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Title: STRESS AT DEFORMATIONS BEYOND THE ELASTIC LIMIT FOR COMPRESSION PERPENDICULAR TO THE GRAIN IN HEM-FIR

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Allowable stresses in compression perpendicular to the grain (C-perp) have been too conservative for most structural uses. This study develops stress data for deformations beyond the proportional limit (PL), up to 0.1 inch for hem-fir. Fifteen boards from four western states were cut into small specimens representing three ring angle classes (0, 45 and 90 degrees) and one large specimen with varying ring angle. Specimens with ring angle of about 45 degrees were the weakest. Stresses for large specimens and small specimens with 45-degree ring angle were remarkably similar. Stresses in C-perp continually increase beyond PL to at least 0.1 inch deformation

without any noticeable failure. If allowable stresses in C-perp were accepted beyond PL, acceptable deformation would then be the new design specification.

Stress at Deformations Beyond the Elastic Limit for Compression Perpendicular to the Grain in Hem-fir

by

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To my wife Kathy and our children Chris, Colleen, Larry and John for their patient and supportive influence.

To my father, Edward J. McLaughlin Sr., who passed away during this study but who influences me more every day.

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Allowable stresses in C-perp limit its use in glue-laminated (glulam) beams even though its bending properties are acceptable. The large commercial supplies of hem-fir also provide us with considerable stimulation to effectively utilize this resource.

Attempts are constantly being made to improve design procedures and methods of determining the actual strength of a given piece of lumber. Wood structures incorporating load sharing systems and the use of metal joint connectors allow the more efficient use of wood. Machine stress rated lumber gives working stress values for actual boards. Each of these methods helps utilize more effectively our depleting supply of high grade lumber. The method of using PL to determine allowable stresses in C-perp is an example of an overly conservative attitude nurtured by previously abundant lumber supplies. A change in the approach to C-perp would provide greater flexibility in wood structural design and more effective utilization of species.

C-perp has long been known to be unique in its resistance to load. Unlike properties such as bending, tension or shear, C-perp does not cause failure until deformation is far beyond PL. As the material under stress compresses beyond PL, it becomes more resistant to additional compression. Present allowable stresses, however, continue to be limited to PL at its respective low level of deformation.

Differences in compression resistance at various growth ring angles to the load has also been known. Angles of 0, 45, and 90 degrees to the load have been established as having significant differences in strength. Specimens with growth ring angles at 45 degrees with the load are weakest. However, the American Society for Testing and Materials (ASTM) recommends the standard test for C-perp be done with small clear specimens at 0-degree ring angle, which is the strongest ring angle.

In recent years the use of small clear test specimens to establish design values for the larger more variable boards found in everyday use has come under considerable question. In C-perp small vertical-grained specimens are tested to determine allowable stresses for all sizes of lumber.

The purpose of this study was to provide compression stress data at deformations beyond the elastic limit. Load-deformation curves were developed for the three major ring angle classes. Smaller specimens were compared to larger specimens to study the effects of combinations of ring angles in larger specimens. Attempts were also made to find a small specimen predictor of large specimen behavior. Characteristic curves were developed for small and large specimens from hem-fir lumber collected from four western states.

BACKGROUND

Structure of Wood

Structural design with wood is basically the same as with concrete or steel with the major difference being in wood's anisotropic nature. Wood shows different properties when stressed along axes in different directions. The cells of wood make up a highly complex structural system that account for this variability. Figure 1 illustrates this system.

Annual rings layered around the tree vary in density from springwood to summerwood. This major variation plus the complex cellular differences along three axes, tangential, radial and longitudinal, account for a large portion of the variation in strength properties. Ray cells and summerwood add stiffness to wood perpendicular to the grain. The length of fibers along the grain add stiffness parallel to the grain. The focus of this paper concerns compression loads imposed perpendicular to the grain (on the tangential or radial face).

Summerwood layers and ray cells are normally perpendicular to each other. They act much as columns as long as the load is applied axially to them. When loads are applied at 45° these columns have less resistance. Figure 2 simulates these three loading situations as laterally supported columnar structures. The angle of the summerwood columns to the load will later be referred to as ring angle.

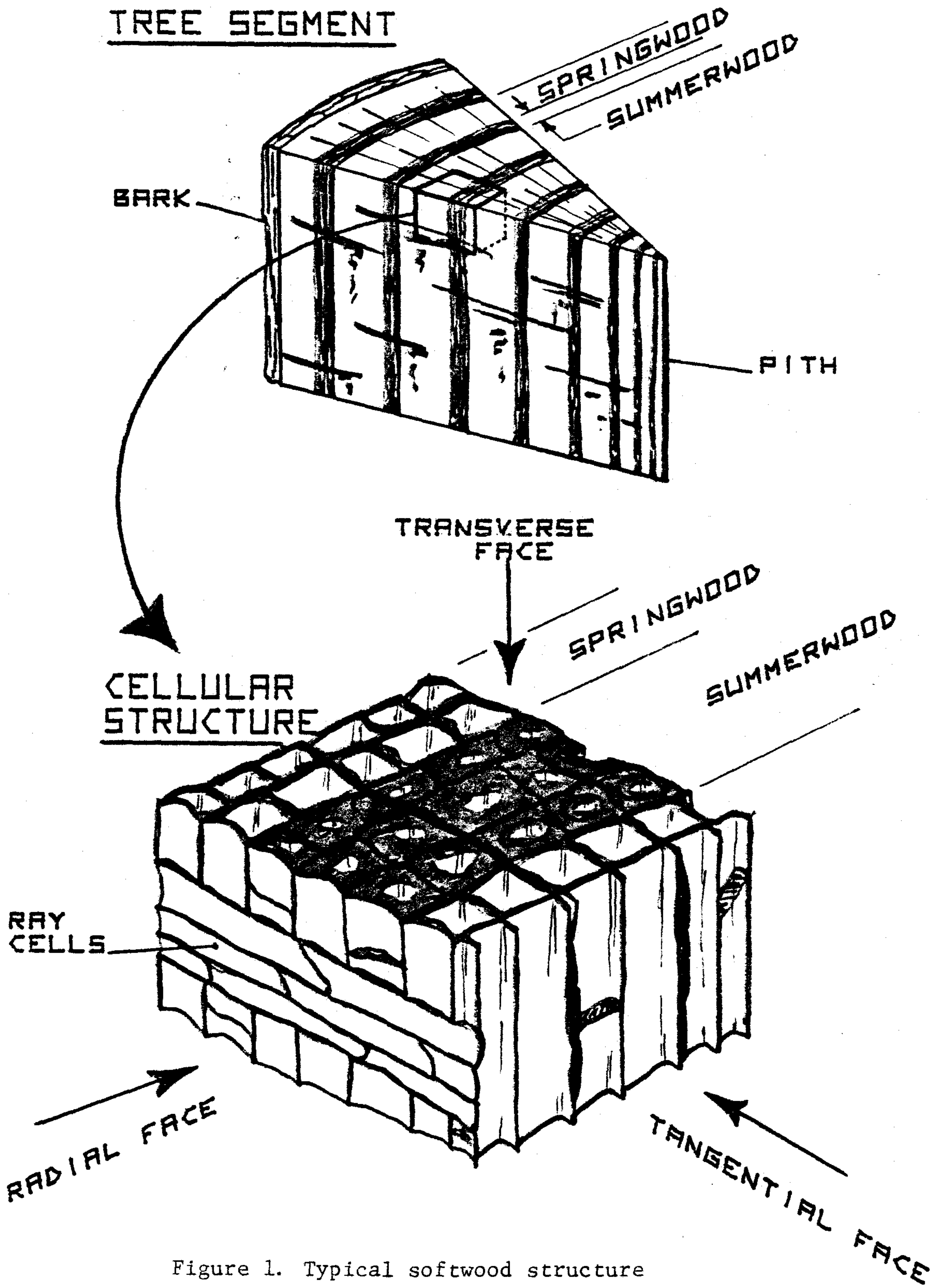

Figure 1. Typical softwood structure

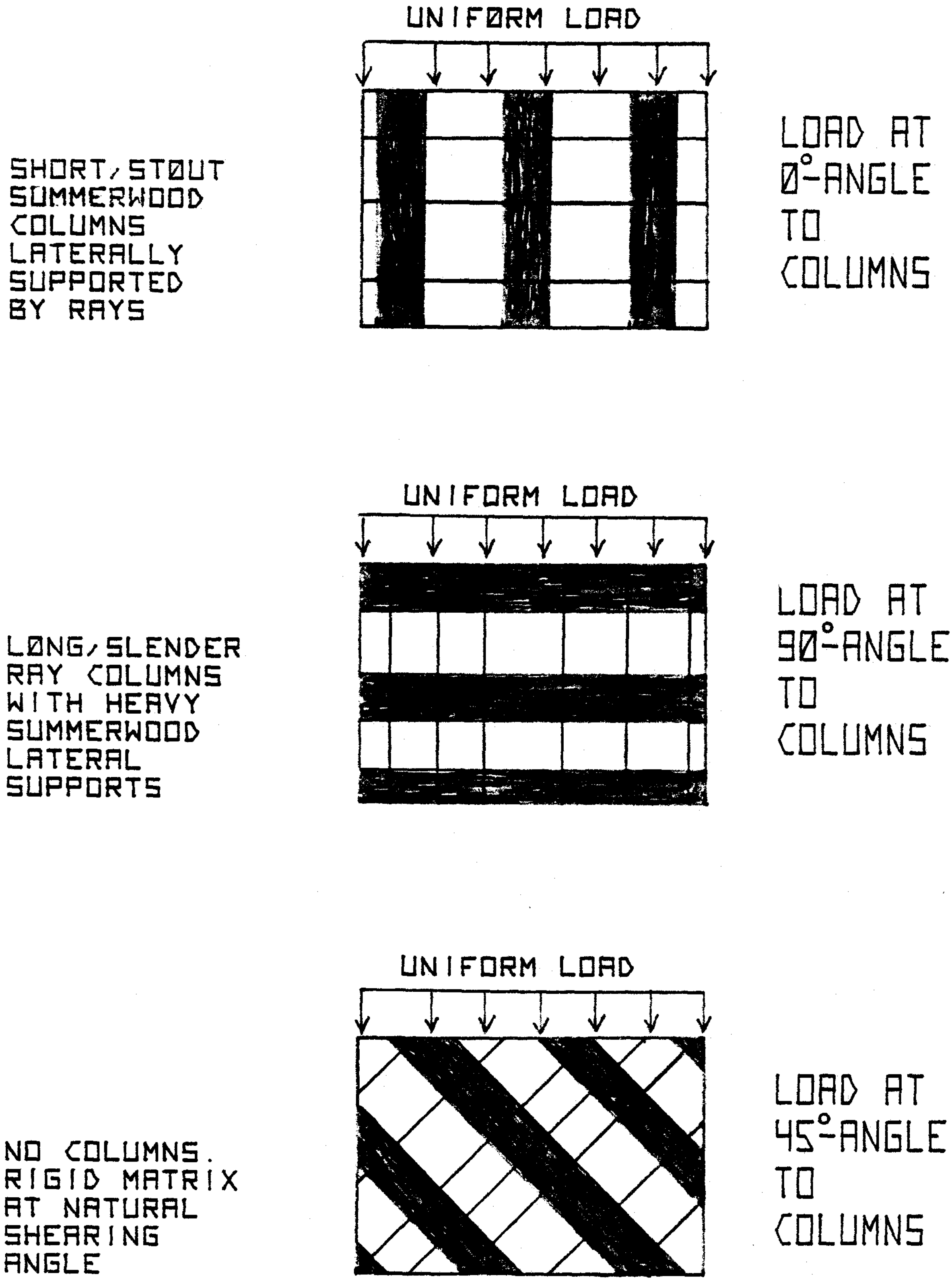

Figure 2. Structural simulation of three ring angle orientations

Terminology

The following is an explanation of terms used in this paper:

The first six definitions refer to Figure 3.

Stress is the load applied per square unit of area or pounds per square inch (psi). It is either actual or allowable.

Deformation is the distance a load moves into the specimen in inches (in.) or the amount of collapse perpetrated by the load. It, too, is either actual or allowable.

The Elastic region is the linear portion of the load-deformation curve up to the proportional limit. Theoretically, up to PL, the wood will recover its original dimension upon removal of the load.

The Proportional (PL) or Elastic limit (EL) is the point at which the load-deformation curve becomes non-linear. It is the highest load at which a specimen retains its elastic properties.

The Inelastic region is any portion of the load-deformation curve beyond PL. Wood can no longer recover its original dimension beyond PL.

Max refers throughout this paper to the stress at 0.1 inch deformation or the completion of the test.

Hem-fir is a commercial combination of species generally marketed as a group which includes Western Hemlock [*Tsuga heterophylla* (Raf.) Sarg.], White fir (*Abies concolor* Gord. and Glend.), Pacific silver fir [*Abies amabilis* (Dougl.) Forbes], Grand fir (*Abies grandis* Dougl.), California red fir (*Abies magnifica* A. Murr.), Noble fir (*Abies procera* Rehd.).

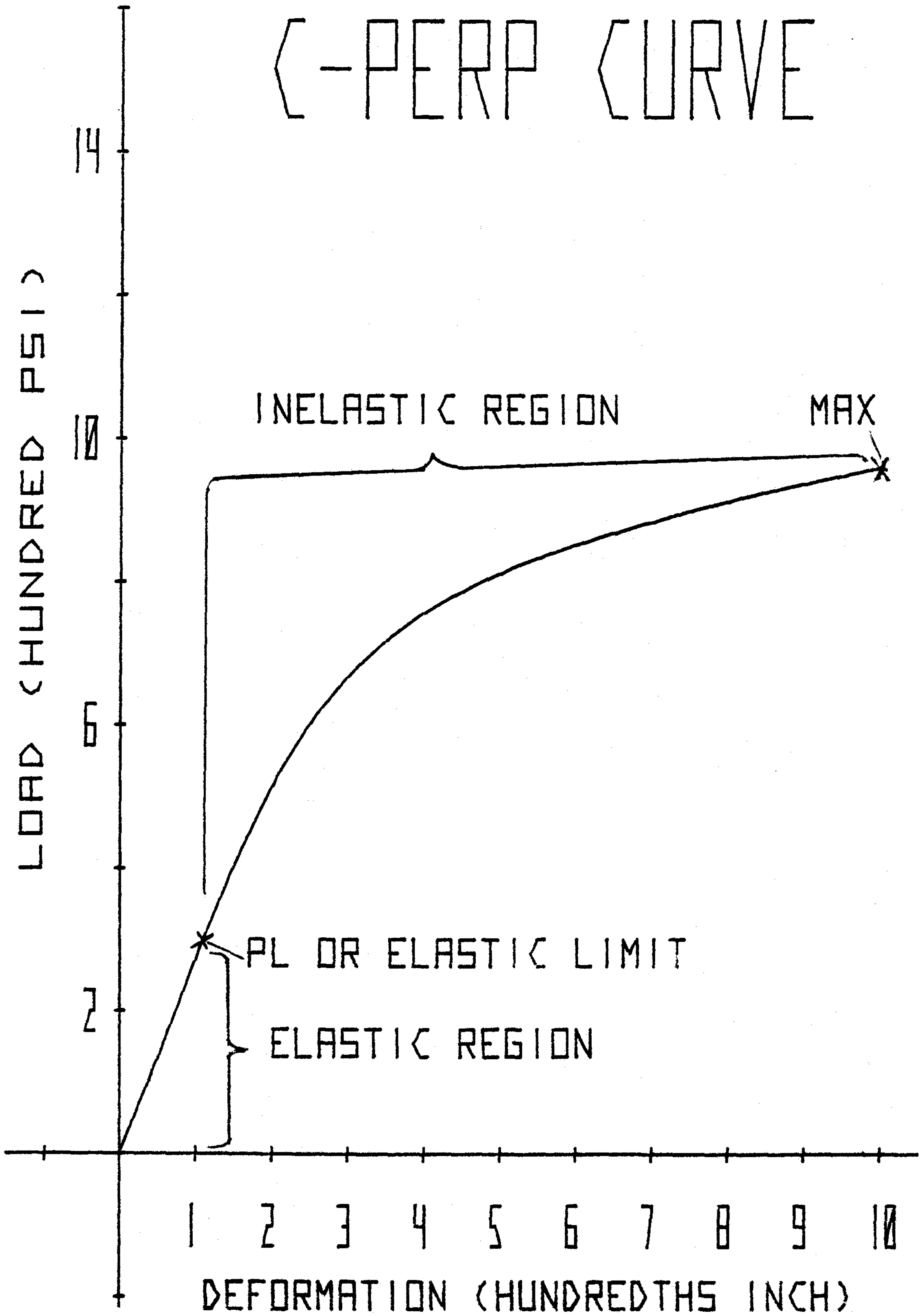

Figure 3. Typical load-deformation curve

Ring angle is the angle formed between the load and the annual growth rings in the specimen. Figure 4 describes this angle for the three classes chosen for study.

