THE RELIEF OF CASEHARDENING STRESSES IN AIRCRAFT LUMBER

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THE RELIEF OF CASEHARDENING STRESSES IN AIRCRAFT LUMBER

By
EDMUND F. RASMUSSEN, Assistant Engineer
and
GLENN VOORHIES, Wood Technologist

Introduction

The demand for precision-dried aircraft lumber calls for accuracy in the manipulation of the dry kiln schedule. This mimeograph concerns but one phase of the drying procedure, namely the kiln-conditioning treatment for the relief of casehardening.

The conditioning treatment is an important part of the drying process, not only for aircraft lumber but also for other stock such as shop, box, and furniture lumber. In looking forward it appears reasonable to believe that the consumer will expect not only the present good quality of lumber, but even better lumber that meets the highest requirements for the use intended. For many purposes this means lumber free of stress.

The Nature of Casehardening

Due to the shrinkage characteristics of wood and the manner in which wood dries it is impossible to dry lumber without introducing casehardening stresses. The nature of casehardening is shown in the following step-by-step discussion of the drying of a piece of lumber:

1. Wood that is above the fiber saturation point will not shrink. The fiber-saturation point is that stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities are free from water. Usually the fiber-saturation point is at a moisture content between 26 and 30 percent.

2. As wood dries, the surface layers become dry first. (Fig. 1, A.)

This mimeograph is one of a series of progress reports prepared by the Forest Products Laboratory to further the Nation's war effort. Results here reported are preliminary and may be revised as additional data become available. The work here reported was done in cooperation with the Materials Laboratory, Material Command, Army Air Forces, Wright Field, Dayton, Ohio.
3. As soon as the outer fibers dry below the fiber-saturation point they tend to shrink. The core of the board is above the fiber-saturation point and consequently cannot shrink. Under these conditions, the shell, being below the fiber-saturation point, attempts to shrink but cannot because the core has not yet decreased in dimension.

4. The shell will be in tension and the core will be in compression. The comparative intensity of the tensile stresses is shown diagrammatically by the solid bars of figure 1 and the compression by the compressed spring symbol. During this stage of the drying the tensile force in the outside layers is at a maximum for the whole drying period and surface checking may develop.

5. Under a condition of tension, the shell continues to dry with the cell walls of this zone remaining in a set position.

6. As adjacent zones become dried below the fiber-saturation point, the set outer shell tends to come back into position because of the tensile force applied by the next adjacent zone. This is shown diagrammatically by B of figure 1.

7. When the core attains a moisture content below the fiber-saturation point the resultant shrinkage of the core will be restrained by the set outer shell. Successive inner zones are subsequently put under a tensile force which progresses as shown by the stress conditions of B and C of figure 1. The degree of the severity of these tensile and compressive forces (collectively termed casehardening) is dependent on the characteristics of the individual piece and the moisture gradient during the drying process. Usually a board contains distinct zones of moisture content. As each zone dries below the fiber-saturation point, that particular zone is in tension. The tensile stress that develops in a given zone is influenced by the amount of shrinkage that has taken place in the adjacent outer drier zone and the resistance to dimension change offered by the wetter interior. The stress in each zone becomes maximum before the adjacent wetter zone becomes dry enough to shrink.

8. The moisture gradient between the shell and core of different boards is likely to cover a wide range of moisture content values, particularly when drying takes place in low relative humidities. As long as checking does not develop, however, the tension in the outer fibers is not objectionable. Such stresses merely cause the outer fibers to become set in an expanded condition. Near the end of the drying period as shown in C of figure 1, the core continues to dry and the moisture gradient becomes less. The set expanded condition of the shell is progressively decreased as it puts more and more tension on the core as the core tries to shrink. The resultant tension in the core stretches it but not enough to cause a set expanded condition. At the end of the drying process the core is still in tension but the shell is in compression. The residual stress in a piece is a measure of the severity of casehardening. From this explanation it follows that the drier the core, the more it will recover from the compression given it in the early stages of drying.
It is for this reason that casehardening is not so noticeable in lumber continuously dried to a moisture content of 5 percent as it is in lumber dried to only a 10 percent moisture content.

