationship was found. It should be pointed out, however, that the non-linear component in the tension relationship was relatively small, and the error involved by assuming a rectilinear relationship would therefore also be relatively small.

Reasonably good agreement was obtained in modulus of elasticity for compression and tension at the lower temperatures and for all moisture contents. Best agreement between tensile and compressive moduli of elasticity was obtained at 6 per cent moisture content. At all other moisture contents the effect of temperature was less in the case of the compressive values. Table 13 shows a comparison of the decrease in modulus of elasticity at the various moisture contents of test. In terms of actual values, the difference is not great, being only approximately 14,000 lb. per sq. in. at the higher temperatures and moisture contents, but when expressed as a percentage of the total value the difference is considerable (30 per cent) at the highest temperature and moisture content. The reason for the divergence of the results at the higher moisture contents and temperatures of test is not clear. However, it is noted that preliminary results of the United States Forest Products Laboratory (private correspondence) show a similar higher modulus of elasticity in compression than in tension perpendicular to the grain at 110°F. in unseasoned oak.
COMPARISON OF RESULTS

A possible explanation of the difference is in terms of experimental error. The most likely sources of experimental error are the effects of the type and dimensions of the specimens used, shear during test, a change in the nature of the material during test (strain hardening), the presence of temperature gradients as a result of heat diffusion through the lignum vitae bearing blocks, or unknown errors in the instrumentation of strain measurement.

With regard to the influence on the results of the type and dimensions of the specimens used, the considerable influence of specimen form on the values obtained was previously discussed in the sections describing the test specimens used for the present investigation. Considering all the variables involved, it is unlikely that the values obtained in this investigation are absolutely true values, but it is thought that they are a close approximation to the true values. The selection of the types of specimens to be used and the method of test for tension and compression testing, although aided by previous experience and limited trial tests, were to a large degree arbitrary in nature. It therefore may be expected that an apparent difference in modulus of elasticity would occur between the two types of test, which can be attributed to specimen size and form and method of test. Unfortunately, it is conjecture whether this explanation can adequately account for the differences obtained in tension and compression, as too little information is available on methods of measuring true values for the types of test described. Shear effects would not be expected to be the cause of the difference below proportional limit. The effect of change in nature of the material during test on the derived properties is difficult to evaluate, as little is known of this in wood. Although it is noted that the major differences between results occur under conditions of temperature and moisture content which may be more favorable to internal readjustment of the wood, this effect could hardly account for the differences observed below the proportional limit.

To determine temperature gradients in the specimen during test, fine wire thermocouples were inserted in the central portion and also near the ends of a compression specimen. The specimen was placed in the test chamber between the lignum vitae bearing blocks. Temperature readings were taken over the time required to test a specimen at 160°F. in the green state, that is, approximately 15 minutes. The specimen was given similar treatment to actual test specimens prior to reading. It was found that, after stable conditions had been reached, a temperature gradient of 40°F. existed between the ends and the central portion of the specimen in the middle of its cross section. The time required for stabilization was 5 minutes, which was the actual time allowed before testing commenced. The temperature gradient found
under the test conditions of 160°F. with green material would be the greatest for any of the test conditions. Temperature gradients would also be at a maximum in the central core of the specimen, as the outer layers were in direct contact with the heating medium. Considering that strength and elasticity measurements were made only over the central inch of length of the specimen, the effect of temperature gradient could not account for the difference in the results between compression and tension. On the other hand, the presence of a slight temperature gradient has the beneficial effect of tending to prevent end crushing of the specimen.

There exists, of course, the possibility that the differences observed are real, and that modulus of elasticity in compression is affected to a lesser degree by temperature at the higher temperatures and moisture contents than is the case with modulus of elasticity in tension.

The effect of moisture content on modulus of elasticity does not appear to differ markedly between tension and compression.

FIBER STRESS AT PROPORTIONAL LIMIT

As has been described previously, the relationship between fiber stress at proportional limit and temperature was curvilinear at all moisture contents for tension and rectilinear for compression. Again, the non-linear component included in the tension proportional limit-temperature relationship was comparatively small, and the resulting deviation from a linear relationship would therefore be small.

Comparison of fiber stress at proportional limit in tension and compression shows reasonable agreement in results for the 6 per cent moisture content material at all temperatures. At all other moisture contents of test, the fiber stress at proportional limit in compression is approximately 50 lb. per sq. in. greater than that in tension. Table 14 shows a comparison of the temperature effect at various moisture contents on fiber stress at proportional limit in tension and compression. It is seen that the temperature effect shows good agreement for the 6 per cent moisture content and green material. This indicates that the fiber stresses at proportional limit in tension and compression show substantial agreement with regard to behavior with temperature, but that the proportional limit is somewhat greater in compression than in tension for at least the 12 and 18 per cent moisture content and green material. The decrease in fiber stress at proportional limit with increasing moisture content is slightly greater in tension than in compression.
COMPARISON OF RESULTS

Table 14. Comparison of temperature effects at various moisture contents on fiber stress at proportional limit of American beech in tension and compression perpendicular to the grain in the tangential direction within the temperature range from 80 to 160°F.

<table>
<thead>
<tr>
<th>Moisture content (per cent)</th>
<th>Average decrease of proportional limit stress per degree F. rise in temperature, expressed as a percentage of its value at 80°F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tension perpendicular to grain</td>
</tr>
<tr>
<td>6</td>
<td>0.41</td>
</tr>
<tr>
<td>12</td>
<td>0.57</td>
</tr>
<tr>
<td>18</td>
<td>0.75</td>
</tr>
<tr>
<td>green</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Strain at Proportional Limit

The mean strain at proportional limit in tension was 0.00579 in. per in., with a range of 0.00357 to 0.00840 in. per in.

The mean strain at proportional limit in compression was 0.00593 in. per in., with a range of 0.00336 to 0.00895 in. per in.