Vertical Grain (Figure 4a) is often used to describe specimens with 0° ring angles. To avoid confusion the term 0°-angle will be used throughout this paper to describe the class (0°-22°) of specimens or groups of specimens with 0° ring angle configuration.

Flat Grain (Figure 4c) is often used to describe specimens with 90° ring angles. The term 90°-angle will be used throughout this paper to describe the class (68°-90°) of specimens or groups of specimens with 90° ring angle configurations.

The term 45°-angle (Figure 4b) is used in this paper to describe the class (23°-67°) of specimens or groups of specimens with 45° ring angle configurations.

The term curve prefixed by 45°-angle, 0°-angle or 90°-angle describes a representative curve for the specified group.

The 5% exclusion limit says that 95% of a sample of boards equal or exceed that specified level of strength. ASTM standard D2915 section 5.4.4. (2) describes the method for establishing this limit. The 5% exclusion limit is represented by the specimen at that level.

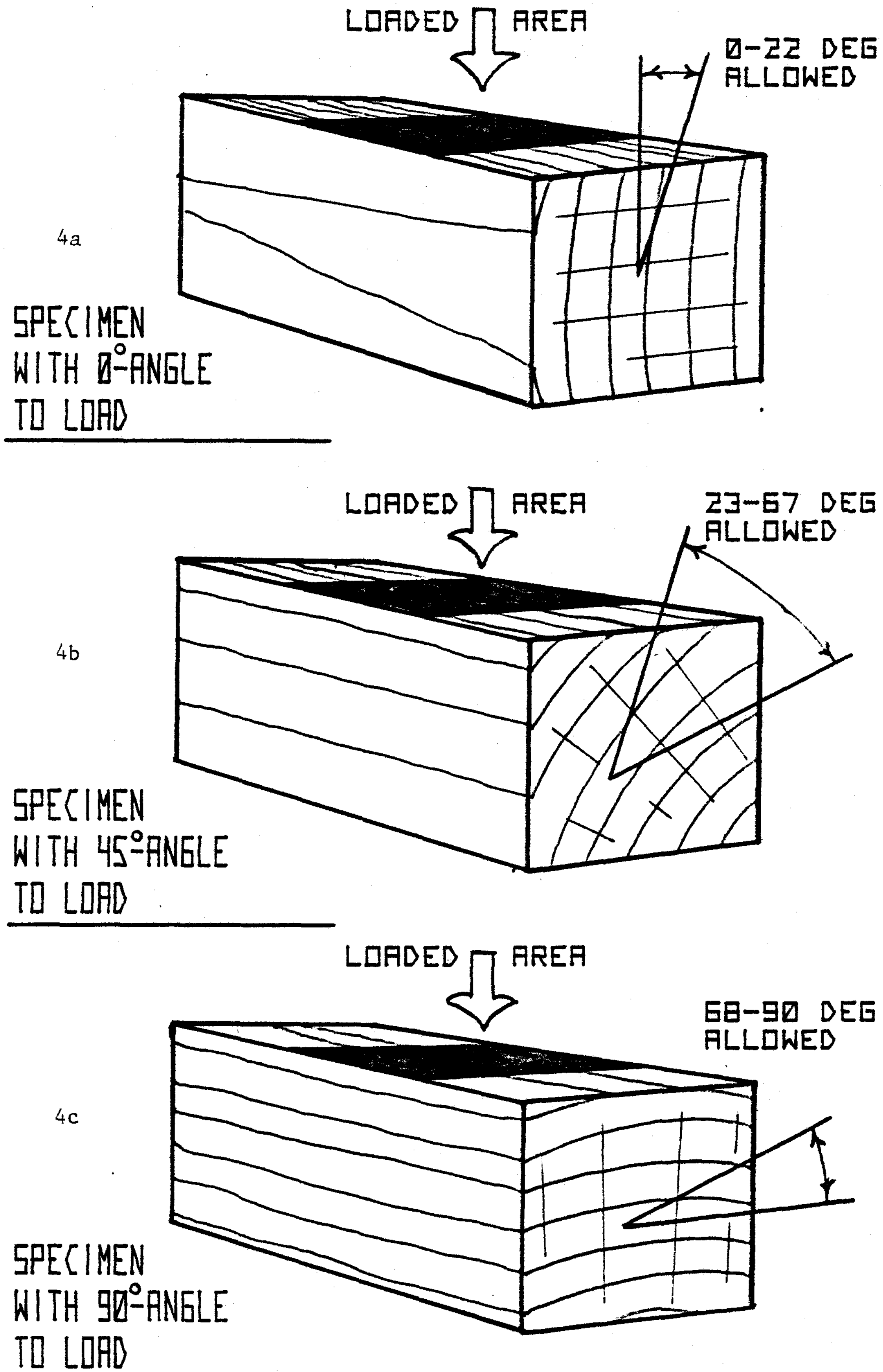

Figure 4. Description of small specimens

LITERATURE SURVEY

Past research points to several factors as prominent in affecting C-perp. The majority of this work reports its data as stress at PL. Although testing by the ASTM standard D143 (1) is taken to 0.1 inch deformation, this was done simply to assure the inclusion of PL in the test results.

Bodig (5) investigated correlations between C-perp stress at PL and mechanically rated modulus of elasticity. He found no significant correlation but recommended that values now in use be slightly increased.

Kunesh (10) found the effects of moisture content, size, thickness and species highly significant. His study was limited to the 90°-angle class. Kunesh also isolated another point besides PL as being highly significant. He called this the first load inflection point, which is the first point at which the load-deformation curve decreases momentarily.

Kennedy in Canada (9) studied the effects of ring angle and specific gravity (SG) in nine wood species on C-perp and modulus of elasticity. He found both mechanical properties at PL to be significantly influenced by both SG and ring angle.

Wynand (12) compared deformations in Canadian Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco.] and hem-fir and Southern pine. He recommended that hem-fir design values at PL be increased from 51% to 90% of values for Douglas-fir.

Hofstrand (7) investigated ring angle, moisture content and rate of growth in Inland-Douglas fir. He found that C-perp at PL increased with decreased moisture content. Modulus of elasticity in C-perp decreased with an increase in the number of growth rings per inch. C-perp at PL also decreased from a maximum at 0°-angle and 90°-angle to a minimum at 45°-angle.

Most recently Fergus (6) and Nall (11) stated that types of loading and joint types have significant effects on Pacific Silver Fir, Sub-alpine Fir [Abies lasiocarpa (Hook.) Nutt.] and Lodgepole Pine (Pinus contorta Dougl.) in light frame construction.

Johnson and McLaughlin (8) tested C-perp in hem-fir for the American Institute of Timber Construction (AITC) in 1977. They also observed 45°-angle as the weakest. They reported results only at the proportional limit. This was also true with the other research previously cited, except Fergus (6) and Nall (11) who reported data to 0.1 inch deformation.

In 1978 Bendtsen, Haskell and Galligan (3) reported on the recent attempts at the U.S. Forest Products Laboratory (USFPL) at Madison, Wisconsin to convert old data into new stress-compression data by developing curves from data points over a range of deformations. The range of deformation reflected the standard ASTM (D143) test (1). The USFPL has no immediate plans to obtain new data, especially for lumber intended for use in glulam construction. In 1979 Bendtsen and Galligan (4) reported their most recent attempts to model the stress-compression relationships using these same data. Fergus (6) and the

USFPL reports (3, 4) both included data beyond the elastic limit at 0.005-inch intervals up to 0.1 inch maximum. Fergus's data represents newly acquired data were the USFPL data were gathered previous to 1949.

Through all of this research there appear several common conclusions. Moisture content, specific gravity and ring angle are the most significant factors affecting C-perp. Since ranges of moisture content and specific gravity are commonly under control in structural lumber, ring angle is a source of high variability. Several questions remain concerning information beyond the elastic limit for these ring angles. What are the characteristics of these load-deformation curves? What is the comparison of strength between a large specimen with combinations of ring angles and small specimens with ring angles of approximately 0, 45 and 90 degrees? Is the ring angle used in the ASTM standard test (1) meaningful? These questions as they relate to hem-fir are the basis for this study.

PROCEDURE

Variation from ASTM Standard

The American Society for Testing and Materials has developed standards for testing in an attempt to make results from various tests comparable. However, an ASTM task group on C-perp is currently laying groundwork for implementing new procedures. Variations from the ASTM standard employed in this study were necessary by experimental design. Literature (4) indicates several of these variations may be incorporated in the new procedures.

The ASTM standard calls for vertical-grained 2-inch by 2-inch by 6-inch specimens. It also limits the reporting of results to stresses at PL. However, the test is to be carried to 0.1 inch deformation to insure the inclusion of PL.

This study used 1 1/2-inch by 1 1/2-inch specimens to simplify collection of boards, since nominal 2-inch lumber is 1 1/2-inches thick. Vertical-grained specimens (0°-angle) were used for comparison of ring angle, but 45°-angle specimens were the focus of analyses since they are the weakest in C-perp.

Results are reported at PL, but it is necessary to report beyond PL if deformations beyond about 0.02 inch are permitted by the new ASTM procedures. Since 0.1-inch deformation was a limit set by the present standard, I performed a side study to determine if tests should be carried to greater deformations.

Seventy-two small specimens of random ring angle were tested to 0.2 inch deformation. Failures in shear were observed in nearly every specimen between deformations of 0.15 and 0.2 inch. Although C-perp stresses continued to increase with increased deformation, this shearing could not be ignored. The potential damage to a real structure would be realized through changes in bending strengths caused by shear. Therefore, I used 0.1 inch as a deformation limit in C-perp for this study.

Sample Preparation

Fifteen hem-fir boards were collected from each of four states; Oregon, Washington, California and Idaho. AITC personnel selected boards that had a range of specific gravities acceptable for glulam use. They were kiln-dried and surfaced of nominal 2- by 6- or 2- by 8-inch lumber.

Three small specimens, 1 1/2- by 1 1/2- by 6-inches, and one large specimen, 1 1/2- by 5 1/2- by 12-inches, were cut from each board. The total number of specimens was 240. The three small specimens were selected to fill ring angle classifications of 0, 45 and 90° (Figure 5). Ring angle classes included 0 to 22°, 23 to 67° and 68 to 90°, respectively (Figure 4). The large specimen had the combination of ring angles present in the original board. Table 4 (Appendix) describes these ring angles. Natural ring angle patterns made it necessary to cut either 0°-angle or 90°-angle small specimens from the same board and turn one 90 degrees at the time of testing to

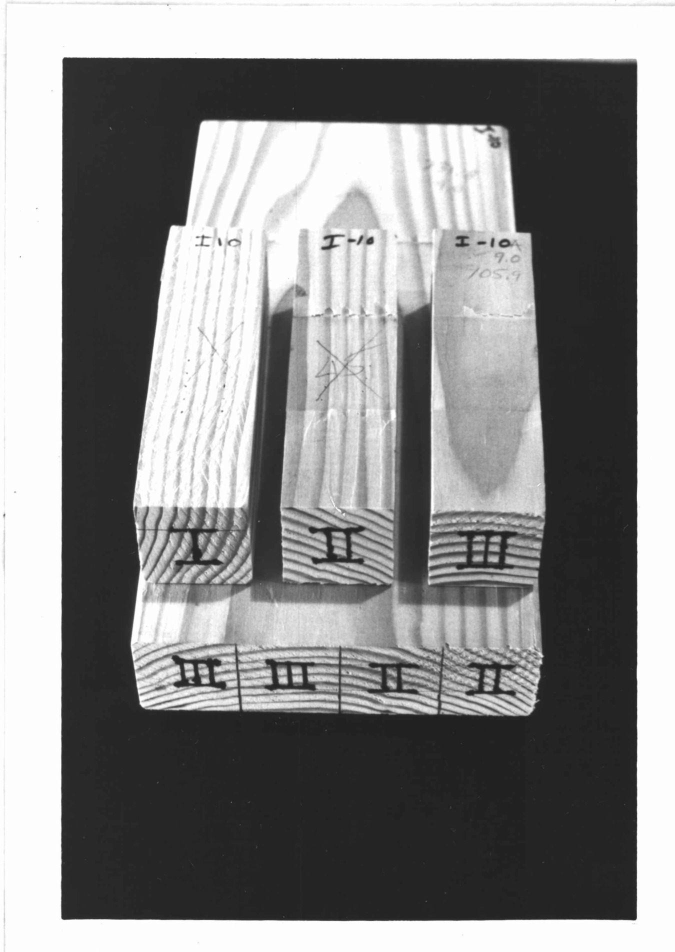

Figure 5. Photo of all specimens cut from a board

give one piece in the 0°-angle class and one in the 90°-angle class from each board.

The specimens were placed in a standard conditioning room for several months to equalize and maintain a moisture content of 8-12%. A schematic diagram of the experimental design appears in Figure 6.

Testing

Moisture content, length, width, depth, weight and average ring angle of each specimen were measured. Specific gravity was calculated later. The ring angle under the load was estimated as the average of the two end cross sections. The angle of the cross section in the small specimens was relatively constant through the length of the specimen. The large specimens were divided as in Figure 5 into four cross sections simulating glued-up small specimens. The angle in each division was measured to form a profile of angles. This profile of the large specimens would later allow a direct comparison to the small specimens.

The small and large specimens were loaded over areas of 1 1/2- by 2-inches and 5 1/2- by 5 1/2-inches, respectively, with load centered on the length of the specimen. Load-deformation curves were generated for each specimen to a maximum of 0.1 inch deflection. Other than the size of the specimens and the different ring angles to be studied, test procedures followed the ASTM standard test (1), which is a test of 2- by 2-inch specimens loaded on the radial face.