The Procedure by Which Casehardening Stresses Are Removed

Removing casehardening stresses in wood is the process of inducing the surface fibers of the shell to attain a moisture content equal to the moisture content of a thin zone midway between the broad faces of the board. In practice, where the required moisture content is between 8 and 12 percent, the same results can usually be obtained by applying a conditioning treatment that will raise the surface fibers to a moisture content about 2 percent higher than the average moisture content. It is therefore necessary that the average moisture content at the end of the drying period be somewhat below the desired final maximum moisture content. If the average moisture content is not less than that desired, the conditioning treatment will produce lumber that is too wet.

A kiln charge of lumber usually contains dry and fairly wet boards which may vary in average moisture content as much as 10 percent. In order to bring these average values closer together it is advisable to establish kiln conditions near the end of the run that allow the drier boards to pick up moisture, the wetter boards to lose moisture, and those of the desired moisture content to remain unchanged. A kiln condition held for a sufficient length of time that will bring about such results is sometimes referred to as an "equalizing period" and is used primarily to bring about uniform moisture distribution in the lumber just prior to a conditioning treatment. Using an equalizing period for this purpose is explained in detail later in this report.

In order to show clearly how the relief of casehardening stresses may be accomplished it becomes helpful to again use the example in figure 1:

1. Assume C of figure 1 to represent the moisture distribution in a board at the end of the kiln drying period and just prior to an equalization treatment. The outer layers of the shell have a moisture content of 5 percent; the maximum moisture content at the center of the piece is 14 percent which results in an average moisture content value of approximately 11 percent. If the board represented by this moisture distribution is to be conditioned and the casehardening stresses removed, the shell must be raised to a moisture content of 14 percent.

2. Assume the moisture gradient in D of figure 1 to represent the moisture distribution in a board following an equalization period. The outer layers of the board have been raised to a moisture content of 8 percent while the maximum moisture content at the center of the piece has been reduced to 11 percent with a resultant average moisture content of approximately 9 percent. The moisture regain results in an increase.
in the compressive forces in the outer shell due to attempted swelling on the moisture regain. This is shown in the corresponding stress diagram of D in figure 1.

3. The moisture regain and final moisture distribution after the conditioning treatment are shown by E of figure 1. The conditioning treatment produces this ideal moisture distribution gradually. First the surface fibers, and then, in order, the successive zones attain a moisture content of 11 percent, which just equals the moisture content of the thin central zone. A suitable conditioning treatment, therefore, is one which employs a relative humidity that will cause the thin central zone to neither gain nor lose moisture and all of the portions of the board will eventually attain the same moisture content as the thin central zone. Such a treatment will produce the following changes and results:

a. The various zones will respectively absorb moisture until they attain a moisture value of 11 percent. Accordingly the outside will absorb the most moisture, the intervening zones lesser amounts of moisture, and the thin central zone will neither absorb nor lose moisture.

b. The surface fibers no longer resist deformation more than the interior fibers and as a result the dimensions of the surface zones are more easily compressed.

c. Each zone attempts to swell in proportion to the moisture it has regained. Referring now to the stress diagram of E in figure 1, the outside zones, which are already in compression, are squeezed still more by the attempts of the wood to swell. As the swelling tendency of each zone is restrained by zones which do not absorb so much moisture, additional tension is applied to the central zones which are already in tension. These additional tensile and compressive forces are just the right amount to cause relief of the casehardened condition of the board; the outside areas in compression being squeezed and the inside areas in tension stretched to a point beyond their elastic limit so that each area will no longer return to its original unleashed dimension. E of figure 1 shows the progressive stresses which occur on the moisture regain and F shows the final result of an ideal conditioning process. By this mechanism the stresses are relieved and upon sawing a sample into prongs there will be no curvature or difference in prong length.