The comparatively small difference in proportional limit strain between tension and compression, although statistically significant, can be neglected in a consideration of stress-strain development in a drying board, as it constitutes only a relatively small proportion of the total strains developed. For the practical comparison of the stress-strain curves in tension and compression, this relatively small difference can be neglected.
GENERAL CONCLUSIONS ON RELATION BETWEEN TENSILE AND COMPRESSIVE STRENGTH AND ELASTIC PROPERTIES

STRENGTH and elastic properties were determined on matched material in tension and compression perpendicular to the grain in the tangential direction over a range of temperatures and moisture contents at time of test.

The specific gravities of both sets of specimens were not significantly different, so that variables introduced by specific gravity can be neglected.

It was found that strength and elasticity in both compression and tension decreased with increase of temperature and with increase of moisture content to fiber saturation point. The comparison of the effect of temperature and moisture content on tensile strength and compressive strength depends upon the criterion adopted for compressive strength, as no true ultimate strength exists as it does in the case of tension perpendicular to the grain. If the compressive stress at the constant strain of 2.5 per cent is adopted as the criterion, then compressive strength shows a greater decrease with temperature at the lower moisture contents than does tensile strength. The effect of temperature on 18 per cent moisture content and green material appears similar in compression and tension. The effect of moisture content on strength in compression is greater than that in tension.

However, maximum strain in tension varied from 1.0 to 2.75 per cent strain, according to the conditions of test. If the criterion of compressive strength is taken at a strain equivalent to the maximum strain in tension, the effect of temperature on compressive strength is very similar to its effect on tensile strength. Increase in moisture content results in similar strength decreases in tension and compression (measured at maximum tensile strain) at 12 per cent moisture content and above, but at 6 per cent moisture content compressive strength reduction with an increase in moisture content is less than that in tension.

The effect of temperature was similar on modulus of elasticity in both tension and compression at the lowest moisture content of test, but, with increasing moisture content, modulus of elasticity in compression showed a smaller decrease with temperature than did the modulus of elasticity obtained in tension. The effect of moisture content on modulus of elasticity in tension and compression was similar for all temperatures. The differences in compressive and tensile modulus of elasticity may be explained in terms of the types of specimens used.
GENERAL CONCLUSIONS

The effect of temperature on compressive fiber stress at proportional limit was more nearly similar to that in tension at the lowest moisture content of test. With increasing moisture content, the compressive fiber stress at proportional limit decreased less with temperature than did tensile proportional limit. The effect of moisture content upon fiber stress at proportional limit was slightly less in compression than in tension.

Above the proportional limit, the stress required to produce a certain strain in tension was greater than that required to produce the same strain in compression. Thus, a more plastic behavior existed in the material under compression. In this regard, differences were greatest at the lower moisture contents and temperatures. Because of differences in fiber stress at proportional limit and modulus of elasticity in tension and compression, equivalence of the compressive and tensile stress and strain relationship therefore only occurs at the compressive stress obtained at a strain value equivalent to maximum tensile strain. The approximate equivalence in stress and strain for compression and tension, both at maximum tensile strain, is only apparent for material tested at 12 per cent moisture content and above. For the 6 per cent moisture content material, the stress in compression required to produce a strain equivalent to maximum tensile strain was lower than maximum stress in tension.
THE RELATION OF SHRINKAGE TO DRYING STRESSES

In the absence of quantitative data on the actual stresses occurring in wood, perhaps one of the best methods by which to evaluate stresses occurring in the drying of wood is to consider its total shrinkage under different drying conditions as representative of the extent and nature of the stresses occurring during drying. In this regard, excessive shrinkage resulting from liquid tension collapse must be considered apart from the shrinkage and sets resulting from drying stresses.

From a consideration of the basic principles of drying stresses in woods as outlined in the Introduction, it would be logical to assume that, for similar material dried to the same moisture content, relatively high shrinkage would mean that considerable compression set had developed in the inner layers of the board, or, in the case of relatively low shrinkage occurring, that tension set was predominant or that compression set was small. Although it is realized that the various hardwoods vary in their reactions to different drying rates and temperatures, particular cases will be considered.

Stevens (28, 29), working with European beech (which should not be confused with American beech used in the present investigation), determined the effect of temperature and drying rate on thin sections 1/8-in. thick along the grain. The temperature of drying varied from 25 to 100°C. and the rate of drying from 7 days to periods of a few hours or even minutes. He found that, at 25°C., the shrinkage of the material which was dried very fast was approximately the same as that of the material dried in 7 days. With increasing temperature of drying, the shrinkage of the material dried in 7 days increased markedly from a value of 12.1 per cent at 25°C. to 20.5 per cent at 100°C. On the other hand, the material which was dried at a very fast rate showed a reduction in shrinkage from 12.6 per cent at 25°C. to 10.3 per cent at 100°C. It therefore may be concluded from these results that greater effective compression of the wood by the outer layers was obtained with increasing temperature under the longer drying time. Under very rapid drying conditions, the slightly reduced shrinkage with increasing temperature indicates the very large influence of drying time (or time of loading) on the effective compression developed. At low temperature the effect of time of drying was negligible. The conclusion to be drawn from this behavior is, then, that creep and relaxation may play a considerable part in the manner in which wood accommodates itself to stresses.
RELATION OF SHRINKAGE

It should be emphasized that the above work was carried out on very thin sections, and it may perhaps be expected that thicker sections would show less effect with temperature under the longer drying times, owing to the relatively greater total internal resistance offered to the shrinking outer layers of the wood.