The test set up (Figures 7 and 8) included a Tinius Olsen 60,000 pound test machine and a Tinius Olsen deflectometer that converted the

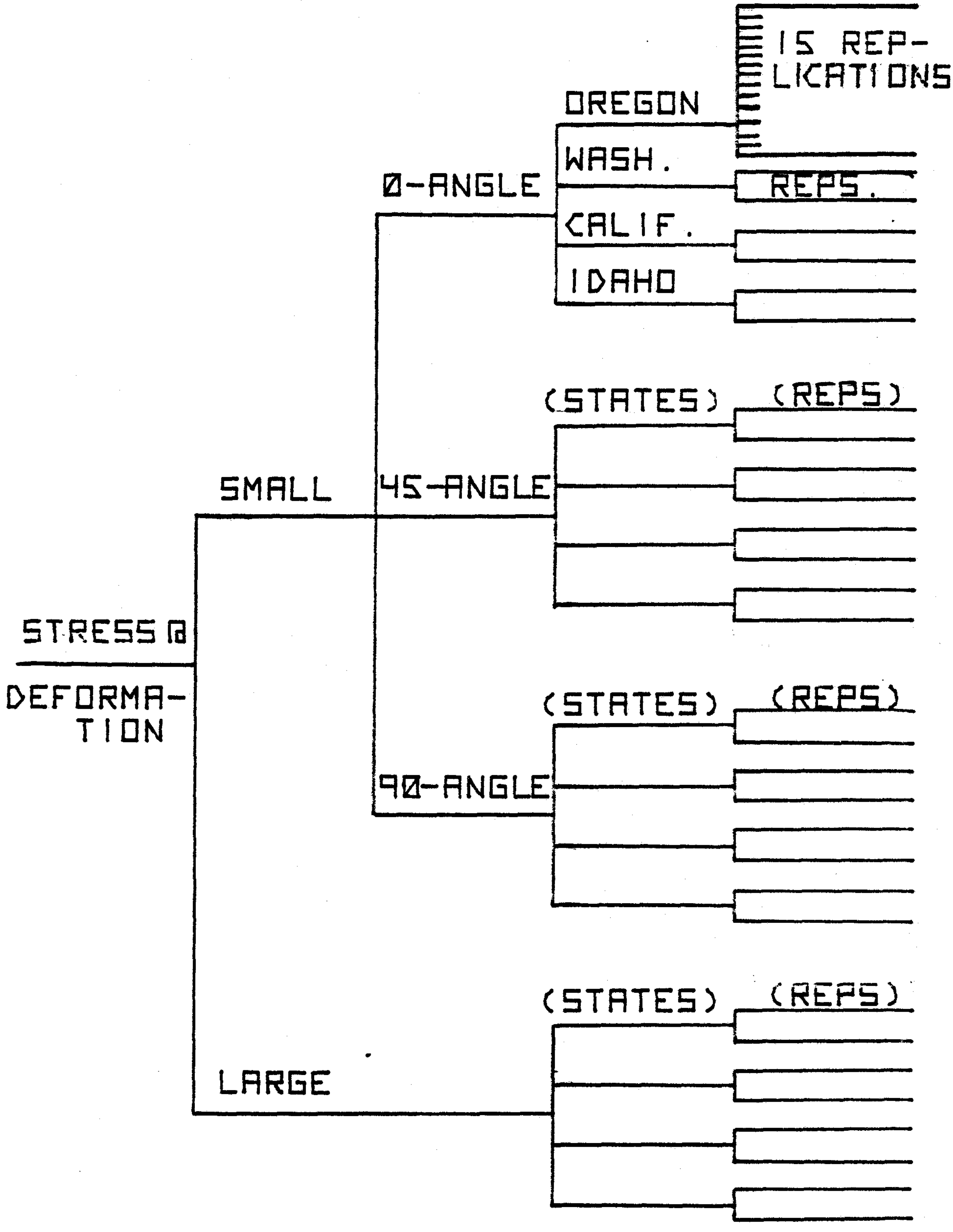

Figure 6. Schematic diagram of experimental design

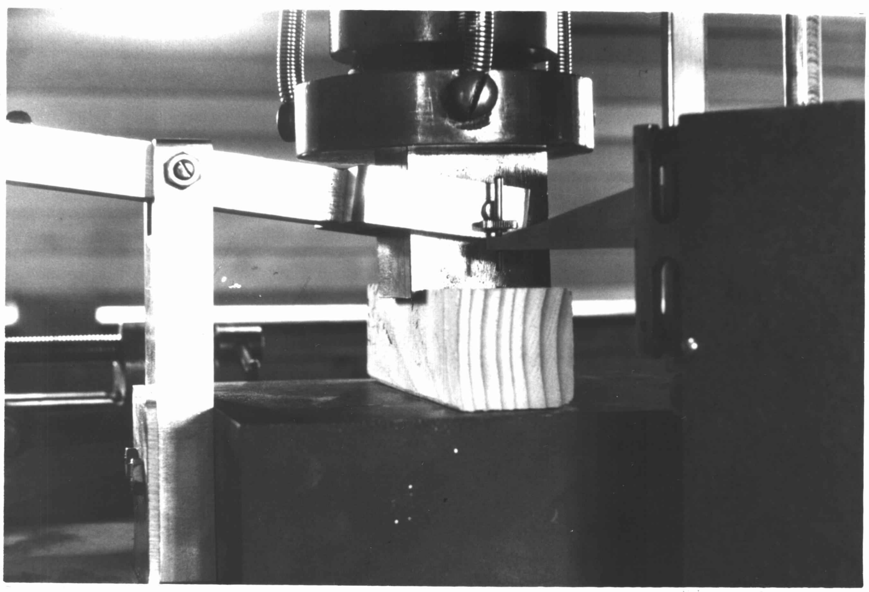

Figure 7. Close-up of test setup

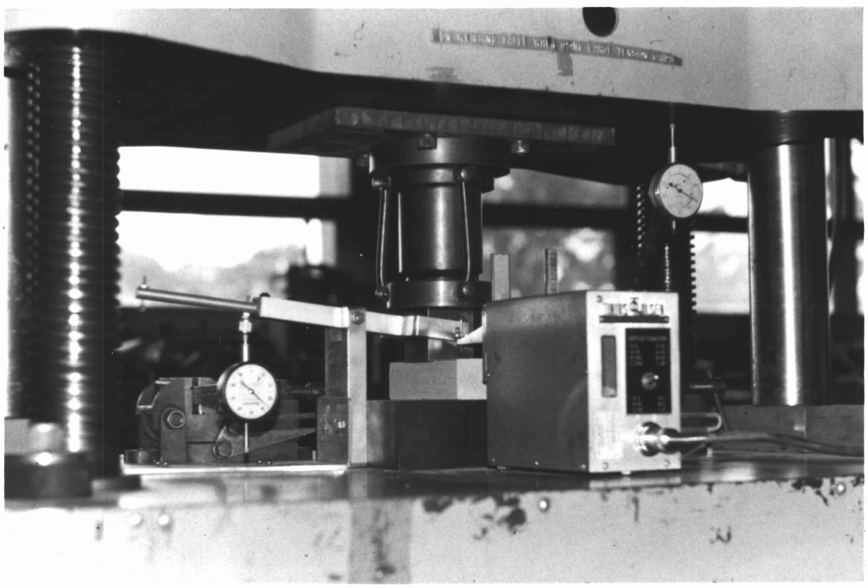

Figure 8. Complete test setup

deflections to the X axis of an XY chart recorder. Load was converted to the Y axis of the same recorder by the weighing table of the testing machine. Load ranges on the testing machine were selected as a result of pretesting for maximum readability. The load was applied through a floating head onto averaging type compressometers devised specifically for the tests of the two sample sizes. The rate of motion of the movable crosshead was 0.012 in./min. ± .003 in./min., according to standard ASTM procedure.

The dial gauges shown in Figure 8 were used to test the set-up for slack. One gauge measured the movement of the crosshead and the other used a lever arm to check the actual deformation being measured by the deflectometer. It was noted that a difference of 0.006 inch existed between the crosshead and the specimen measurements. This slack usually occurred at the very beginning of the test and was attributed to compression in the swivel head and take up of slack in the general apparatus.

Analyses

Proportional limits for each specimen were determined by noting the point at which the initial linear part of the load-deformation curve became non-linear. A device using a piece of thin transparent acetate with two parallel lines inscribed was devised to identify PL. Figure 9 illustrates this process.

Although the initial portion of the test is theoretically a linear relationship, it is often curved because of startup factors such as

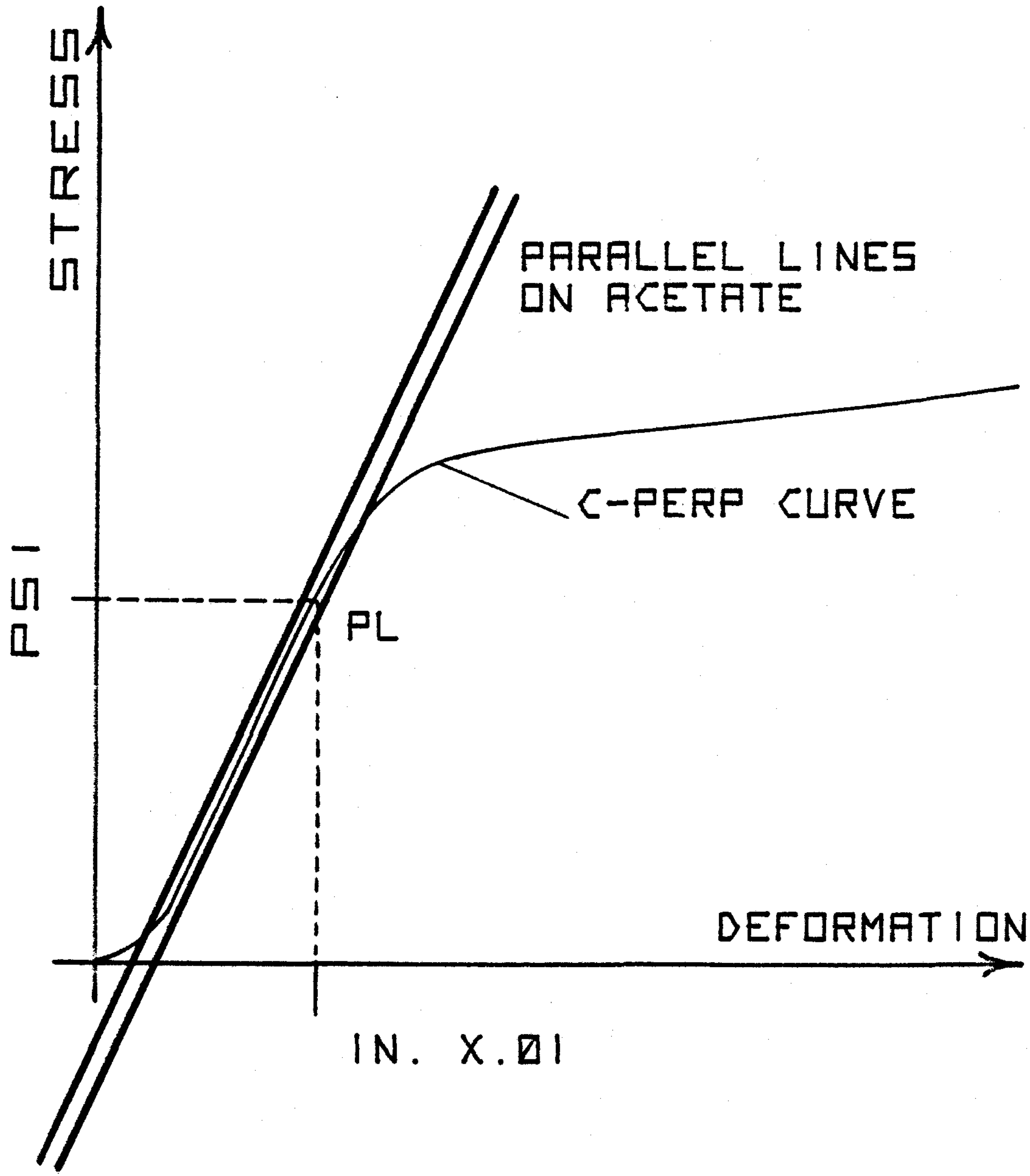

Figure 9. Selecting proportional limits

machine drag, quality of the specimen surface, and apparatus slack. The origin can be corrected by extending the linear portion of the curve back to the X axis, creating a new corrected origin (Figure 10).

The load-deformation curves were then digitized at 0.005-inch intervals of deformation. This was done with a Hewlett-Packard data acquisition system. A program was written to convert loads to stress in pounds per square inch (psi) by dividing the load by the loaded area for each individual sample. The program calculated specific gravities and categorized data by ring angle for later analysis. The general formula for specific gravity is:

$$SG = \frac{\text{oven dry weight of wood}}{\text{weight of displaced volume of } H_2O}$$

Oven dry weight (O.D.) was calculated by the formula:

$$O.D. = \frac{\text{wet weight of wood}}{\text{moisture content} + 1}$$

Moisture content, wet weight and volume were measured at the time of testing. Moisture content was measured with a moisture meter. The weight of displaced volume of water was calculated by multiplying the volume of the specimen by the density of water.

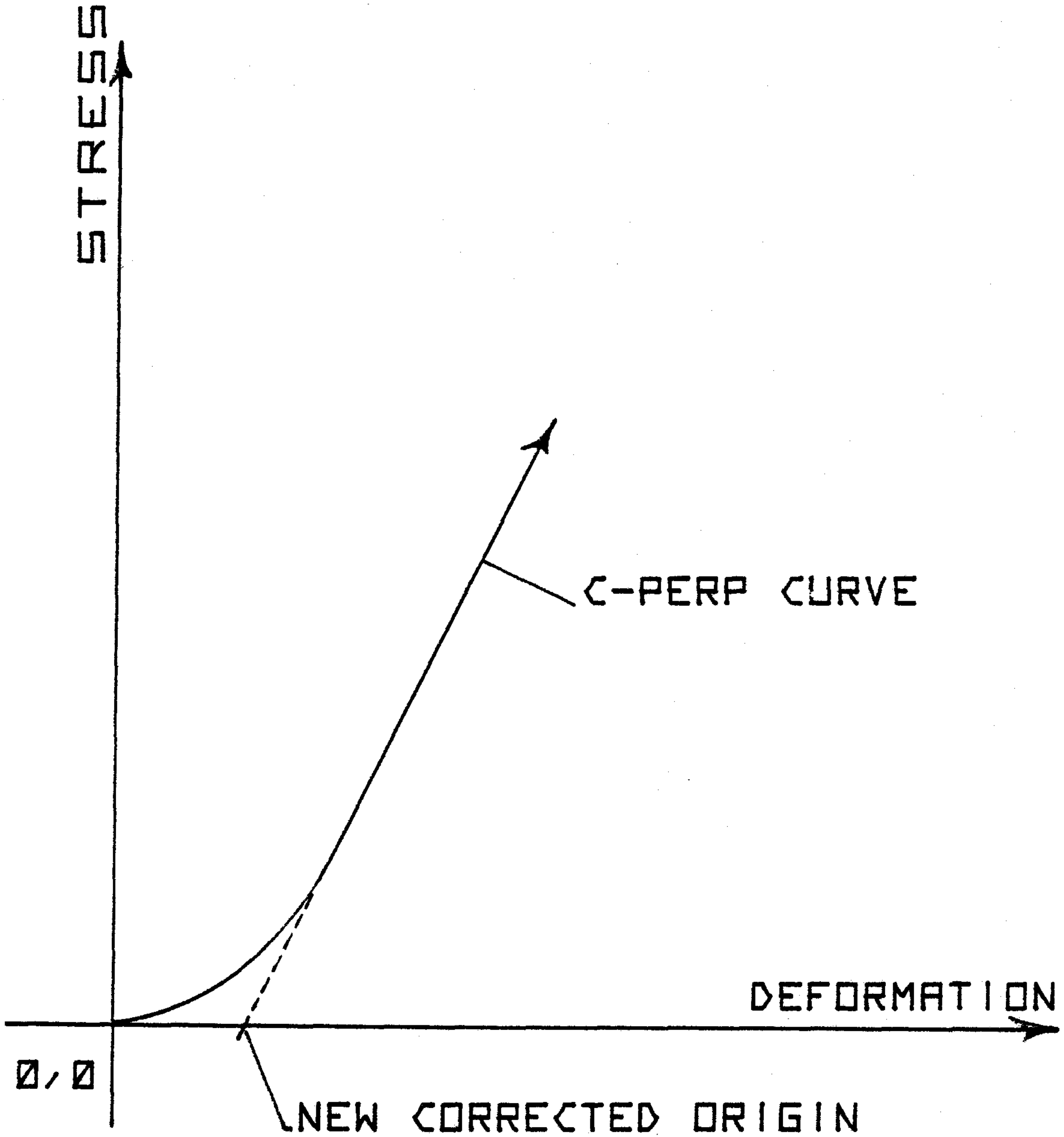

Figure 10. Correcting the origin

RESULTS AND DISCUSSION

Table 5 in the Pocket presents the stress-deformation data for individual specimens. Stress values are given for PL, 0.04-inch and max deformation. Specific gravity, moisture content (MC), ring angle and deformation at PL are also given. One can readily see the MC's were in the range of the experimental design, 8-12%. Specific gravities varied considerably, but were limited by the selection process.