4. Care should be exercised in adjusting the relative humidity so that the outside zones will not pick up moisture in excess of that of the thin central zone. If a board with a moisture gradient such as in D before conditioning is subjected to an atmosphere so that the outside zones will come to 14 percent moisture, then a reversed condition of tension and compression will be produced. Tremendous compressive forces will be applied to the external zones in going through a moisture change.
from 5 to 14 percent, their dimensions fixed by the dimension of the central zone. Under these conditions the shell will fail excessively in compression and as it dries to the moisture content equal to that of the core its stress-free dimension will be affected not only by the amount of shrinkage but by the amount it has failed in compression as well. A board that has been given such a treatment would, after resawing, cup away from the center and not toward the center as one would expect in casehardened stock. This condition of stress is termed "reverse casehardening."

From the foregoing discussion it will be readily realized that conditioning treatments are necessary and can be successful only when certain facts are known: the average moisture content, the manner in which the moisture is distributed throughout the cross section of the board, and the exact kiln conditions.

Methods for Accurately Determining the Oven-dry Weight of Kiln Samples

Since it is necessary to know, within close limits, the moisture content values of the stock before establishing relative humidity conditions for conditioning, it becomes necessary to examine the accuracy of the moisture content determinations.

Unequal moisture distribution along the length of the board, so-called "water pockets" and sap streaks, especially in western hemlock and noble fir, have a decided effect on the computed moisture content values of kiln samples. The shaded areas in figure 2 show the location of assumed water pockets within the board. These assumptions are made for the purpose of showing the possibility of error in the determination of the original moisture content values of the kiln samples. Moisture section A-1 shows a rather large water pocket covering about one-third of the volume of the section. In section A-2, however, a much smaller water pocket is shown. Moisture content values will consequently be quite high in section A-1 and low in section A-2. The average of these two values will be much lower than the actual moisture content of kiln sample A-1 because a large volume of this sample, roughly about 50 percent of the total, contains concentrated water areas.

Conversely, both moisture sections may be cut from areas containing moisture values much higher than those found in the kiln sample. Thus the calculated moisture content of the kiln sample may be much higher than its true value.

It is, of course, entirely possible that sometimes the concentration of water within the moisture sections and the kiln sample may be in the same proportion, giving a true calculated moisture value based on the average moisture value of the sections.

In any event it is necessary to obtain a reasonably true conception of the moisture content values of the stock in order to determine within practical limits the time at which the equalization and final conditioning treatments are to be given the kiln charge.
Figure 3 graphically shows the moisture content values of all the samples in a charge of 4/4-inch noble fir aircraft lumber. The unshaded bars represent the moisture content in percent of each of the kiln samples on the basis of the original moisture content calculations. The black bars represent the same samples following an intermediate moisture content determination. There is a wide variation between the moisture content values based on the original and intermediate determinations. Since the samples have dried to a relatively low moisture content, the intermediate determination is the more accurate.

An intermediate determination should be made when the wettest kiln sample shows a moisture content of approximately 14 percent, based on the original moisture determinations.

Since the samples should all be thoroughly end-coated prior to kiln drying, end drying will have been held to a minimum and the 6-inch cut as shown in figure 4 should be ample to eliminate the zone of fast end drying.

The 1-inch section is oven-dried and the moisture content values of the section and the oven-dry weight of the sample calculated in the regular manner. The new kiln sample is end-coated, reweighed, and replaced in the kiln for future moisture determinations.

If the original sample is cut 30 inches instead of 24 inches in length, there will be a larger sample left for future moisture determinations.

Alternate Method of Determining Oven-dry Weight of Kiln Samples

The specification for the kiln drying of aircraft lumber requires that the oven-dry weight of kiln samples be computed according to the formula:

\[
\text{Original weight} \times \frac{100}{100 + \text{Original moisture content (percent)}}
\]

It is suggested that it may be desirable to check the value obtained by an alternate method that eliminates the variable of moisture distribution along the length of the board. In such species as western hemlock, the moisture content may vary more along the length of a board than does the specific gravity. Therefore the following proportional-weight method for computing the oven-dry weight of kiln samples may be highly accurate if it is carefully conducted:

1. Select kiln samples of uniform dimensions and saw 1-inch cross sections (moisture sections) from each end of kiln samples. Measure the length of the sections to the nearest 0.001 inch.

\[\text{Army-Navy Aeronautical Specification AN-W-2a, Wood; Method for Kiln Drying, July 1943.}\]
2. Saw the kiln sample approximately 24 inches long. Be sure all cuts are square. Measure the length to the nearest 0.01 inch.