Fleischer (5) studied the influence of drying conditions on thin sections of yellow poplar at high temperatures. He found that shrinkage decreased with increasing temperature of drying. This confirms the results of Stevens for beech dried under very fast drying conditions. Fleischer also found that shrinkage decreased with increasing thickness of specimen, which may be expected from the greater proportion of the cross section which would be initially under compression by the outer shrinking layers, and therefore relatively greater resistance to compression would be offered. In addition a greater tension set would develop in the outer layers of the thicker specimen.
RELATION OF COMPRESSIVE AND TENSILE PROPERTIES PERPENDICULAR TO THE GRAIN TO DRYING PROBLEMS

FULL and proper application of the results obtained in this study to drying problems can only be made after their integration with the effects of duration of heating, duration of load, and influence of shear stress. However, at this stage, several important facts can be brought out from the data presented.

DEVELOPMENT OF SET AND CHECKING

As has been shown, the reduction in strength in both compression and tension resulting from changes in moisture content is far greater than that resulting from temperature changes which would be encountered generally in the kiln drying of hardwoods. It therefore becomes apparent that the stress-strain relationships within a drying board may be more affected by moisture gradients (apart from any shrinkage effect) than by temperature changes, at least within the range of temperatures used in this investigation. For this reason, it becomes of lesser importance whether tensile strength is greater than compressive strength or vice versa, or which is affected more by changes in temperature, and the moisture content influences become relatively more important. Also, as it is practically impossible to dry wood without developing set, the stress-strain relations above the proportional limit are of greater relative importance than the elastic portion of the stress-strain curve when limiting conditions for defects are considered.

In the simplified case of a drying board at the early stages of drying, when tension set is developing to a maximum and the danger of surface checking is present, the center portion may be considered to be above fiber saturation point while the outer layers are below fiber saturation point. This means that to avoid surface checking the outer portions of the board must be stronger than the inner portions if equal volumes of wood above and below the fiber saturation point are considered. In actual fact, in the usual thickness of lumber stock, the drying outer layers react in the early stages of drying against a much larger bulk of wood above the fiber saturation point. It is therefore not strictly correct to balance unit stresses in tension and compression, as the thickness of the drying shrinking layers relative to that of the non-shrinking wet core determines the average unit stresses in each zone.
Nevertheless, to evaluate the relative effects of temperature and moisture content on the stress and strain development in a drying board, the following idealized, simplified, hypothetical case of the drying of a beech board will be discussed in relation to the data obtained from tests in compression and tension under static loading conditions.

It must be noted that the test data were obtained under static loading conditions, and therefore the following treatment does not make allowance for effects associated with duration of stress.

Consider a unit section, a b c d, of a flat-sawn drying board from the mid-point of the cross section to a drying surface, as shown in Figure 8A. Let section a e f d represent a drying shrinking shell, and let section e b c f represent a non-shrinking core of equal volume above the fiber saturation point. After drying commences, section a e f d will begin to shrink, but will be partially restrained by the section e b c f which is still above the fiber saturation point. Therefore, after drying has proceeded for some time, the unit section will be as represented in Figure 8B. The outer strip, if able to shrink without restraint, would shrink to a length aa a'a'. Owing to
the restraint offered by the wet inner layers, it assumes the length ff \( f'f' \). The length 2 ff aa represents the tensile strain to which the layer is subjected. If the restraint to the shrinkage of the layer were removed, it would assume the dimensions bb b'b'.

The length 2 ff bb represents the elastic recovery of the strip on release from tension restraint. The dimension 2 bb aa represents tension set as a result of stressing beyond the proportional limit.

The inner layer, being above the fiber saturation point, shows no true shrinkage, and therefore its normal unrestrained dimension would be cc c'c'. However, owing to the force exerted upon it by the shrinking outer layers, it assumes the dimension ee e'e'. The dimension 2 cc ee therefore represents the compressive strain to which the layer is subjected. If the pressure on the inner layer were removed, then the layer would assume the dimension dd d'd'. The dimension 2 dd ee therefore represents the elastic recovery from compression. Since the layer was stressed in compression beyond the proportional limit, then 2 cc dd represents the set in compression attained by the layer.

As a result of the mutual interaction of adjacent self-applied stresses in tension and compression, shear stress will be present. The resulting shear deformation in the radial-tangential plane is represented in Figure 8B by the angle \( \phi \).

Poisson's ratio is also involved as a result of deformation along a structural axis, but the expansion in thickness of the inner layer resulting from a compression stress acting on it along the tangential axis would be compensated for by a corresponding decrease in thickness in the tension zone.

In the simplified case, shear stresses and Poisson's ratio will be neglected, as it is considered that these factors are secondary to the interaction of the primary tensile and compressive stresses. In actual drying, a moisture gradient exists between the drying shell and the wet non-shrinking core, so that the condition represented is more severe than is the actual case.

The model just described illustrates the system of internal stresses produced in a drying board in which the tensile and compressive forces are of the same magnitude, since they are mutually induced. In the quantitative analysis of these forces, it is considered that the deformation resulting from self-applied loads would be equivalent to the deformation arising from externally applied loads of the same dimension and type. Therefore, the results obtained from testing in compression and tension perpendicular to the grain can be applied, with the reservation that the conclusions apply only to short-term static loading conditions.
COMPRESSIVE AND TENSILE PROPERTIES

Table 15 summarizes the data for beech which can be applied to the model just described. The mean tangential shrinkage for the beech specimens tested was approximately 12 per cent from green to the oven-dry condition. Therefore, if a fiber saturation point of 24 per cent is assumed, the shrinkage to any moisture content can be derived from the straight line relationship between shrinkage and moisture content. In this regard, it would be more correct to use the fiber saturation point pertinent to each temperature of test, but a uniform value of 24 per cent has been adopted for simplicity in this instance. Calculations of stress and strain relationships were made for the conditions of a core section above fiber saturation point at all temperatures and for shell sections totalling the same thickness as the core, at 6, 12, and 18 per cent moisture content at 80, 100, 120, 140, and 160°F. The shrinkage from the green condition to each shell moisture content was calculated. The resulting dimension can be represented by aa a’a’ in Figure 8. The maximum tensile strain that the wood can undergo at the particular condition was subtracted from the shrinkage, and the value obtained represents the minimum strain necessary for the core section to assume if failure in tension in the outer shell is to be avoided. (See Table 15, Column 3.)