Stress-deformation curves representing values for average and the 5% exclusion limit are included in the text for a more complete understanding of data among tabled values in the appendix. Typical examples of the variation about PL and max can be found in Figures 11 and 12. These histograms are for the 45°-angle specimens. The 5% exclusion limit for stress at PL falls at 297 psi for this group. The range of stresses above the exclusion limit includes quantities over three times the 297 psi allowable level. Figure 12 shows a similar distribution of stresses at maximum deformation. The exclusion limits and means of these distributions over the range of testing are described as curves in Figure 15.

Curves in Figure 13 graphically show differences in means for size and ring angle class. Large specimens and 45°-angle small specimens appear to have relatively similar load-deformation relationships.

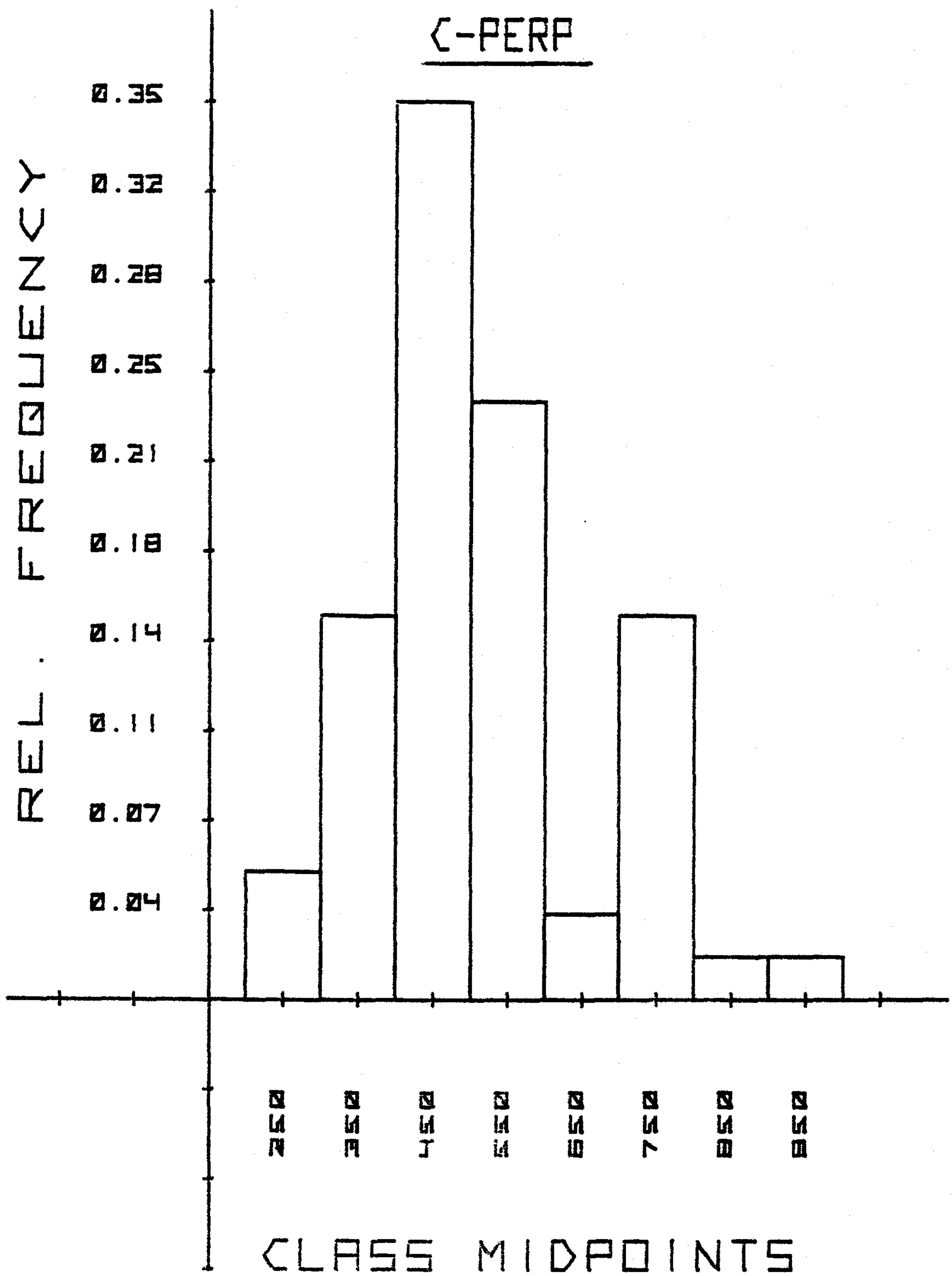

Figure 11. Relative frequency histogram of stress at PL for 45°-angle class of hem-fir lumber

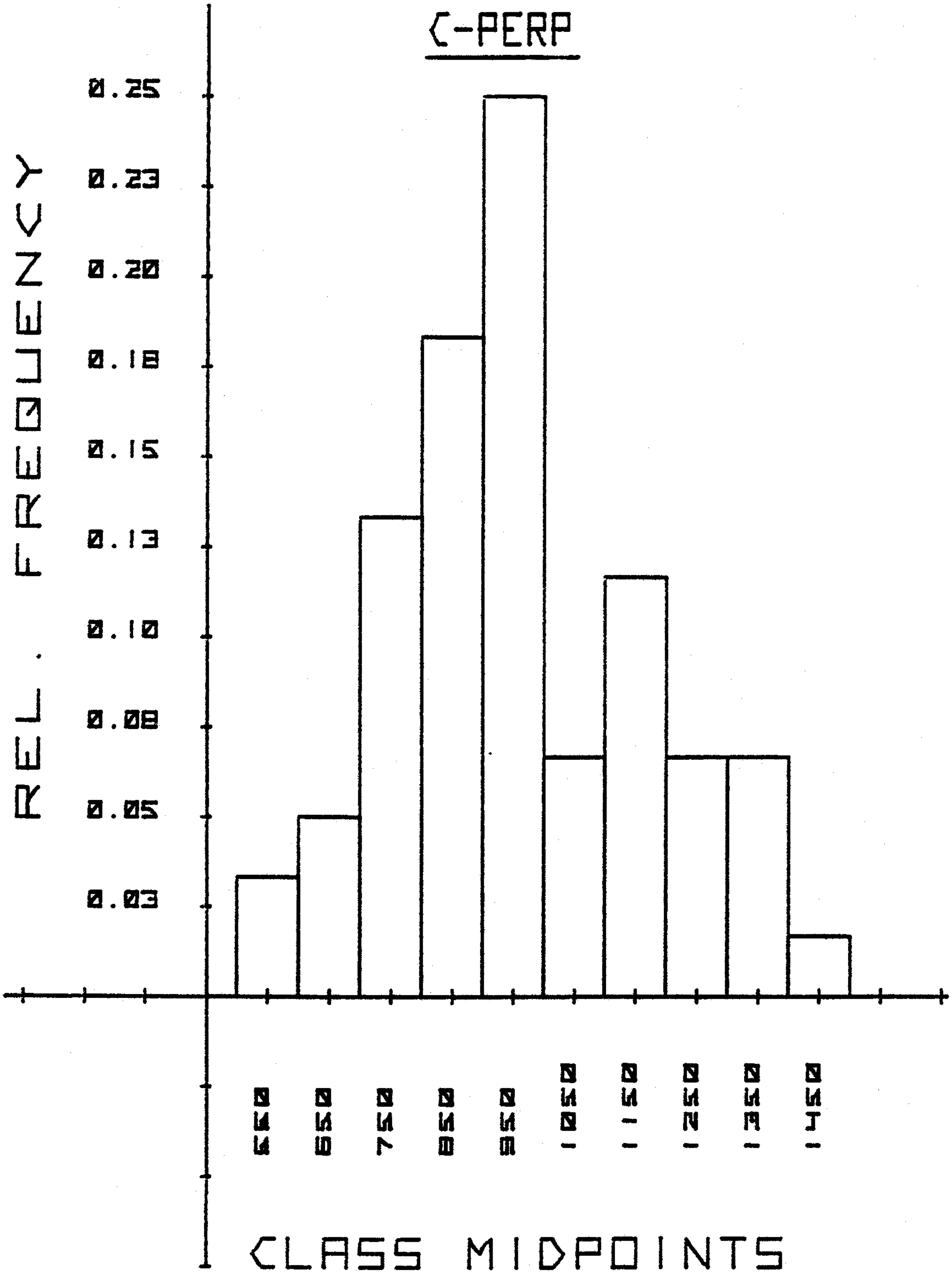

Figure 12. Relative frequency histogram of stress at Max for 45°-angle class of hem-fir lumber

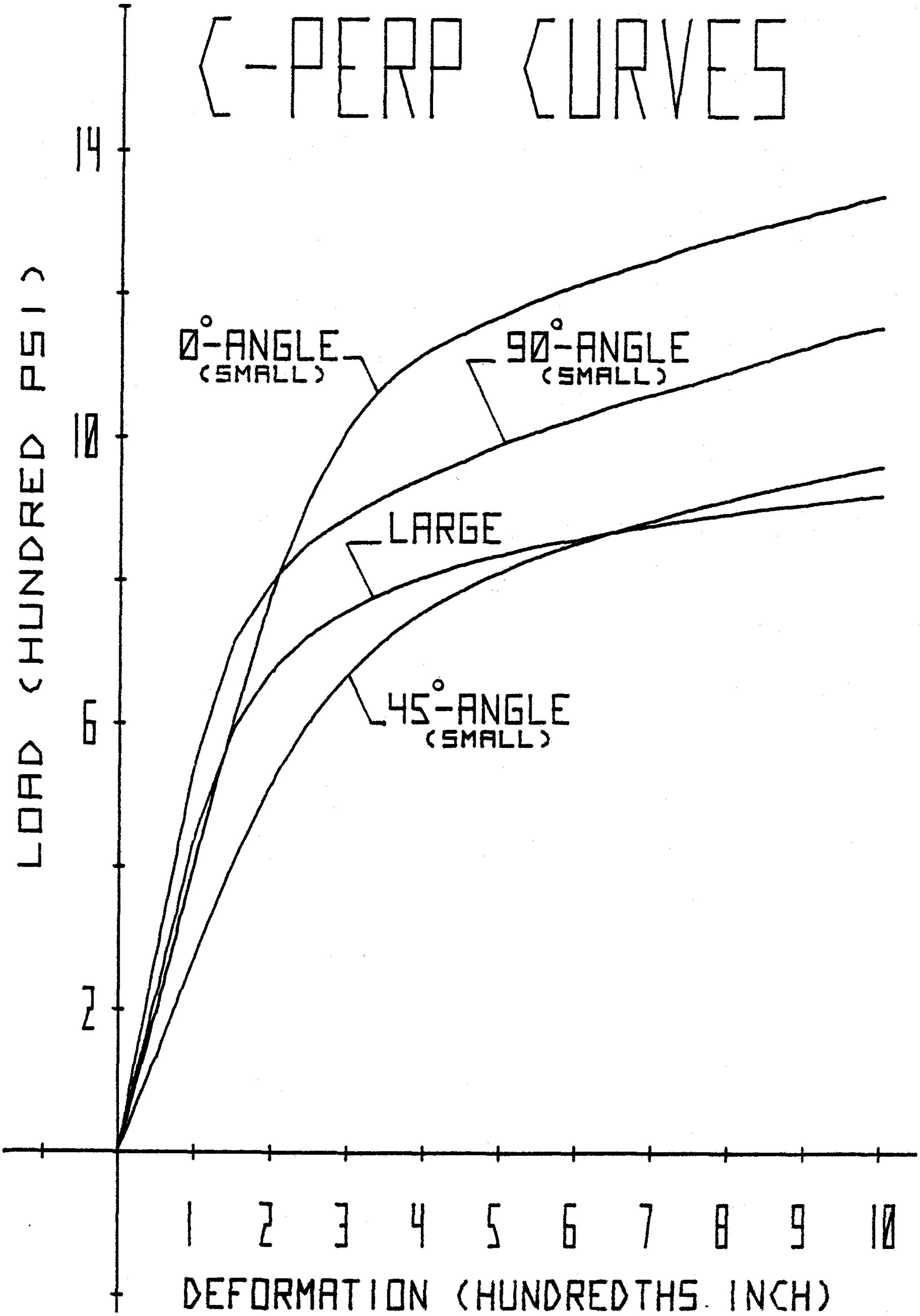

Figure 13. Family of mean curves for large and small specimens from hem-fir lumber

Small Specimens

Significant differences were found between classes of ring angle at deformations beyond 0.04 inch deformation. Figures 14 through 16 show curves for the mean and 5% exclusion limit for each ring angle class. The 0°-angle class has the highest PL of 814 psi at a deformation of 0.021-inch. The 90°-angle class follows with 670 psi at a deformation of 0.013-inch. The 45°-angle class has the lowest PL with 516 psi at a deformation of 0.020-inch. Maximum loads at 0.1-inch deformation are correspondingly higher at 1,337, 1,154 and 960 psi respectively.

Beyond the PL and prior to reaching 0.04-inch deformation, the stress-deformation relationship becomes curvilinear. After 0.04-inch the average relationship appears to be linear again for all three ring angles. Stresses for the 0, 90 and 45 degree specimens are 1,119, 945 and 750 psi respectively for 0.04-inch deformation. Curves for all three ring angles are not only linear but parallel from 0.04 to 0.10 inch (Figure 13).

What are the real strength differences between ring angles? Proportional limit values vary considerably. The modulus of elasticity (MOE) in C-perp also varies considerably. MOE is the relationship of change in stress to the change in deformation. Essentially MOE is the slope of the curve in the elastic region. Just beyond PL there is a settling region that is curvilinear up to approximately 0.04-inch deformation. Beyond this curvilinear region we experience another relatively straight line portion with similar slopes.