3. Oven dry the sections at 212 - 221° F. until there is no further loss in weight.

4. Compute the oven-dry weight of the kiln sample as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length along grain of the section from one end</td>
<td>0.997 inch</td>
</tr>
<tr>
<td>Length along grain of the section from the other end</td>
<td>0.996 inch</td>
</tr>
<tr>
<td>Total length along grain</td>
<td>1.993 inch</td>
</tr>
<tr>
<td>Oven-dry weight of one section</td>
<td>46.65 grams</td>
</tr>
<tr>
<td>Oven-dry weight of the other section</td>
<td>48.00 grams</td>
</tr>
<tr>
<td>Total oven-dry weight of sections</td>
<td>94.65 grams</td>
</tr>
</tbody>
</table>

\[
\frac{94.65}{1.993} = 47.49, \text{ the average oven-dry weight per inch of length.}
\]

Length of kiln sample = 24.02 inches.

\[47.49 \times 24.02 = 1140.70, \text{ the oven-dry weight of the sample in grams.}\]

To convert the weight in grams to weight in pounds, divide by 453.59:

\[\frac{1140.7}{453.59} = 2.51 \text{ pounds, the oven-dry weight of the kiln sample.}\]

**Equilibrium Moisture Content and the Equalizing Period**

It has been shown that there is a practical method for accurately determining the actual moisture content values of the kiln samples. It now becomes necessary to find a method for equalizing the moisture content values of the shell and core, as well as the differences between individual boards. It is a well-known fact that if wood is subjected to one temperature and relative humidity condition for a sufficient period of time the wood will take on or give off moisture until eventually the moisture content of the wood is in balance with the stable atmospheric condition surrounding it. This condition is known as the equilibrium moisture content, or abbreviated, the E.M.C. These relationships, for a wide range of temperatures and a variety of relative humidity conditions are shown in figure 5. This chart is useful in establishing satisfactory equalizing conditions.
Assume that a kiln is operating at a dry-bulb temperature of 150° F. and an equilibrium moisture content of 5 percent, and the average moisture content of the lumber is 11 percent, (condition C of figure 1); it is then desirable to establish a condition of an 8 percent equilibrium moisture content in the kiln.

1. Find 8 percent on the vertical axis of figure 5 and 150° F. on the horizontal axis of the chart. The intersection of the lines indicates a wet-bulb depression of 20° or a relative humidity of 57 percent.

2. This is the condition indicated in D of figure 1. If these conditions are held for a sufficient length of time in all parts of the kiln the shell will come to 8 percent moisture content.

3. Due to temperature variations along the length of the kiln as well as the time element required, the 8 percent may not actually be attained in each piece.

4. If the conditions are maintained for a period of 24 hours for each inch of thickness, the equalization from a practical standpoint will have been accomplished.

5. During the equalization period, the core will continue to dry, even though the shell may be picking up moisture, the core being of a higher moisture content than the set equilibrium moisture content condition.

Referring again to figure 3 it is quite obvious that on the basis of the original moisture content determinations an equalization period of 24 hours for the 4/4 stock would have failed to bring all of the samples below an 11 percent moisture content and the final conditioning at an 11 percent equilibrium moisture content would have failed to relieve the stresses in the higher moisture content samples. It was therefore necessary to dry the stock shown in figure 3 for an additional two days at a 5 percent equilibrium moisture content before starting the equalizing treatment.