The compressive stress required to produce the derived compressive strain was then computed from the average compressive stress–strain curve for green material at each testing temperature. (See Table 15, Column 4.) For large values of strain, the curves were extrapolated. Exploratory tests showed that no large deviation occurred from the general trend of the curve, at least up to 5 per cent strain. To determine the margin of safety in tensile strength, that is, the proximity of the tensile stress required to produce the compressive stress in Column 4 to that at failure, the difference between ultimate tensile\(^{10}\) strength and compressive stress for the condition was expressed as a percentage of compressive stress. (See Table 15, Column 5.)

To compute the tension set at each condition (shown in Table 15, Column 6), the value from Column 4 was plotted on the average stress-strain curve in tension for each test condition. From this value a line was drawn parallel to the elastic portion of the stress-strain curve to intercept the strain axis, and the strain value obtained at the intercept was adopted as set.\(^{11}\) Similarly,

\(^{10}\) Ultimate tensile strength is synonymous with stress at maximum load, but will be used hereafter to avoid confusion with other stresses relating to tensile strength.

\(^{11}\) This procedure is not exactly correct as it is believed that a part of the set so derived may be recoverable over a period of time.
Table 15. Calculated Stresses and Strains Occurring in a Hypothetical American Beech Board in the Early Stages of Drying.
(See text for explanation.)

<table>
<thead>
<tr>
<th>Temp. of drying board °F.</th>
<th>M.C. of outer shell (per cent)</th>
<th>Total compressive strain of core needed to prevent failure in shell (in. per in.)</th>
<th>Compressive stress needed to produce strain in column 3 (lb. per sq. in.)</th>
<th>Excess of ultimate tensile strength over compressive stress (column 4) (percentage of compression stress)</th>
<th>Tension set developed in shell (in. per in.)</th>
<th>Compression set developed in core (in. per in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>6</td>
<td>0.0800</td>
<td>1510</td>
<td>1</td>
<td>0.0015</td>
<td>0.0602</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.0445</td>
<td>1040</td>
<td>24</td>
<td>0.0014</td>
<td>0.0309</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>0.0121</td>
<td>580</td>
<td>79</td>
<td>0.0001</td>
<td>0.0047</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>0.0787</td>
<td>1200</td>
<td>23</td>
<td>0.0006</td>
<td>0.0607</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.0386</td>
<td>790</td>
<td>47</td>
<td>0.0010</td>
<td>0.0266</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>0.0091</td>
<td>480</td>
<td>79</td>
<td>0.0004</td>
<td>0.0017</td>
</tr>
<tr>
<td>120</td>
<td>6</td>
<td>0.0775</td>
<td>900</td>
<td>57</td>
<td>0.0001</td>
<td>0.0635</td>
</tr>
<tr>
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<td>640</td>
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<td>0.0008</td>
<td>0.0284</td>
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<tr>
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<td>94</td>
<td>0.0001</td>
<td>0.0007</td>
</tr>
<tr>
<td>140</td>
<td>6</td>
<td>0.0753</td>
<td>700</td>
<td>89</td>
<td>none</td>
<td>0.0558</td>
</tr>
<tr>
<td></td>
<td>12</td>
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<td>97</td>
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<tr>
<td></td>
<td>18</td>
<td>0.0069</td>
<td>280</td>
<td>106</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>160</td>
<td>6</td>
<td>0.0766</td>
<td>520</td>
<td>126</td>
<td>none</td>
<td>0.0620</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.0373</td>
<td>420</td>
<td>122</td>
<td>none</td>
<td>0.0255</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>0.0039</td>
<td>140</td>
<td>150</td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>
compression set (see Table 15, Column 7) was obtained by applying the value in Column 4 to the average stress-strain curve for green material at each temperature of test.

In interpreting the values shown in Table 15, it should be borne in mind that in drying from the green condition the shell layers must progressively pass through 18, 12, and 6 per cent moisture content, and therefore the tension sets shown in Column 6 will be cumulative to a certain degree.

It is seen from the table that the development of set in compression greatly exceeds that developed in tension. Tension sets as such appear to contribute comparatively little to the change in overall dimension of a drying board, although it is realized that, as drying progresses, each successive layer in depth becomes subject to stress in tension, while the outer layers are successively placed in compression. It may therefore be concluded in this instance that differences in final shrinkage due to different conditions of drying are determined chiefly by the variation in compression set.

It is believed that evidence for the greater magnitude and importance of compression set in determining shrinkage may be derived from data presented by the United States Forest Products Laboratory (8) on the changes in shrinkage and stresses in the different zones of a 2- by 10-in. flat-sawn sweetgum heartwood plank, previously discussed. (See Figure 1 for original data.) The material was dried under initial conditions of 135°F. and 17.5 per cent equilibrium moisture content. In this work, the tensile and compressive strains, as derived from the strip technique of stress analysis, were plotted against time of drying. Also, the total shrinkage of each strip, when dried to the oven-dry condition, was shown for each stage of drying. Once the strip was removed from the plank, care was taken to prevent further set developing in each strip during drying to the oven-dry condition. Therefore, the set present at the stage when the strip was taken from the plank can be obtained by comparing its shrinkage with that of a stress-free section. Unfortunately, no data were available on stress-free shrinkage, so that the average tangential shrinkage of the species (10 per cent) was taken as a criterion. The use of published values for shrinkage for such applications as this may be questionable because not entirely stress-free sections are used in standard shrinkage determinations. At each stage of drying, the set in the outer and center portions of the plank was then calculated, and the total strain in the strip at each stage obtained by adding to the set the contraction or expansion on cutting from the board. The total strain obtained was then plotted against time of drying, as shown in Figure
Figure 9. Calculated total strains occurring in the outside layers and center of a 2-by 10-in. flat-sawn heartwood plank of sweetgum during drying. (Calculated from data published by U.S. Forest Products Laboratory.)

