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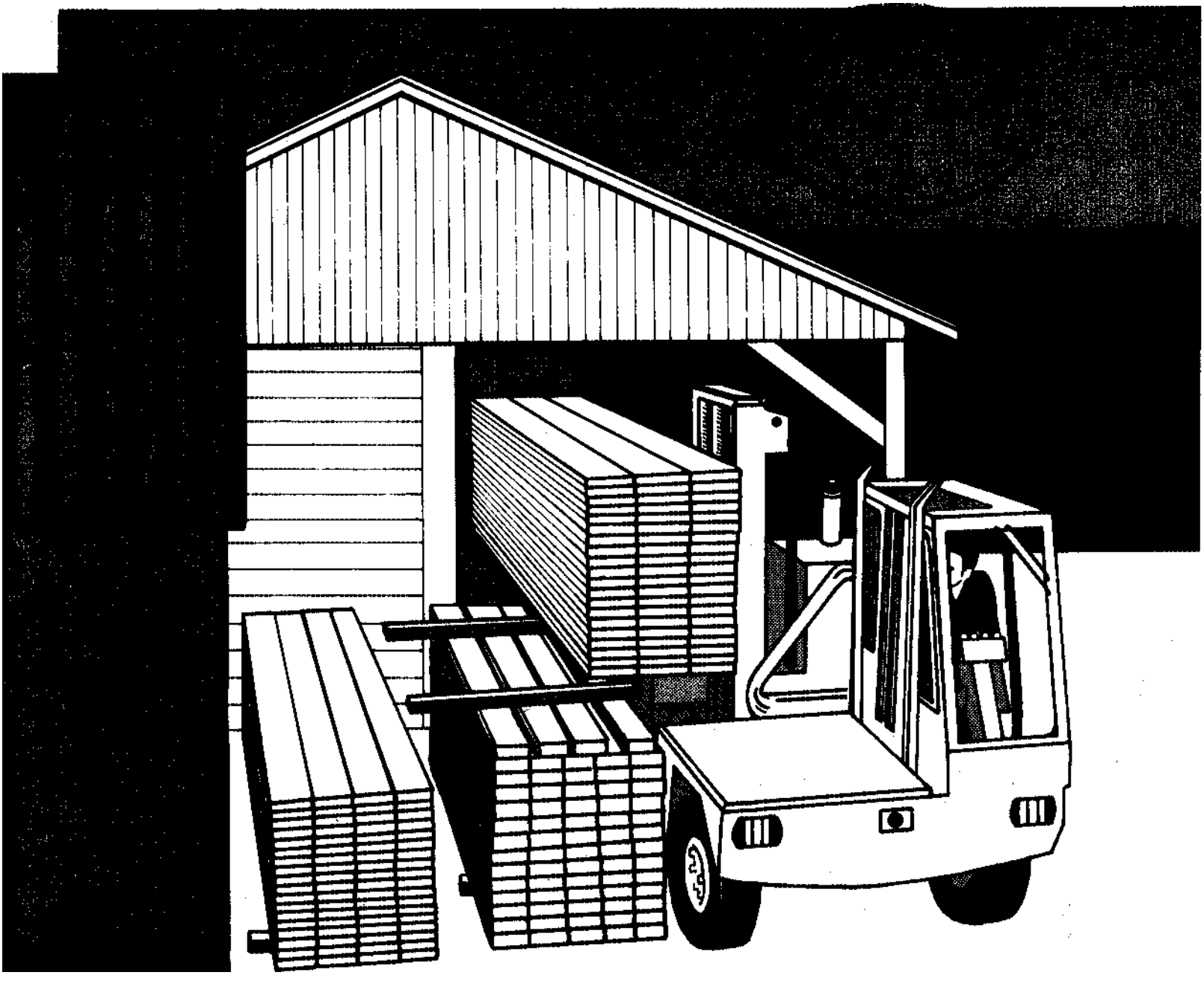
# Wood Joist Floors: Probabilistic Analysis of Joist Stiffness Measured at Retail Lumberyards