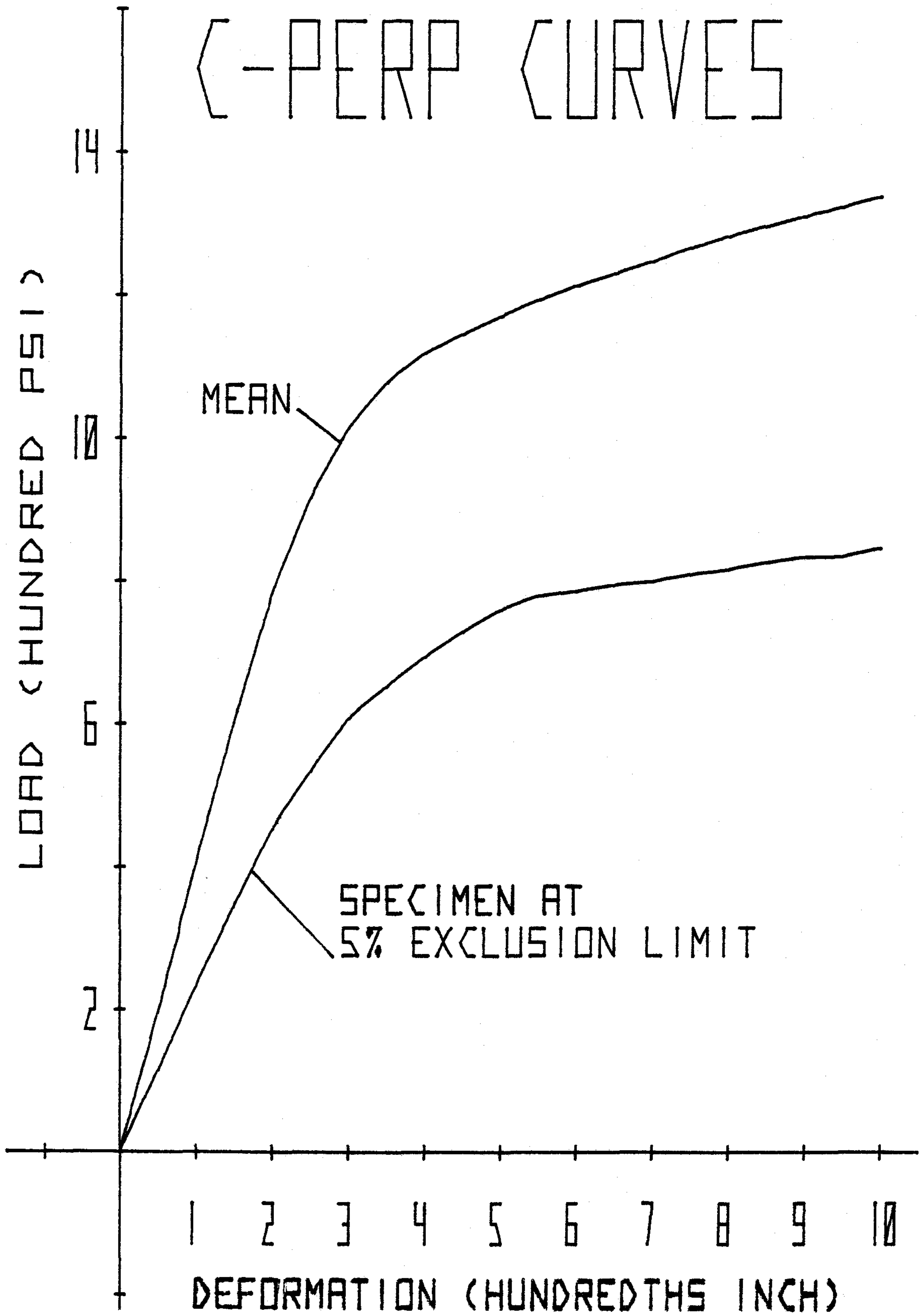

Figure 14. Curves for 0°-angle specimens of hem-fir

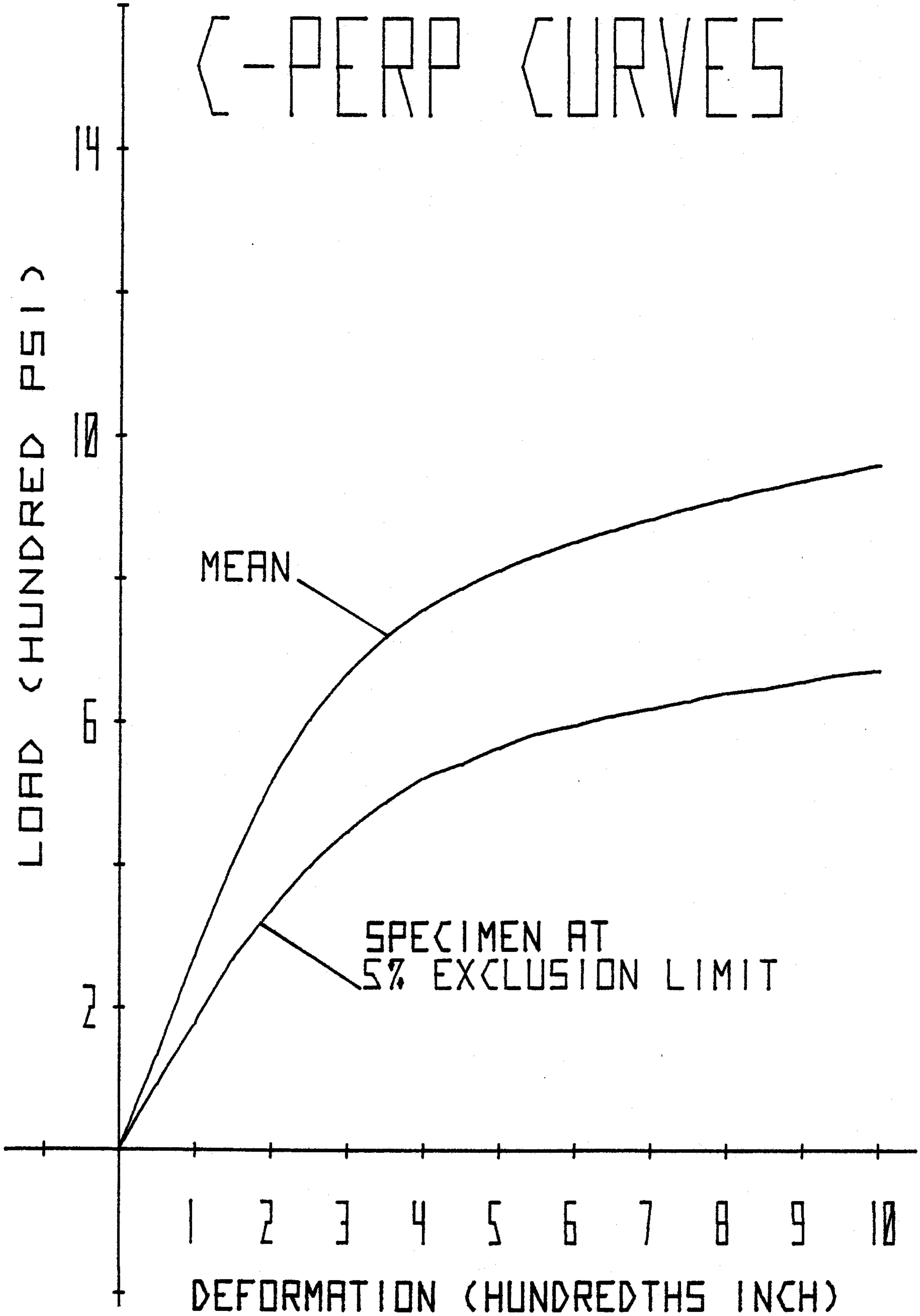

Figure 15. Curves for 45°-angle specimens of hem-fir

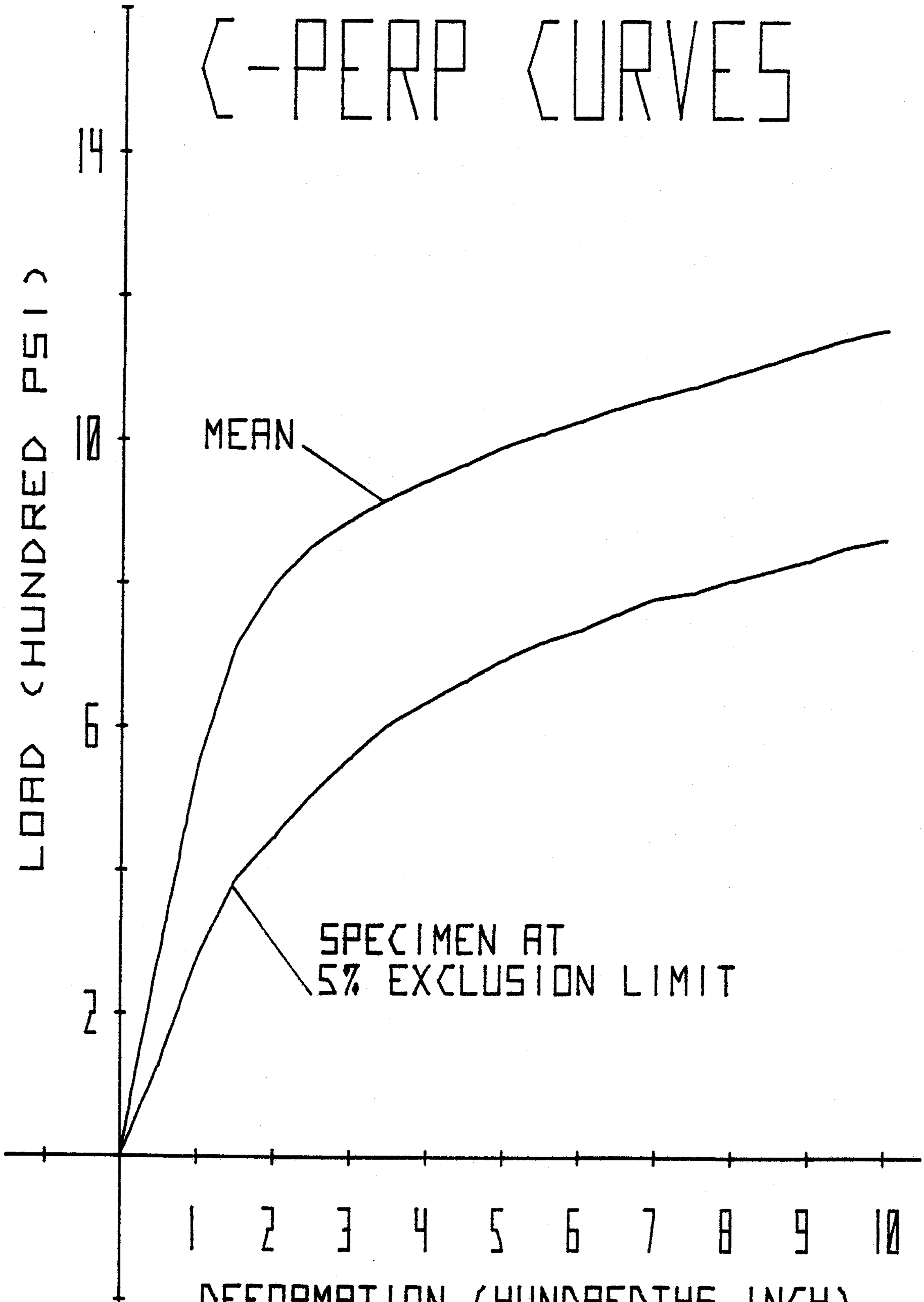

Figure 16. Curves for 90°-angle specimens of hem-fir

We know that these growth ring variations have unique structural differences (Figure 2). We also know that these systems will collapse differently when loaded. After initial collapse, however, the system densifies and rearranges itself to collapse more uniformly. The parallel nature of ring angle data beyond 0.04-inch deformation seems to support this. It also implies no difference in resistance to additional loading among ring angles once their original strength has been utilized.

Assuming the five percent exclusion limit is a valid tolerance limit, Figure 17 describes a safe linearization (dotted line) of the inelastic region for the 45°-angle class. The area above this line and below the actual curve represents additional capacity to resist compression. In actual testing, however, a smooth curve seldom occurs in the inelastic region. More often it is slightly wavy indicating minute collapses of cell walls, buckling of rays and shearing of density layers. These failures are seldom large but do exist. Figure 18 is not actual data but illustrates this characteristic in individual specimens. The straight line between PL and max, below the curve is conservative.

Since the 45°-angle tests relate to full-size specimens, it seems natural to model this relationship beyond PL. The 5% exclusion limit stress at PL was 297 psi, while the stress at max was 599 psi (Figure 17). The deformations were 0.022- and 0.100-inch respectively. Using these load-deformation coordinates, one could then plot the straight line between them. The formula for a straight line is:

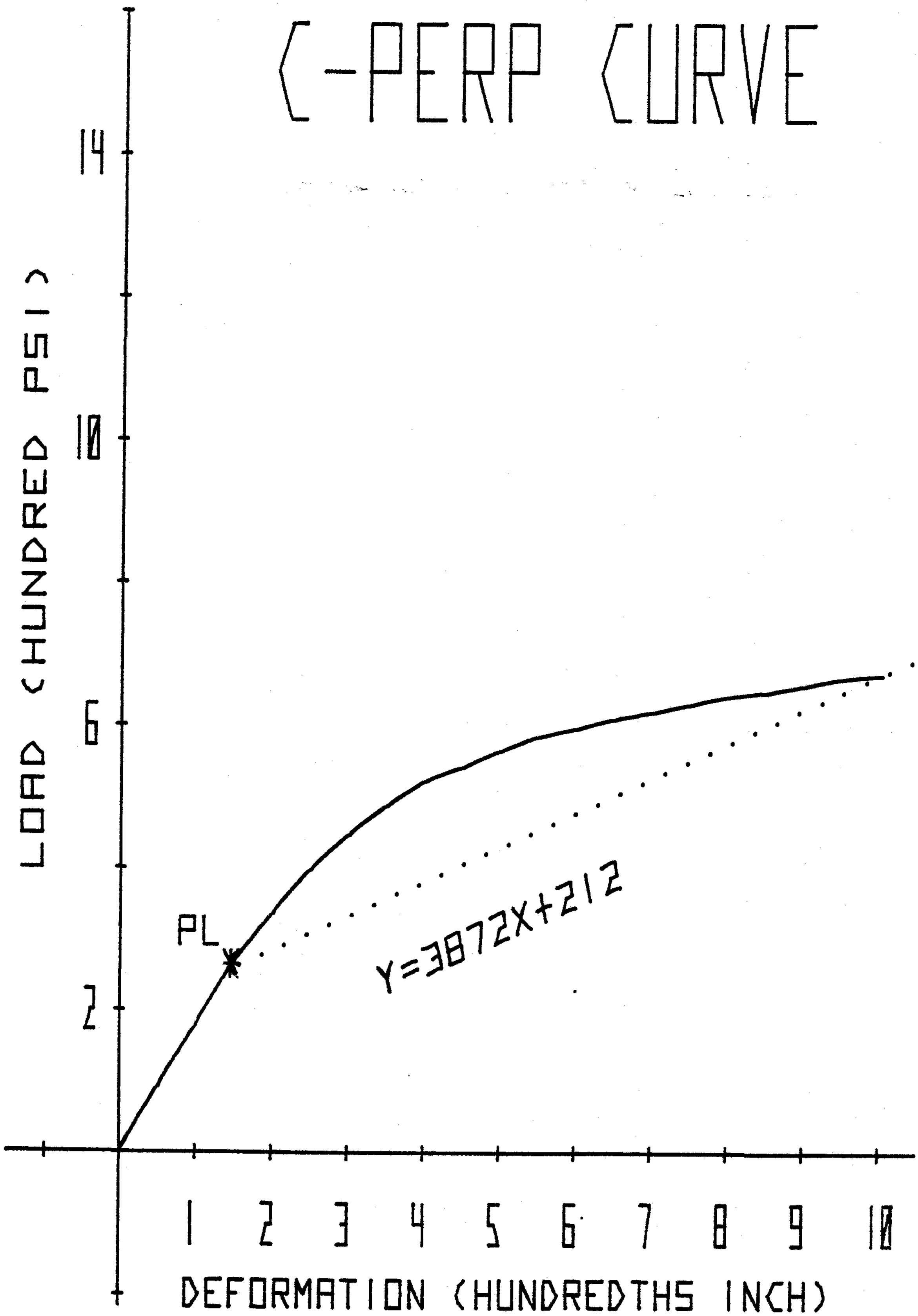

Figure 17. Linearization at the 5% exclusion limit of 45°-angle specimens of hem-fir