9. It is seen from Figure 9 that the total unit strain in compression greatly exceeded that in tension, and, in addition, as seen from Figure 1, a greater cross section of the wood was subjected to compression than tension in the early stages of drying. As a result, the total shrinkage of the plank amounted to 12 per cent, which was 2 per cent greater than the average shrinkage of the species. Although a direct comparison cannot be made between the strains shown in Figure 9 and Table 15 because different species and different relative cross sections in tension and compression are concerned, it is noted that the order of compressive strains is similar. The question also arises as to
COMPRESSIVE AND TENSILE PROPERTIES

how the relatively small tension zone can cause such large compressive strains in the inner layers. It is considered that, to explain this behavior, creep must be assumed to play a significant part.

In the hypothetical example considered, it is seen from Table 15 that compression set increases markedly as the moisture content of the shell falls from 18 to 6 per cent. With a surface moisture content of 6 per cent, and a core moisture content above fiber saturation point, compression set shows no definite trend with temperature. With surface moisture contents of 12 and 18 per cent, compression set tends to diminish with increasing temperature, therefore indicating a decreased overall shrinkage with increasing temperature of drying. This trend has experimental confirmation in the behavior of the rapidly dried thin sections observed by Stevens and Fleischer. Both investigators found that, under rapid drying conditions, the total shrinkage decreased with increasing temperature of drying. From the fundamental assumptions involved in the present hypothetical case, it would also be expected that increasing thickness of specimen would result in reduced overall shrinkage, as a relatively greater cross section of the board will be placed under compression, and therefore the unit stress in compression would be less than that in tension. In confirmation, Fleischer found that the total shrinkage of thin sections of wood showed a decreased overall shrinkage with increasing thickness of specimen.

It is seen from Column 4 of Table 15 that the stress required to produce strain of the green inner core sufficient to prevent strain to failure of the shell increases very markedly with decreasing moisture content of the shell and temperature. The force required to carry out the compression is derived from the shell layers, and Column 5 shows the relationship between the required compressive stress and ultimate tensile stress. If the ultimate tensile stress is exceeded, then of course surface checking will result. While the actual values in Column 5 have only limited application because equal volumes of compression and tension zones are assumed, they do provide information as to the relative effect of each drying condition. It is seen that, at low temperature and low surface moisture content, the ultimate tensile strength is more closely approached than under any other condition. Therefore, it may be expected that, if the core section is still above fiber saturation point at this stage, the danger of surface checking is more prevalent under these conditions than under any of the others considered. This affords an explanation of the author's earlier observation that severe surface checking of beech occurred under winter air-drying temperatures, whereas matched
material did not show much severe checking under a variety of kiln schedules. It also affords an explanation of Kollmann's observation that surface checking appeared to be more prevalent in oak at lower temperatures.

The margin of safety in tensile stress (that is, the excess of tensile strength over the stress required to compress the core in order to prevent surface checking) for all surface moisture contents increases very rapidly with temperature, and the increase is greatest in the case of the 6 per cent surface moisture content material. At the two highest temperatures used, and with surface equilibrium moisture contents of 6 and 18 per cent, drying stresses do not exceed or, at the most, only slightly exceed, the proportional limit in tension of the shell layer, and consequently little or no tension set develops at this stage. The value in Column 5 of Table 15 may be interpreted, not only as an indication of the danger of surface checking, but also as an indication of how large a core section can be compressed without the development of surface checks. For example, at 160°F. and with a surface moisture content of 18 per cent, the drying shell could compress a green core of nearly 2 1/2 times its own cross section as a maximum, and checking would not develop. On the other hand, at 80°F. and with 6 per cent surface moisture content, the danger of surface checking exists when the shell and core zones are equal in cross section. Thus, from the point of view of surface checking, safer conditions are obtained under the higher temperatures of test, and, at these temperatures, surface moisture contents appear less critical than is the case at the lower temperatures. It is of interest to note that Ladell (19), reporting on the drying of certain Canadian softwoods at high temperature, stated that very few drying checks occurred. He attributed the fact that the lumber could be dried at low humidities without severe structural degrade to modified relationships at high temperature between relative humidity, drying rate, and moisture content. Although the drying data were obtained for softwoods, it is believed that the drying behavior at high temperature may be more satisfactorily explained by the type of stress and strain analysis described above with respect to a beech board.

It is also apparent that liability to surface checking will be great if rapid drying is started before the center of the board reaches approximately the same temperature as the drying surface. In this regard, in superheated steam drying, the material is initially subjected to heating without drying, or otherwise surface checking generally occurs.
COMPRESSIVE AND TENSILE PROPERTIES

MODIFICATION BY DURATION OF LOADING

When attempting to compare the results from Table IS with observations reported from various sources on the behavior of beech, and wood in general, with drying conditions, a number of facts still remain unexplained. In particular, Table IS does not explain the observed behavior that at least some woods tend to develop an increased overall shrinkage when dried under relatively long term drying conditions at high temperatures. It is also apparent from the table that under very few temperature-moisture content combinations tested could the outer drying layer effectively compress much more than twice its own cross section to avoid surface checking. As previously described, in the usual case of drying, the outer drying layer is considerably smaller than the inner layers under compression during the early stages of drying. While it is considered that some relief of stress may be obtained by shear deformation, the core section still needs to be compressed considerably in order to avoid stress relief by checking in the surface layers. It is therefore considered that, to account for observed behavior, creep and relaxation effects must be investigated.