The equalizing period together with the prior intermediate moisture content determinations will give the following:

1. A full knowledge of the actual conditions of the stock.

2. A reduction of differences in moisture content between the shell and core.

3. A reduction of differences between the moisture content of the various samples.

The Final Conditioning Treatment

If the equalizing period has been successful it is then possible to continue with the final conditioning treatment. Considering again the charge of stock previously described as having attained approximately an 8 percent shell moisture content with an 11 percent maximum core moisture content as illustrated by D in figure 1, the following steps are used:

1. From figure 5 select the maximum allowable temperature of 165° F. with a corresponding relative humidity of 75 percent. This corresponds to the maximum core moisture content of 11 percent.

2. By means of the process previously described, the shell moisture content will be increased and the stresses relieved. (E of fig. 1.)

3. The use of an equilibrium moisture content of less than the maximum core moisture content will fail to relieve the stress. (D of fig. 1 and fig. 6.)

4. The use of an equilibrium moisture content of more than the core moisture content will produce reversal of stress. (D of fig. 1 and fig. 6.)

5. The time required for the conditioning treatment will vary with the thickness of stock, the uniformity of moisture content, and the species being treated. Usually, 7 hours per inch of thickness for softwoods and from 18 to 24 hours for hardwoods will be effective in relieving stress. Tests, however, must be made to determine the adequacy of the treatment.

Figure 6 shows the result of proper and improper conditioning. The center pieces were subjected to the correct equilibrium moisture content during the conditioning treatment. The three pieces on the left show the result of using an equilibrium moisture content that was lower than the core moisture content while the two pieces on the right show the result of conditioning with an equilibrium moisture content higher than the core moisture content.

Figure 7 shows the distribution of shell and core moisture content values of samples representative of a charge of 1-5/8-inch Douglas-fir that was subjected to the equalizing treatments as suggested.

Samples and Test Sections

Because of the close tolerances required by most aircraft specifications it is necessary to cut sufficient casehardening samples to prove the effectiveness of the treatment. Fifty samples per kiln charge are not too many for proper evaluation of the results. These stress sections should be cut as shown in figure 8.
In evaluating the sections for stress it is essential that after cutting the prongs, the sample be brought to a uniform moisture content. As an expedient the kiln operator may place the cut sections in the oven for a short period and then inspect for prong curvature. This is a rather severe test, but it allows a quick decision as to whether or not the particular stock will require further conditioning. Too much reliance, however, should not be placed on one, two, or even three samples.

In this discussion considerable emphasis has been placed on the desirability of obtaining uniform moisture distribution and freedom from stress in each board in the kiln charge. From a practical standpoint it is not always commercially expedient to obtain such perfection because of the difference in drying characteristics of individual boards. For this reason a small percentage of the pieces may show slight casehardening or slight reverse casehardening.

Conclusions

Since the moisture content as obtained by the green weight of the sample may be in error it is highly desirable to obtain more nearly correct moisture content values by using an intermediate moisture determination.

An equalizing period will assist in bringing the lumber to a uniform moisture content. Reasonably uniform moisture content values are necessary before conditioning starts.

For successful conditioning, the equilibrium moisture content conditions must be adjusted to correspond to the moisture content of the thin zone midway between the broad faces of the board, which is about 2 percent above the average moisture content of the stock. To make this adjustment, accurate wet- and dry-bulb control is essential.

An ample number of stress samples must be prepared in a uniform manner to evaluate the results.
Figure 1.--Moisture–stress relationship during six stages of kiln drying.
Figure 2.—Example of moisture distribution commonly found in green western hemlock and noble fir lumber. Shaded areas indicate zones of high moisture content.

Figure 3.—Moisture content values of samples based on original and intermediate determinations of 4/4-inch noble fir aircraft kiln samples.

Figure 4.—Method of saving kiln sample for the purpose of making an intermediate moisture content determination.
Figure 5.—Equilibrium moisture content of wood as a function of dry-bulb temperature and wet-bulb depression.
Figure 6.—Results of proper and improper conditioning of Douglas-fir and western hemlock aircraft lumber.
Figure 7.—Distribution of shell and core moisture content values after equalizing and conditioning treatment of 1-5/8-inch Douglas-fir.

Figure 8.—Method of cutting casehardening sections.