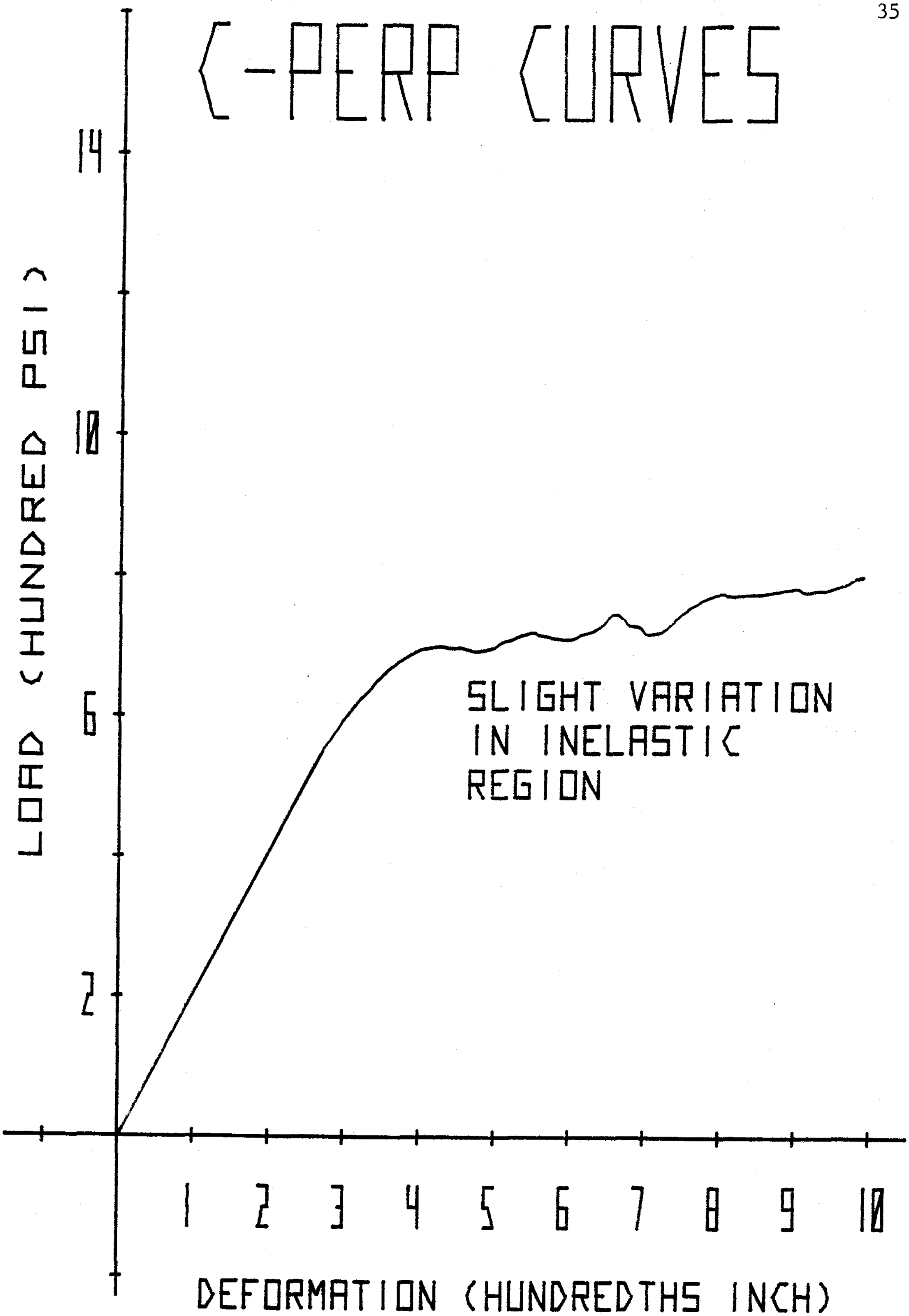

Figure 18. Typical load-deformation curve

$y = mx + b$

y = predicted load (psi)

x = deformation (inches)

b = y intercept = 22

m = slope of line $= \frac{\Delta y}{\Delta x} = 3872$

The specific formula for this case is:

$y = 3872x + 212$

x = desired deformation (inches)

y = allowable stress (psi)

It is then necessary to qualify the range of this formula from 0.022- to 0.100-inch deformation. An alternative to this formula is a table of allowable stresses derived from the formula (Table 1). Convenient multiplying factors also appear and are shown in the same table. When these factors are multiplied times PL a new set of stresses are generated. If the slope in the formula holds true for other species, these factors could be used for determining stresses at deformations beyond PL with existing PL data.

Is the ring angle of zero degrees used in the ASTM standard test meaningful? The boards sampled for this study showed an insignificant quantity of zero (vertical) grain. Only one board out of 60 had at least 75% of the grain vertical; only five others had even 50%. Less than 10% of the boards had any vertical grain at all. Tests on zero degree material seem to have little relationship to actual boards.

TABLE 1. ALLOWABLE STRESSES BEYOND PL FOR 45°-ANGLE CLASS

ALLOWABLE STRESSES IN C-PERP BEYOND PL

	@ DEFORMATIONS OF				
	PL .02	.04	.06	.08	MAX .10
LINEARRIZED 5% EXCLUSION STRESSES(PSI) [Y=3872 X+212]	297	367	444	522	599
CONVENIENT MULTIPLYING FACTORS	1	1.25	1.50	1.75	2
STRESSES(PSI) GENERATED BY MULTIPLYING FACTORS	297	371	446	520	594

Comparing Small and Large Specimens

The large specimens included a variety of ring angles in the cross-sectional area, which apparently influenced the results. Figure 19 shows curves at the mean and 5% exclusion limit for the large specimens. Proportional limit was at 582 psi and 0.014-inch deformation. Maximum load was 920 psi. As in the small specimens, a second linear portion of the curve is apparent from 0.04 inch to maximum deformation (0.1 inch). Average load at 0.1 inch was 805 psi. The major difference between the large and small specimens in this region beyond PL was the slope of the curves. The larger specimens required less increase in load for greater deformation than did the smaller specimens (slope was less steep).

The PL for the 5% exclusion limit was 334 psi at 0.008 inch deformation and 696 psi at maximum. The nearest ring angle class in the small specimens is 45 degrees with 297 psi at PL. Figure 20 shows the full family of curves.

Data from the large specimens were treated identically to data from 45°-angle specimens as shown in Figure 17. Using the same method described in Figure 17 for the small specimens, the formula for the linearized inelastic region for the large specimens is derived as:

$y = 3935x + 301$

y = allowable load (psi)

x = desired deformation (inches)

The range of x is from 0.008 to 0.100 inch.

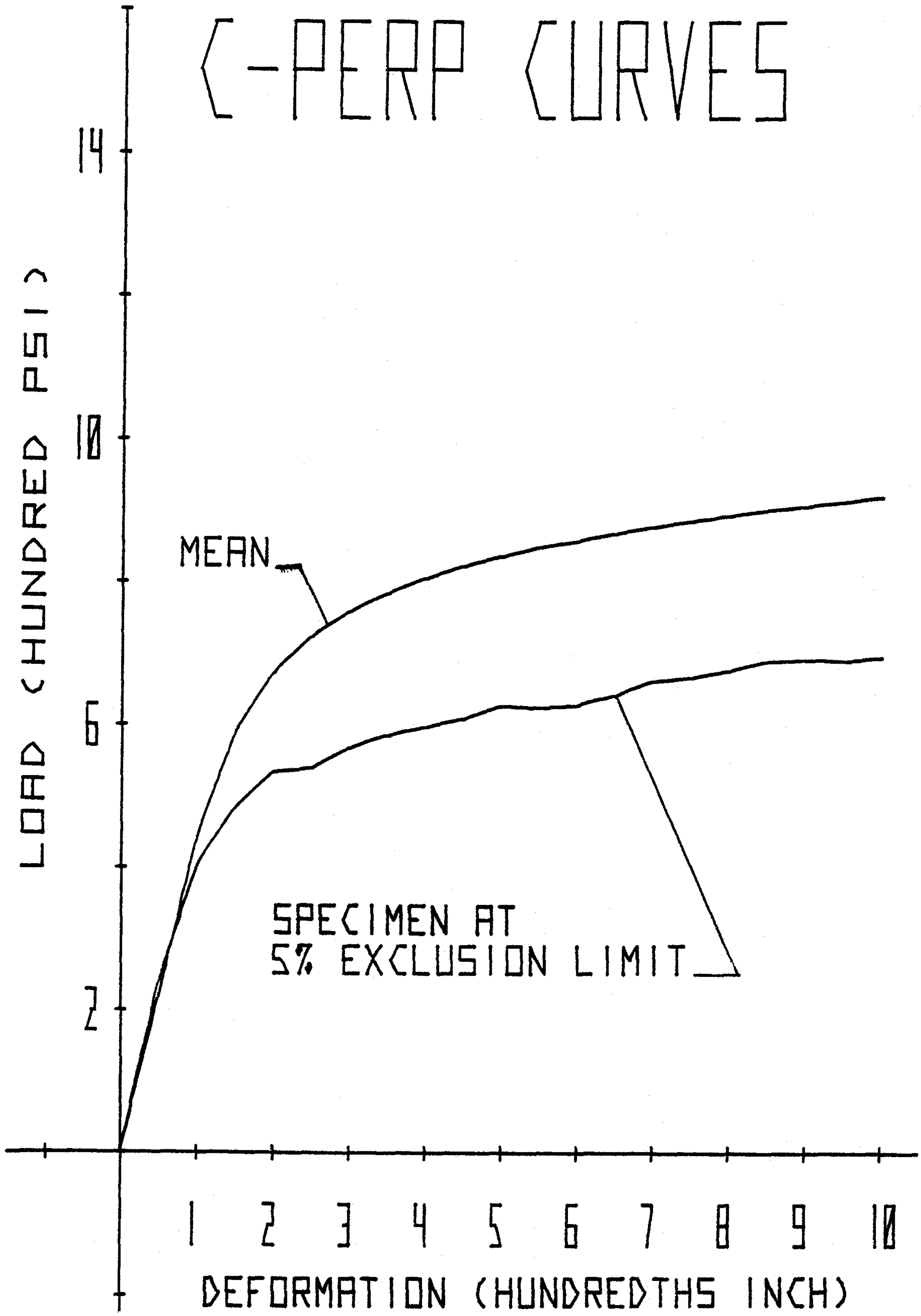

Figure 19. Curves for large specimens from hem-fir lumber

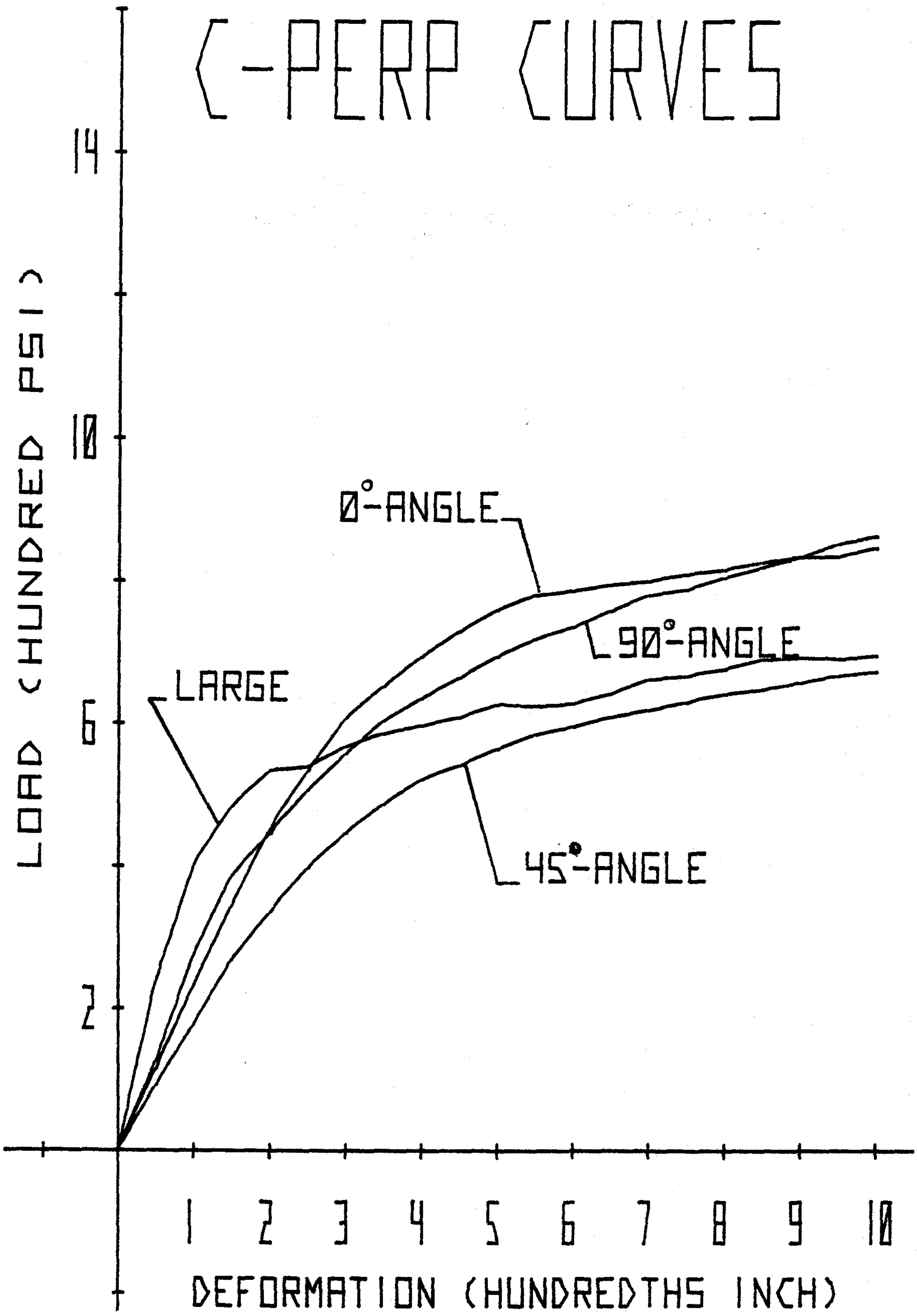

Figure 20. Family of curves at the 5% exclusion limit

The similarities found in the 45°-angle and large specimen curves prompted further investigation and analysis. Figure 21 overlays the mean 45°-angle and large-specimen curves. Average stress in the large specimen increases rapidly with deformation and shows considerable resistance up to PL. Again there is linearity from 0.04 to 0.1 inch deformation. Figure 22 shows 45°-angle and large specimens at the 5% exclusion limit.

Table 4 shows the ring angle profile of each large specimen. These profiles have similarities that allow their division into five classes. Table 2 describes these classes and shows the percent of each found in the 60 boards. Obviously the representative sample has very few zero degree (vertical-grained) boards.

Shearing in most materials takes place naturally at angles of 45° to the load. The 45°-angle combined with alternating density layers of wood at the same angle reduces resistance to shearing. Collapse of the cell walls is more easily accomplished. The summerwood layers and the ray cells (Figure 1) are normally perpendicular to each other. They act much as columns resisting the load as long as the load is applied axially to them. When loads are applied at 45° these columns have less resistance.