Loading Repetitions

With the object of determining stress and strain behavior after proportional limit had been exceeded, repetitions of load were carried out on several specimens in tension perpendicular to the grain. An attempt was made to load the specimen repeatedly at a value slightly below its maximum strength under one short-term load, and then to compare its strength and elastic properties with closely matched controls which were loaded to failure in one test. Repeated loading to 88 per cent of the ultimate strength of the controls, in the case of material tested in tension at 80°F. and 6 per cent moisture content, showed the following results:

The modulus of elasticity increased after the first loading to a more or less constant value some 12 per cent higher than that obtained on the first loading.\textsuperscript{10} At the first repetition the strain at maximum test load showed a marked decrease, and then showed a very slight decrease with each successive repetition. At the same time, the set developed at each successive loading

\textsuperscript{10} Editor's note: Subsequent work suggests that the apparent increase in modulus of elasticity reported here is not a permanent effect but is associated with a delayed recovery of strain resulting from the preceding load application.
showed diminishing increments. The specimen failed on the eighth loading with a maximum stress which was 12 per cent less than that of the matched control that was stressed to failure in a single load application. The unit strain (assuming zero strain at the no-load condition) at failure on the eighth loading was 0.00734 in., compared with 0.01000 in. for the control.

When cumulative set was added to the deformation at each loading, it was found that at the eighth loading the total deformation approached very closely that of the control, being, in fact, only 7.7 per cent less. The relation of modulus of elasticity and total strain to loading repetition is shown in Figure 10.

Evidence is available from other investigations (9) that repeated loads have a cumulative effect, but that the sum of all loaded periods before failure will equal the duration of a continuous load at the same stress level.

From the above evidence it is suggested, then, that repeated stressing and probably long-term loads do not increase the ultimate deformation at failure in tension. Applied to the drying problem, stress repetition as a result of repeatedly wetting and drying the surface layers of a board apparently confers no improvement in the ability of the wood to accommodate tensile stresses by way of a greater deformation at failure. The higher stiffness would help appreciably the ability of the outer drying layers to compress the wet inner layers or core, so that the tendency to surface checking may be reduced. This, of course, neglects to take account of the effect of moisture gradients, which would determine the amount of shrinkage in the outer zones relative to the movement in the inner zones.

**Constant Load**

To explore differences in creep between compression and tension and the effect of temperature and moisture content upon these values, the following tests were carried out:

In tension, creep was determined in two specimens at 6 per cent moisture content and 80 and 160°F. In compression, one specimen was tested at 6 per cent moisture content and two specimens in the green condition were tested at 80 and 160°F. Instead of the clip gauge, a strain gauge was attached directly to the surface of the specimen in these tests. The testing procedure adopted was to load both the tension and compression specimens up to a stress which was approximately 90 per cent of the ultimate tensile stress for the particular test condition. The rate of loading to this point was the same value as that used in the tests to determine tension and compression strengths. The load was then maintained at the 90 per cent value of
Figure 10. Effect of repetition of load in tension perpendicular to the grain on the modulus of elasticity and strain behavior of American beech at 6 percent moisture content and 80°F. (Loaded to 88 percent of maximum stress of controls.)
maximum tensile stress for 2 hours, continuous adjustment of the movable platen of the testing machine being made to allow for the creep occurring in the specimen. Strain readings were taken at intervals during the 2-hour period. In the case of the tension specimen tested at 160°F, the constant load was applied until failure occurred.

Figure 11 shows the relationship between creep in tension and compression at various moisture contents and temperatures. In this figure, zero time is taken at the time of commencement of the constant load which was maintained for 2 hours. Consideration of the relative differences between creep in compression and tension above the proportional limit and at the same stress shows that at 80°F and 6 per cent moisture content the rate of increase in deformation of the compressed material is practically twice that obtained in tension. Also, the unit deformation of the material tested in tension tends to level out earlier than that of the material tested in compression.

The rate of increase in deformation shows diminishing increments of deformation, so that, beyond a relatively short time, the increase in deforma-
tion becomes relatively small. Although very little is known of creep in wood, the configuration of the creep curves for this material is in general conformity with at least the initial behavior of creep in other materials (16). It perhaps may be expected that creep would be greater in compression than in tension, as the plasticity above the proportional limit was shown to be greater in the case of compression. Further, as shown in Figure 11, creep increases considerably with moisture content, the creep of the green material tested at 80°F. being more than twice that of the material tested in compression at 6 per cent moisture content. Therefore, with reference to the drying model discussed in the previous section, in which the interaction was considered of a drying shell about a core above the fiber saturation point, the actual stress applied to the core to prevent stretching the outer shell beyond its maximum tensile strain may be considerably less under loads of greater duration. Consequently, when the time of drying becomes an appreciable factor, as is the general case in lumber drying as distinct from thin sections, the actual stress-strain relationships existing in the various zones of a drying board are considerably modified with respect to the situation discussed for the hypothetical case. Increased drying time (or duration of load) means that, in general, greater strains would be obtained relative to stress, and, because of greater creep in compression than in tension, greater total shrinkage would occur. This effect would increase under those conditions which were conducive to high creep.

The effect of creep in relation to the development of surface checking will not be known until the influence of load duration is found for both tension and compression properties.

The fact that creep occurs relatively rapidly in the direction perpendicular to the grain indicates that, beyond a relatively short period in the total drying time, increase in time of drying would not cause large increases in creep. This principle may explain why thin sections showed no difference in shrinkage between 2 and 7 days drying time (28, 29), although a considerable reduction in shrinkage occurred when very fast drying times were involved at the same temperature. Apparently, the major part of the creep which could occur had taken place in less than 2 days, and additional drying time (or duration of load) did not result in significantly increased creep. On the other hand, creep effects apparently did not develop fully in the material which was dried very rapidly.