These facts lead one to consider the effect of having 45-degree ring angle edges on the larger specimens. Sixty percent of the sample of large specimens had one edge with ring angle of 45 degrees. Eighteen percent more had two 45 degree edges. In total 78% of the sample had 45 degree edges and 22% had either zero or 90 degree edges

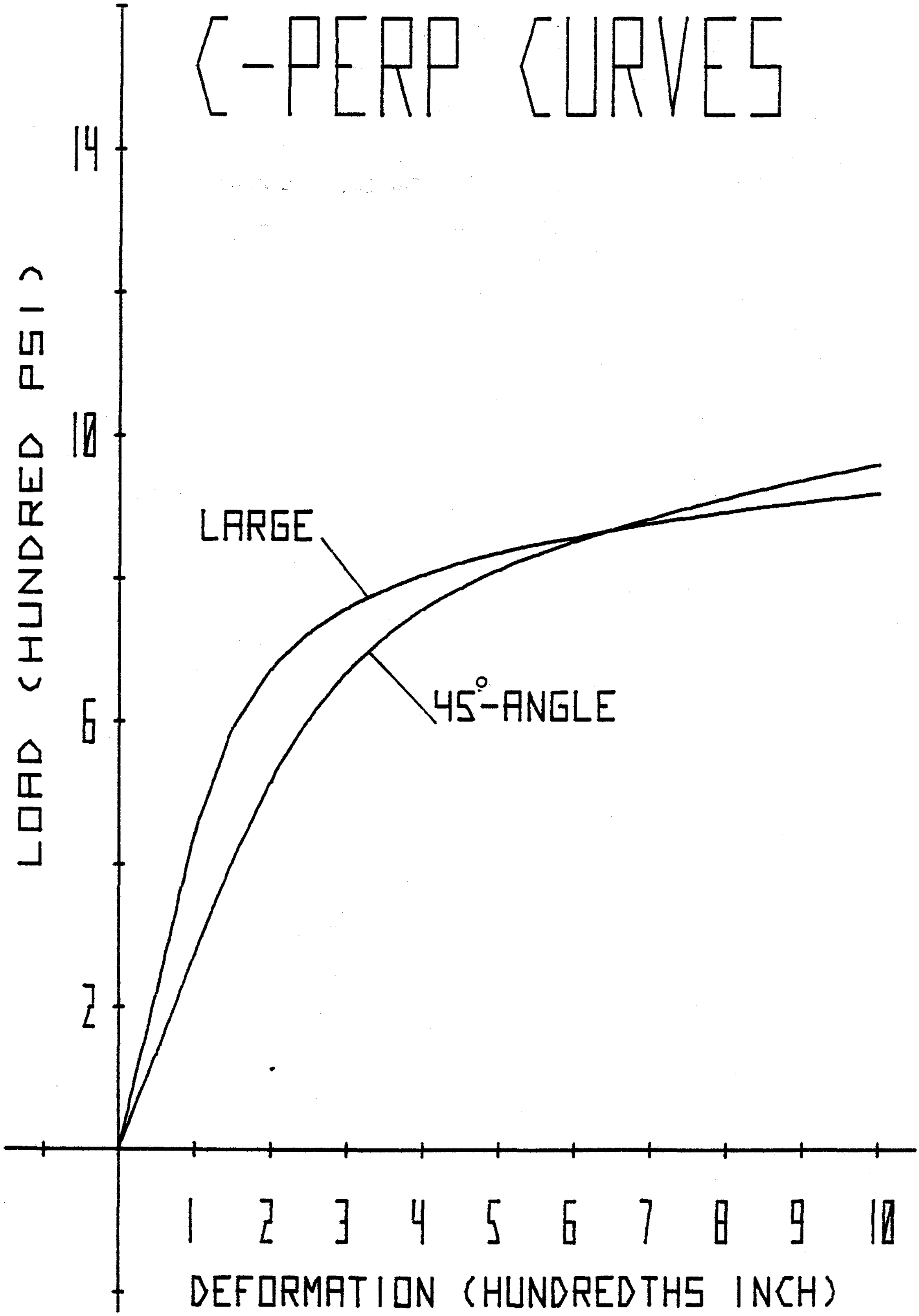

Figure 21. Mean curves for the large and 45°-angle specimens

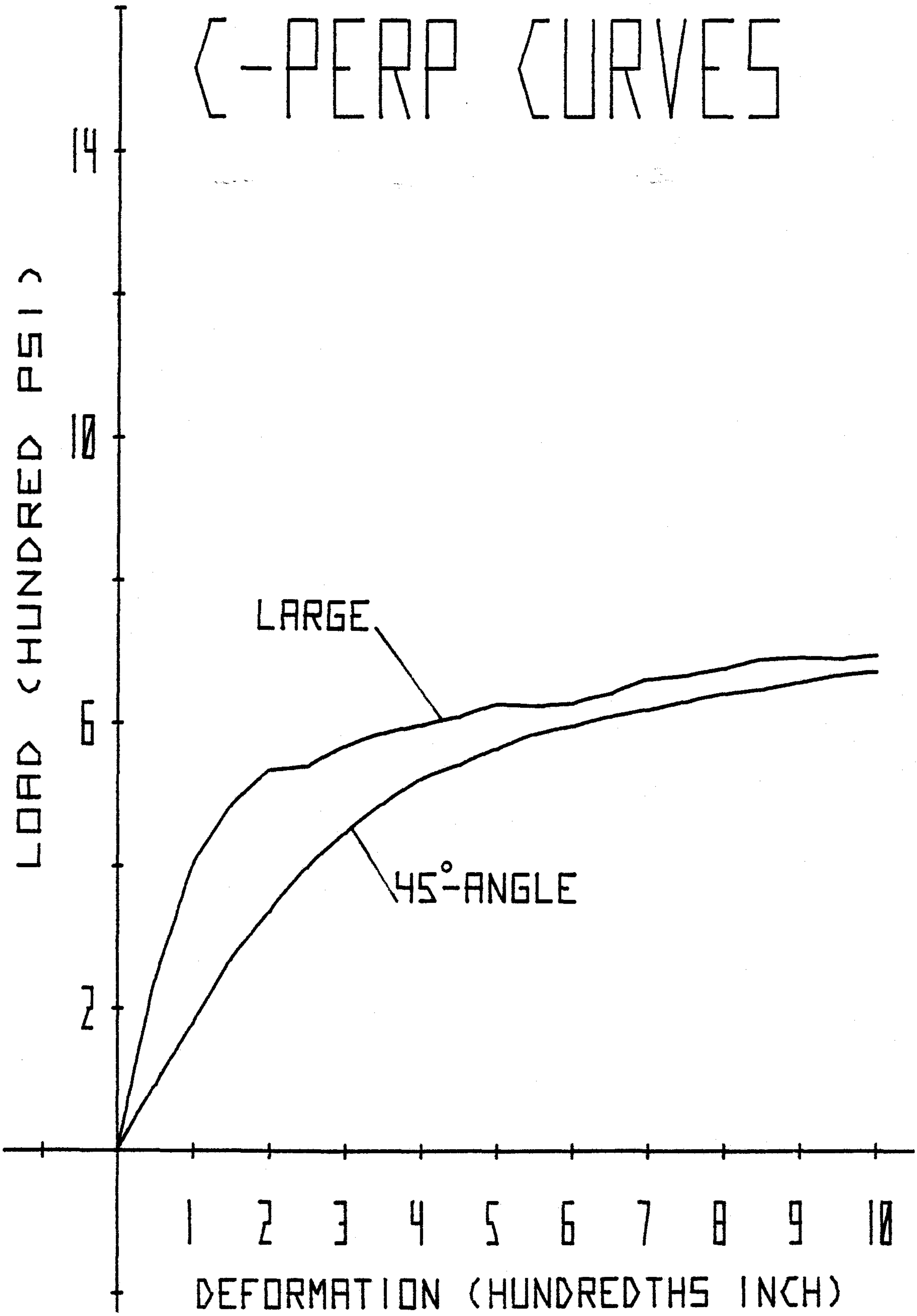

Figure 22. Curves at the 5% exclusion limit for large and 45°-angle specimen

TABLE 2. SUMMARY OF RING ANGLE CLASSES IN LARGE SPECIMENS

RING ANGLE CLASSES FOR LARGE SPECIMENS

CLASS	CROSS SECTION DESCRIPTION	PCT. FOUND IN SAMPLE
I	75% 0°-ANGLE	1.7%
II	50% 0°-ANGLE 50% 45°-ANGLE	8.4%
III	75% 45°-ANGLE	24.9%
IV	50% 45°-ANGLE 50% 90°-ANGLE	31.7%
V	75% 90°-ANGLE	33.3%

(Table 4). Table 3 compares mean C-perp values at PL and maximum deformation for small specimens with the large specimens having 45° edges. The comparison is surprisingly close.

Since the load-deformation curve for 45°-angle specimens appears to be safely under the curve for large specimens (Figure 22), it seems appropriate to use the 45-degree 5% exclusion limit for allowable stresses in design. Small specimens at 45° ring angle orientation can be tested to provide design data for full size specimens. Examination of board cross sections indicate 45°-angle specimens occur commonly.

When quantities of predominantly vertical or flat-grain boards are available, exclusion limit data from the zero and 90 degree class should control. Boards in this study, however, show a 78% chance that this will not happen. Table 3 strengthens the use of 45°-angle predictors.

An interesting way to visualize the effects of 45° edges and the resulting lower stress levels is to consider the diagrams in Figure 23. The stressed area is 5 1/2-inches by 5 1/2-inches or 30.25 square inches. A 45-degree edge is present. If one were to predict the load at 0.050-inch deformation by weighted averages using the 5% exclusion limit you would have 22 square inches at 838 psi for the flat section and 8.25 square inches at 507 psi for the 45° section. The predicted stress would be 747.7 psi. But I have previously stated that experimentally the stress would be closer to that of a 45°-angle value. What happened? Imagine first a high initial MOE in response to the flat-grained section and the edge still sound. But PL is reached quickly

TABLE 3. SELECTED COMPARISONS OF PL AND MAX STRESSES

SELECTED COMPARISONS OF PL AND MAX

CLASS	PL(PSI)	MAX(PSI)
45°-ANGLE	516	960
LARGE WITH 1 45°-ANGLE EDGE	577	933
90°-ANGLE*	670	1154
LARGE WITH NO 45°-ANGLE EDGES	695	1010

* PROFILE OF LARGE SPECIMENS INDICATE 90°-ANGLE IS PREDOMINANT WHEN NO 45°-ANGLE EDGES ARE PRESENT

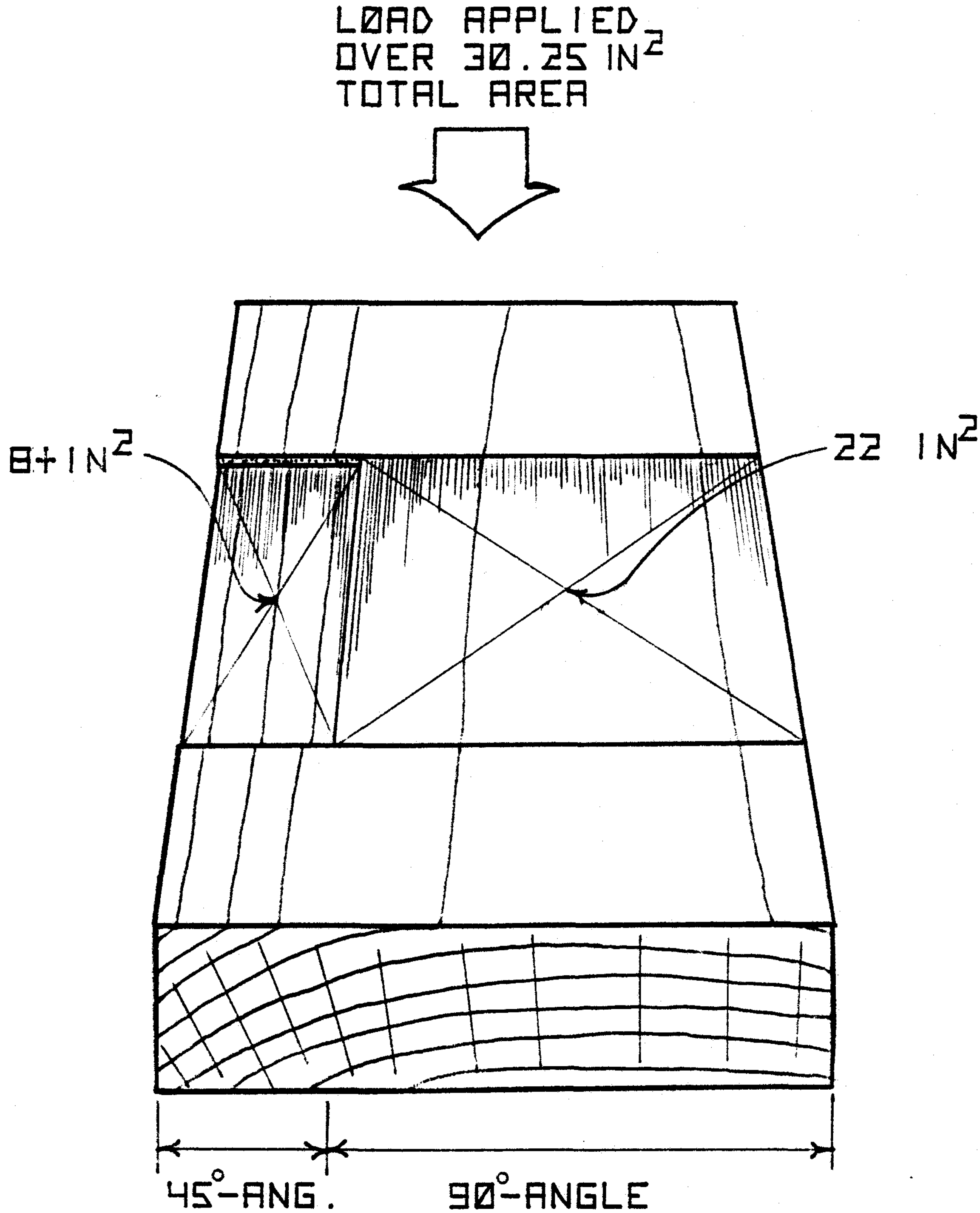

Figure 23. Hypothetical compression in large specimens of lumber

as the 45° edge fails almost catastrophically compared to the flat section. Now we have no resistance by the 45° area and the balance of the area, 22 square inches, is carrying the total load. We now have 18,436 pounds of resistance, but we must divide this over the whole area, 30.25 square inches to give us the total area stress of 609.5 psi. This value is 18% lower than our weighted average prediction. It is also more accurate. This example was purely hypothetical, but simulates what might be happening if a piece of wood under compression was thought of as a purely structural system under load.

It is difficult to compare stress differences between specimens of varying ring angle and size without referring directly to a single point of comparison. The proportional limit is a convenient point for these comparisons. In design, however, it is not desirable to depend on a point whose stress has a highly variable deformation associated with it. In C-perp, where structural failure (below 0.1 inch) is not apparent, it is desirable to have allowable stresses established on the basis of acceptable deformation for the end use of the board under stress. Since PL generally is reached at a relatively low and almost insignificant deformation, it is my opinion that for most structural uses designing beyond PL is not only recommended but imperative to the optimum use of wood.

CONCLUSIONS

This study supports the following conclusions:

1. Compression perpendicular to the grain (C-perp) in small specimens of hem-fir lumber is highly dependent on the angle of growth rings. Ring angles of zero degrees to an applied load have the greatest stress resistance to deformation. Ninety-degree ring angle material has 10-15% lower stresses and 45-degree material has still another 20% lower. Change in stress is not differentiable among ring angles at deformations beyond 0.040 inch although relative differences in stress stay constant. Stresses up to the proportional limit are the real differences in ring angle.

2. The ASTM standard test of vertical-grained (0-degree ring angle) material is impractical since 45-degree ring angle material is the weakest and therefore has the controlling influence.

3. Data from small specimens with 45-degree ring angles are conservative predictors of stresses for large specimens. Edges of large specimens with 45-degree ring angle reduce compression resistance considerably; these edges occurred in 70-80% of the hem-fir boards in this study.

4. If C-perp stresses increase beyond the proportional limit to deformations as much as 0.100 inch, no dangerous shearing should occur. Aesthetic considerations would be minor if any at all. A safe linear formula is readily available for establishing allowable design stresses for hem-fir at deformations beyond the proportional limit up to 0.100

inch. If deformations were allowed to 0.100 inch, then allowable stresses in C-perp for hem-fir could be almost double those presently used. However, this does not imply that these values would be used directly in design. Adjustments would need be made for moisture content, duration of load and safety. Further studies on these factors beyond the proportional limit would be necessary.