With respect to the effect of temperature on creep, the test carried out on green material in compression at 160°F. was not satisfactory as the bond
of the strain gauge to the moist surface of the specimen was inadequate under the relatively high temperature used. However, from the few readings obtained in this test, a creep value greater than that of any other specimen of the series tested was indicated. The creep obtained for the tension specimen tested at 160°F. and 6 per cent moisture content was more than twice that of the specimen tested in tension at 80°F. at the same moisture content (see Figure II), indicating that temperature has a considerable influence on the rate of deformation. This particular specimen was maintained under constant load until failure occurred after 144 minutes. A loss of approximately 10 per cent of the ultimate tensile strength under static loading conditions is therefore indicated as a result of increased duration of load.

The total unit strain of the specimen at failure (that is, strain to the go per cent load plus strain under constant load) was 0.0153 in., which differed by only 1 per cent from the maximum tensile strain of the control specimen tested to failure under static loading conditions. This behavior confirmed the results of the strain behavior obtained in repeated loads in tension discussed in the previous section.

Because creep increases with temperature, and creep in compression is greater than that in tension, it is possible to explain the tendency for certain hardwoods to show increased total shrinkage with increasing temperature of drying when the time of drying, and therefore the duration of drying stresses, is sufficient to allow substantial creep to occur.

The foregoing results relating to the determination of creep should be interpreted in a relative sense only, as too few tests were conducted to allow an accurate evaluation to be made for each testing condition.
RECOMMENDATIONS FOR FURTHER STUDY

IN AN earlier part of this bulletin it was considered that the current experimental method of determining stress distribution in a drying board may give an indication of the time of maximum stress development, but does not afford an absolute measure of the magnitude of actual stress. Evidence was presented to show that the form of the stress-strain curve for American beech varied considerably with temperature and moisture content, and that the plastic range showed large variation. Assuming that the recovery of a strip, on cutting from a board, is parallel to the elastic portion of the stress-strain curve, then the actual stress condition can be determined from the stress-strain curve for the appropriate temperature and moisture content conditions of the wood. This procedure should be possible with the data presented.

It should be a valuable study to correlate the results obtained from the strip technique of stress analysis and the calculated stress condition in a drying board from a knowledge of the stress-strain relations under various temperatures and moisture contents.

In the limited work dealing with loading repetitions in tension, recovery curves were plotted on each repetition of load, and the recovery curve generally appeared to parallel that of the elastic portion of the loading curve. However, it should be pointed out that, at least in tension under both repetitive loading and constant loading above the proportional limit, an apparent increase in modulus of elasticity occurred. Supposing now that the recovery curve were parallel to the altered elastic curve, then a smaller dimensional change would be observed on removal of a strip from a board. Thus, the strip may be actually closer to failure (for example, if in tension) than would be indicated by the dimensional change. The need for investigation of the characteristics of recovery curves with nature and time of loading is indicated.

It is apparent from the previous discussions that data obtained from tensile and compressive tests cannot be immediately applied to predict drying stresses and liability to drying defects in the usual cases of lumber drying. This is because the length of time of drying modifies the stress and strain behavior of a board owing to the occurrence of creep. Similarly, relaxation effects must be considered. It is therefore essential that creep data be obtained over a range of temperatures and moisture contents in order to evaluate the stresses in a drying board.
PROPERTIES OF AMERICAN BEECH

Also, it is known that a reduction in strength occurs with increasing duration of load. It therefore becomes essential to establish the rate of loss in strength with duration of loading, and in particular the loss of maximum tensile strength, so that a series of limiting values can be applied for different drying times.

In the present investigation, particular attention has been given to stress development in the early stage of drying, because, in the drying of hardwoods, this is the critical stage with respect to the development of surface checks and subsequent internal checking at the later stages of drying. For the purpose of calculating expected stresses and resultant behavior, at each surface moisture content, static loading conditions were assumed. Actually, in the case of a drying board, conditions are dynamic in that tension stresses tend to move into the center of the board, while compression stresses, which initially develop in the inner zones, also develop in the outer layers as the tension stresses move inward. Therefore, with changing moisture content, the various zones within a board change from tension into compression and vice versa. Also the relative cross sections under tension and compression may change with time. The pattern of stresses therefore tends to become more complicated as drying proceeds. In order to calculate stresses developed in these later stages of drying, it is therefore necessary to establish with some accuracy the degree of set developed in the early stages.

It is suggested that a study be made of recovery of wood sections mechanically stressed at various levels for various times under a range of moisture contents and temperatures, to establish the extent of set developed and its degree of permanence.

Further, as shear stresses are involved in the interaction of tensile and compressive stresses in a drying board, a study is warranted of their relative effect under various temperatures and moisture contents.

Although only flat-sawn material has been considered in this bulletin, an extension of investigations to include material both quarter sawn and at 45° to the growth rings would provide additional information, particularly on drying conditions which may produce checking.

Although frequent reference has been made throughout this bulletin to stresses in "layers" and "zones," the stresses concerned can only be an average condition for the layer, as these stresses are not discontinuous, but exist as a gradient within and between the layers.
SUMMARY

1. The present status of the method of establishing drying schedules for wood was first critically reviewed. As a fundamental approach to the understanding of drying stresses and defects, a study of the mechanical properties of wood in a direction perpendicular to the grain was undertaken. Variation of strength and elastic properties of American beech, perpendicular to the grain, in tension and compression, with temperature and moisture content, was studied, and a technique for carrying out these tests is described.

2. For properties in tension perpendicular to the grain in a tangential direction, within the temperature range of 80 to 160°F. and moisture content range from 6 per cent to the green condition, the following was established for American beech:

i. Stress at maximum load, modulus of elasticity, and fiber stress at proportional limit decrease with increasing temperature and moisture content. Within the range of conditions used, moisture content has the greater effect on strength and modulus of elasticity is most affected.

ii. Ultimate tensile strength shows a rectilinear relationship with both temperature and moisture content. The maximum temperature effect was found at 18 per cent moisture content, and the moisture content effect increased at the higher temperatures. Regression equations are given for the effect of temperature on ultimate tensile strength at the nominal moisture contents of test.

iii. The relationship of both modulus of elasticity and fiber stress at proportional limit to temperature is predominantly linear, but significant quadratic effects are also present. Both properties bear a curvilinear relation to moisture content. The moisture content effect is not markedly influenced by temperature. Regression equations are given for the effect of temperature on both properties at the nominal moisture contents of test.

iv. Maximum strain at 6 per cent moisture content was markedly lower than that obtained at other moisture contents. Maximum strain increased in a predominantly linear manner with temperature at all moisture contents, although the increases were comparatively small.

3. For properties in compression perpendicular to the grain under the same range of test conditions as were used for tension testing, the following was established for American beech:

i. Stress at 2.5 per cent strain, modulus of elasticity, and fiber stress
PROPERTIES OF AMERICAN BEECH

at proportional limit decrease with increasing temperature and moisture content.

ii. Compression strength has no real maximum value. The actual level of strength and its decrease with temperature and moisture content depend upon the total strain at which it is determined. The compression stress at 2.5 per cent strain shows a rectilinear decrease with increasing temperature and moisture content, which is greater for lower moisture contents than that in tension. Compression stress at maximum tensile strain showed greater overall agreement with ultimate tensile strength in both value and rate of decrease with temperature and moisture content with the exception of the 6 per cent moisture content material, which fell 9 to 11.5 per cent below the ultimate tensile strength. Regression equations are given for the effect of temperature on stress at 2.5 per cent strain at the nominal moisture contents of test.

iii. Modulus of elasticity and fiber stress at proportional limit show a rectilinear decrease with temperature for all moisture contents, and a curvilinear decrease with moisture content for all temperatures. The effect of moisture content on the reduction of the value of these properties was not markedly influenced by temperature in the range of conditions used. Regression equations are given for the effect of temperature on both properties at the nominal moisture contents of test. At the lowest moisture content, agreement with tensile values was reasonably good. With increasing moisture content, compression values were greater than those in tension, particularly at the higher temperatures of test. The difference in modulus of elasticity between the two tests is considered to be a result of the type of testing and the form of the specimens.

iv. The proportional limit strain is similar in both tests, and the apparent plasticity (above the proportional limit) is greater in compression than in tension.

4. The variation of total shrinkage with drying conditions, which has been observed for certain hardwoods, is discussed in relation to drying stresses. It is considered that this variation is a result of variation in set and therefore may be interpreted as an indication of the nature of drying stresses.

5. The data obtained from tests in compression and tension, under static loading conditions, were integrated and are discussed in relation to drying stresses and defects. A model was set up of a beech board in the early stages of drying and calculated drying stresses and strains were applied to it for
SUMMARY

various drying conditions. Under the limitations of short-term loading (or drying time) conditions, and the restrictions of the model, it was shown that: (I) variation of total shrinkage with drying conditions is mainly a function of compression set, (2) both tension set and compression set tend to decrease with increasing temperature of drying and moisture content of the surface layers, and (3) susceptibility to surface checking is more apparent at the lower temperatures of drying and at the lower surface moisture contents.

These results may explain the observed behavior of thin sections of certain hardwood species that show reduced total shrinkage with increasing temperature of drying under very fast drying conditions. Also they may afford an explanation of the observed tendency of certain hardwood species to surface check more severely at low drying temperatures.

6. As the application to the drying model of strength data obtained under static loading conditions did not fully explain the observed behavior of hardwood lumber in usual commercial thicknesses, exploratory tests were carried out to determine creep behavior in tension and compression. A limited number of specimens at selected temperatures and moisture contents were subjected to a constant load in tension or compression above the proportional limit. It was found that: (I) creep occurred relatively rapidly in both tension and compression, creep in compression being more than twice that in tension for the same stress; (2) duration of stress apparently did not affect the tensile strain at failure, and (3) increase in temperature and/or moisture content resulted in a considerable increase of creep.

Although these tests were too limited in number to allow their quantitative application, the results may afford an explanation of the behavior of certain hardwood species which show a considerable increase in total shrinkage with increasing temperature of drying when substantial drying times are involved. They also indicate (at least for beech) that susceptibility to surface checking may be less at higher temperatures of drying.

7. Recommendations for further study are given. In the application of the work to the strip technique of stress analysis a study is recommended of the relation between the results obtained from the strip technique of stress analysis and the calculated stress condition in a drying board from a knowledge of the stress-strain relations under various temperatures and moisture contents. Investigation of the nature of recovery curves with type and time of loading is indicated, so that the stress analysis may be more fully evaluated.
In order to aid prediction of drying stresses and liability to surface checking under various drying conditions, it is recommended that creep and relaxation data be obtained in compression and tension at various temperatures and moisture contents, as well as establishment of the rate of loss in strength with duration of loading. Additional studies are indicated on the effects of shear stresses and inclination of the growth rings on stress and strain behavior in compression and tension perpendicular to the grain.
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81
PROPERTIES OF AMERICAN BEECH

PLATE I

Arrangement for testing in tension perpendicular to the grain.
A. Heating and humidifying compartment
B. Test compartment
PLATE II

Construction of portable testing chamber used in tests.
A. Fan                       C. Tray of saturated salt solution
B. Strip heater               D. Thermo-regulator.
PLATE III

Construction of clip gauge and its attachment to the tension test specimen.
PLATE IV

Test arrangement of compression specimen fitted with compressometer and clip gauge.
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