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APPENDIX

Table 4
Large Specimen Cross-sectional Profiles
of Ring Angle

Oregon

Specimen	Ring Angle				Class*
1	0	45	45	90	II
2	90	90	90	45	V
3	90	90	90	90	V
4	90	90	90	90	V
5	45	45	45	45	III
6	0	90	0	0	I
7	45	45	90	90	IV
8	90	90	90	90	V
9	0	0	45	45	II
10	90	90	45	45	IV
11	90	90	90	90	V
12	90	90	45	45	IV
13	0	0	45	45	II
14	45	45	90	90	IV
15	90	90	90	45	IV

Washington

Specimen	Ring Angle				Class
1	90	90	90	45	V
2	45	90	90	45	IV
3	45	90	45	45	III
4	45	45	90	90	IV
5	0	45	90	45	II
6	45	45	0	0	II
7	45	45	90	90	IV
8	90	90	45	45	IV
9	90	90	90	45	IV
10	90	90	45	45	IV
11	45	90	90	90	V
12	90	90	90	45	V
13	90	90	90	45	V
14	90	90	45	45	IV
15	0	0	0	90	I

California

Specimen	Ring Angle				Class
1	45	90	45	45	III
2	45	45	45	90	III
3	45	90	90	45	IV
4	90	90	45	45	IV
5	90	90	90	45	V
6	90	90	45	45	IV
7	90	90	45	45	IV
8	90	90	45	45	IV
9	45	45	45	45	III
10	45	45	45	45	III
11	90	0	90	45	II
12	0	45	45	45	III
13	90	90	90	90	V
14	0	45	45	45	III
15	90	45	45	45	III

Idaho

Specimen	Ring Angle				Class
1	90	90	90	45	V
2	90	90	90	45	V
3	90	90	90	90	V
4	90	90	90	90	V
5	90	90	45	45	IV
6	90	90	90	90	V
7	90	90	90	90	V
8	45	45	90	90	IV
9	45	45	45	45	III
10	45	90	90	45	IV
11	45	45	45	45	III
12	90	90	90	90	V
13	90	45	45	45	III
14	90	90	45	45	IV
15	90	90	90	90	V

* Explanation of classes in Table 2

Table 5

Individual Specimen Data

State	Specific Gravity	Moisture Content(%)	Proportional Limit (PL) Stress (psi)	Proportional Limit (PL) Deformation(in)	Stresses Deformations of .04in.	Stresses Deformations of .10in.	Ring Angle (degrees)*
CALIF	0.46	11	490	0.021	710	896	50
CALIF	0.38	12	334	0.019	573	708	57
CALIF	0.41	9	399	0.021	606	789	45
CALIF	0.47	9	567	0.034	654	908	45
CALIF	0.37	8	396	0.020	640	809	40
CALIF	0.39	9	552	0.018	793	975	61
CALIF	0.48	9	410	0.016	702	901	60
CALIF	0.37	10	489	0.017	825	958	58
CALIF	0.40	11	550	0.017	731	875	71
CALIF	0.40	11	417	0.023	610	773	17
CALIF	0.39	10	531	0.017	923	1074	22
CALIF	0.39	10	462	0.022	642	830	63
CALIF	0.42	9	662	0.020	1017	1174	55
CALIF	0.36	9	520	0.021	707	811	21
CALIF	0.36	12	732	0.017	1235	1279	68
CALIF	0.35	12	563	0.024	748	832	65
CALIF	0.37	10	747	0.023	898	973	16
CALIF	0.35	10	734	0.018	1085	1350	74
CALIF	0.44	12	1187	0.024	1475	1569	5
CALIF	0.42	11	1040	0.012	1190	1361	88
IDAHO	0.40	9	812	0.016	1057	1249	87
IDAHO	0.42	10	1002	0.030	1179	1333	13
IDAHO	0.42	9	736	0.020	1069	1281	24
IDAHO	0.37	9	462	0.016	751	898	51
IDAHO	0.31	11	317	0.016	506	604	37
IDAHO	0.43	8	741	0.019	904	1120	65
IDAHO	0.42	8	743	0.014	977	1099	60
IDAHO	0.34	9	462	0.016	653	827	72
IDAHO	0.37	10	409	0.026	558	792	44
IDAHO	0.35	10	426	0.019	704	850	22
IDAHO	0.36	9	419	0.019	585	741	68
IDAHO	0.41	8	576	0.015	866	959	60
IDAHO	0.40	10	495	0.010	754	961	78
IDAHO	0.39	10	425	0.014	769	915	18
IDAHO	0.35	9	495	0.034	565	903	25
IDAHO	0.38	12	425	0.014	644	806	72
IDAHO	0.41	11	812	0.024	1048	1188	18
IDAHO	0.40	11	1053	0.021	1338	1558	0
IDAHO	0.37	10	770	0.012	1077	1264	66
OREGON	0.53	8	1234	0.020	1637	1890	10
OREGON	0.53	9	539	0.013	967	1258	80
OREGON	0.44	8	1050	0.023	1303	1469	15
OREGON	0.44	8	926	0.022	1201	1573	82
OREGON	0.40	9	548	0.020	822	1034	55
OREGON	0.40	9	572	0.016	924	1130	62
OREGON	0.44	8	421	0.019	663	854	50
OREGON	0.40	8	581	0.014	941	1140	30
OREGON	0.44	8	399	0.021	571	743	52
OREGON	0.42	8	439	0.020	648	837	54
OREGON	0.44	8	959	0.039	986	1350	40
OREGON	0.42	8	743	0.025	978	1188	57
OREGON	0.46	8	390	0.019	674	855	45
OREGON	0.50	10	716	0.014	1075	1324	70
OREGON	0.49	8	563	0.014	954	1320	30
OREGON	0.45	8	568	0.015	990	1279	22
OREGON	0.43	8	417	0.017	767	1035	68
OREGON	0.42	8	453	0.025	599	870	45
WASH	0.48	9	735	0.023	1029	1382	65
WASH	0.45	11	778	0.030	943	1361	0
WASH	0.46	10	1021	0.014	1245	1485	89
WASH	0.43	9	403	0.023	620	839	43
WASH	0.46	10	401	0.015	682	900	47
WASH	0.48	10	727	0.012	1050	1304	74
WASH	0.43	10	421	0.014	738	943	52
WASH	0.43	9	287	0.013	593	785	47
WASH	0.37	10	357	0.021	543	680	48
WASH	0.49	9	891	0.020	1209	1474	45
WASH	0.46	9	402	0.022	543	728	48
WASH	0.41	9	423	0.021	578	733	54
WASH	0.48	9	452	0.020	674	870	52
WASH	0.43	9	576	0.018	753	988	67
WASH	0.47	10	1194	0.024	1615	1948	22
WASH	0.46	9	926	0.011	1214	1581	85
WASH	0.43	9	418	0.018	611	840	75
OREGON	0.46	7	492	0.008	984	1228	72
OREGON	0.48	8	1214	0.035	1347	1502	15
OREGON	0.51	9	750	0.023	1071	1338	30
OREGON	0.43	7	503	0.018	953	1238	25
OREGON	0.39	8	533	0.020	883	1044	20
OREGON	0.37	8	495	0.011	770	953	85
OREGON	0.40	7	783	0.010	1181	1432	85
OREGON	0.40	8	1018	0.019	1265	1497	5
OREGON	0.44	7	1052	0.019	1459	1701	10
OREGON	0.43	8	624	0.014	967	1325	80
OREGON	0.46	9	539	0.012	901	1121	77
OREGON	0.45	9	1093	0.025	1508	1576	15
OREGON	0.46	9	814	0.014	997	1185	85
OREGON	0.46	9	1106	0.022	1398	1475	0
OREGON	0.48	9	741	0.015	1280	1502	18
OREGON	0.44	10	864	0.015	1055	1310	75
OREGON	0.45	8	1151	0.011	1596	1876	80
OREGON	0.45	8	1105	0.020	1421	1734	5
OREGON	0.43	9	767	0.011	1109	1315	85
OREGON	0.44	8	843	0.019	1351	1456	10
OREGON	0.53	9	772	0.016	974	1168	60
OREGON	0.52	8	796	0.019	1133	1478	20
OREGON	0.44	8	436	0.018	735	972	47
OREGON	0.51	9	1006	0.019	1454	2132	12
OREGON	0.51	10	1101	0.019	1374	1722	80
OREGON	0.43	7	428	0.005	820	1065	85
OREGON	0.42	7	893	0.020	1095	1367	0
IDAHO	0.42	10	500	0.020	777	971	53
IDAHO	0.40	10	1008	0.023	1329	1515	5
IDAHO	0.39	10	424	0.012	586	747	75
IDAHO	0.42	10	482	0.024	691	1006	55
IDAHO	0.40	10	1058	0.009	1338	1490	84
IDAHO	0.43	10	800	0.018	1182	1532	0
IDAHO	0.38	9	541	0.010	782	984	85
IDAHO	0.38	9	604	0.018	938	1085	10
IDAHO	0.31	13	319	0.013	535	637	75
IDAHO	0.31	12	499	0.022	693	772	0
IDAHO	0.43	9	617	0.014	756	948	68
IDAHO	0.44	9	890	0.019	1207	1579	0
IDAHO	0.42	10	814	0.011	1065	1279	85
IDAHO	0.43	9	923	0.021	1359	1592	0
IDAHO	0.37	9	476	0.020	713	846	72
IDAHO	0.35	8	502	0.016	827	882	0
IDAHO	0.34	9	297	0.022	460	599	50
IDAHO	0.43	9	716	0.010	946	1093	90
IDAHO	0.41	9	698	0.021	1135	1358	20
IDAHO	0.35	7	471	0.036	512	691	42
IDAHO	0.33	9	495	0.015	704	826	70
IDAHO	0.34	10	416	0.015	777	911	12
IDAHO	0.33	10	279	0.025	389	587	35
IDAHO	0.37	10	475	0.017	812	970	55
IDAHO	0.37	9	997	0.010	1210	1355	80
IDAHO	0.36	10	854	0.030	1030	1285	15
CALIF	0.40	12	440	0.010	785	982	85
CALIF	0.40	12	649	0.018	930	1229	17
CALIF	0.40	9	734	0.013	1039	1132	90
CALIF	0.38	9	672	0.021	1043	1171	0
CALIF	0.40	10	711	0.010	918	1089	90
CALIF	0.40	11	825	0.028	921	1166	0
CALIF	0.43	11	741	0.009	1103	1330	90
CALIF	0.47	11	1187	0.020	1410	1859	0
CALIF	0.38	10	1017	0.012	1220	1425	90
CALIF	0.36	9	1046	0.023	1205	1379	0
CALIF	0.39	8	709	0.018	883	1130	75
CALIF	0.38	9	513	0.017	919	1104	20
CALIF	0.39	11	730	0.011	1030	1191	85
CALIF	0.38	11	876	0.015	1050	1135	0
CALIF	0.37	10	701	0.013	1047	1220	80
CALIF	0.38	10	686	0.016	1039	1194	10
CALIF	0.36	11	304	0.016	514	633	50
CALIF	0.36	10	341	0.014	673	783	42
CALIF	0.43	9	864	0.016	1189	1448	75
CALIF	0.43	10	1042	0.023	1402	1578	16
CALIF	0.33	11	410	0.021	646	846	40
CALIF	0.37	11	624	0.008	802	1100	90
CALIF	0.37	11	896	0.018	1137	1204	0
CALIF	0.41	10	606	0.014	982	1119	59
CALIF	0.47	10	780	0.028	1007	1283	35
WASH	0.45	10	521	0.011	889	1039	90
WASH	0.49	9	621	0.025	862	1213	20
WASH	0.42	10	557	0.013	764	918	75
WASH	0.41	10	749	0.036	812	1110	12
WASH	0.45	11	523	0.022	755	962	27
WASH	0.42	11	498	0.013	737	930	70
WASH	0.41	11	675	0.021	1024	1219	13
WASH	0.42	10	740	0.021	1136	1330	15
WASH	0.48	10	537	0.019	811	1036	67
WASH	0.41	12	699	0.013	1143	1468	21
WASH	0.37	11	363	0.012	527	713	85
WASH	0.48	10	476	0.015	650	834	69
WASH	0.53	10	1267	0.027	1618	2082	10
WASH	0.42	11	468	0.009	748	972	80
WASH	0.38	11	608	0.022	864	1060	5
WASH	0.47	11	1303	0.014	1661	2032	80
WASH	0.45	11	1006	0.020	1344	1584	0
WASH	0.46	10	795	0.012	1105	1287	90
WASH	0.44	10	517	0.021	740	921	20
WASH	0.44	10	513	0.011	742	931	80
WASH	0.43	10	782	0.016	1066	1350	19
WASH	0.47	10	589	0.012	924	1120	73
WASH	0.47	10	751	0.019	1085	1347	8
WASH	0.44	10	512	0.011	827	1027	73
WASH	0.45	10	718	0.015	1114	1298	5
WASH	0.44	10	509	0.020	750	960	45
WASH	0.47	10	760	0.022	1063	1250	13
WASH	0.43	10	479	0.013	726	919	60
IDAHO	0.42	10	553	0.015	689	766	99
IDAHO	0.43	11	419	0.012	589	672	99
IDAHO	0.41	10	942	0.015	1145	1217	99
IDAHO	0.37	11	554	0.016	698	774	99
IDAHO	0.30	13	371	0.016	491	582	99
IDAHO	0.43	10	506	0.012	664	755	99
IDAHO	0.42	11	844	0.012	1003	1068	99
IDAHO	0.35	9	475	0.012	638	721	99
IDAHO	0.35	9	321	0.020	471	562	99
IDAHO	0.40	9	578	0.011	727	796	99
IDAHO	0.35	8	465	0.026	562	647	99
IDAHO	0.33	9	405	0.013	661	746	99
IDAHO	0.35	12	361	0.021	492	577	99
IDAHO	0.36	10	567	0.014	826	911	99
IDAHO	0.35	12	910	0.010	1074	1096	99
WASH	0.44	10	396	0.012	563	655	99
WASH	0.43	12	477	0.011	755	968	99
WASH	0.41	11	309	0.014	514	710	99
WASH	0.44	11	386	0.009	683	832	99
WASH	0.45	11	613	0.014	964	1076	99
WASH	0.40	12	552	0.024	755	905	99
WASH	0.48	10	451	0.018	586	723	99
WASH	0.38	10	407	0.012	594	698	99
WASH	0.47	11	1204	0.017	1492	1655	99
WASH	0.43	10	567	0.013	801	884	99
WASH	0.41	10	441	0.013	566	646	99
WASH	0.47	10	395	0.010	637	776	99
WASH	0.44	10	516	0.016	692	835	99
WASH	0.45	10	703	0.012	1010	1106	99
WASH	0.44	10	592	0.019	813	1018	99
CALIF	0.42	12	449	0.014	666	758	99
CALIF	0.37	10	405	0.013	664	781	99
CALIF	0.40	11	532	0.012	722	794	99
CALIF	0.48	11	561	0.012	804	903	99
CALIF	0.38	11	689	0.012	914	1014	99
CALIF	0.39	10	628	0.021	835	947	99
CALIF	0.42	11	472	0.013	650	806	99
CALIF	0.39	10	773	0.016	908	978	99
CALIF	0.39	11	354	0.017	523	609	99
CALIF	0.38	9	540	0.023	724	826	99
CALIF	0.44	10	857	0.012	1164	1230	99
CALIF	0.36	9	531	0.021	728	808	99
CALIF	0.38	11	642	0.011	861	944	99
CALIF	0.41	9	593	0.020	883	1036	99
CALIF	0.46	12	648	0.017	841	984	99
OREGON	0.53	8	742	0.014	1094	1363	99
OREGON	0.42	8	653	0.013	839	990	99
OREGON	0.39	8	489	0.016	758	891	99
OREGON	0.40	9	839	0.012	959	1051	99
OREGON	0.45	8	486	0.015	736	877	99
OREGON	0.43	8	833	0.013	1228	1308	99
OREGON	0.47	8	541	0.011	728	832	99
OREGON	0.45	9	695	0.011	785	876	99
OREGON	0.47	8	763	0.017	1127	1302	99
OREGON	0.45	7	790	0.013	1084	1239	99
OREGON	0.45	8	532	0.009	784	923	99
OREGON	0.56	10	735	0.010	1208	1434	99
OREGON	0.56	9	970	0.012	1583	1703	99
OREGON	0.42	8	550	0.011	792	909	99
OREGON	0.44	8	333	0.008	597	696	99

* A ring angle of 99 indicates large specimen variation. More specific information can be found in Table 4.