## Abstract

A systematic sampling of joist lumber was carried out at retail lumber yards over two summers to observe and measure physical and mechanical properties close to point of purchase and use. The study sought to define "acceptable" performance of the dimension lumber in terms of floor system performance, using a composite of current standards. Measured properties of the material were discussed in terms of that tentative criterion. This interim report emphasizes sampling procedures, testing methods, and techniques of statistical analysis used. In a first phase of the study, joist lumber was sampled in serial lots to develop statistical data on joist properties. In a second phase, the effect of time on serial sampling was considered. The survey showed that. approximately 50 percent of 2 x 8 joists were of smaller dimensions than would be anticipated by reference to the ruling standards. Some differences occurred in sample properties over the sampling interval of 1 year, even in material from the same lumberyards.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## Abbreviations Used

E = Modulus of elasticity

EI = Stiffness

FSP = Fiber saturation point

I = Moment of inertia

MC = Moisture content

SG = Specific gravity

ASTM = American Society for Testing and Materials

ALS = American Lumber Standard

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# Wood Joist Floors: Probabilistic Analysis of Joist Stiffness Measured at Retail Lumberyards

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## Introduction

Improved lumber grading methods developed through research are a step toward more efficient use of the timber resource. Yet the growth of machine grading, the newest stress-grading technology, has been slow. Is machine grading of genuine value to consumers? To clearly demonstrate the commercial value of such innovations, the reliability of present systems of stress grades, designs, and construction practices must be measured (*8*).[2] The stress-grade norm in the United States is the visual grading system; virtually all structural lumber is visually graded. Characterizing the visual grades in a quantitative way can serve as a point of departure for developing advanced grading systems.

During the summers of 1972 and 1973, a systematic sampling of joist lumber was carried out at retail lumberyards throughout Indiana as a cooperative project of the Purdue University Agricultural Experiment Station and the U.S. Forest Products Laboratory at Madison, Wis. The broad objective of the study was to observe and measure physical and mechanical properties of dimension lumber close to the point of purchase and use. This paper discusses the philosophy which prompted the study and presents the results in a probability format.

## Study Philosophy and Background

Lumber quality is difficult to define unless the term "quality" is used in a restricted sense; it is particularly difficult to measure in terms of a practical reference base. (Just what level of material performance is required for a specific end use?) Nevertheless, for stress-graded dimension lumber, there are numerable measurable aspects of quality. In the context of traditional deterministic design, quality implies adherence to the stated criteria of an industry standard. These criteria may include moisture content (MC), size, density, grade stamp legibility, and member stiffness (EI)–all of practical importance to the architect, engineer, and other structural wood users. Lumber which does not adhere to the standard may cause consumer dissatisfaction.

This study was confined to lumber graded and marked in accordance with grading rules developed under PS 20-70, Voluntary Product Standard for American Softwood Lumber (*19*). This standard stipulates minimum lumber size and maximum MC at time of production. The standard references contain several important American Society for Testing and Materials (ASTM) standards used to derive grades of lumber and their associated allowable design properties. In accordance with PS 20-70, agencies are certified to grade lumber. These agencies, therefore, require adherence to PS 20-70 at time of manufacture.

However, "lumber" as viewed by the consumer may be different than "lumber" at time of production. During the interim period between manufacture and use by the consumer, lumber may change dimensions and grade as a function of MC change. In addition, the grade stamp may be obliterated by various causes. Lumber from many sources and of many grades may be mixed in the distribution process. It is important, then, to examine lumber grades as close to the point of consumption as possible so as to evaluate the product as it "arrives" for a particular use.

Property data acquired for lumber at point of use are not therefore expected to have properties identical with those

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

[2] Italicized numbers in parentheses refer to literature cited at the end of this report.

specified by PS 20-70. These data can be consumer-relevant, however, if the proper sampling and analyses are carried out. By linking the characteristics of the product to measurements of frequency of occurrence, probabilistic statements may be made regarding the consistency of "quality" in retail lumber. The probability of obtaining acceptable lots of product can then be stated within the statistical limits of the sampling program.

The retail lumberyard is an efficient location for a survey of dimension lumber. The practical difficulties of sampling large quantities of lumber from a multitude of heterogeneous users at job sites closer to the builder becomes unwieldy. Obviously, some lumber reaches its end use other than through a retailer, but the lumber found at the retail lumberyard level was felt to adequately represent the joist lumber population for purposes of this study.

Our characterization of visually graded joist lumber assumes that houses built using current construction techniques provide reliable floor structures. In conventional light-frame housing, structural floor failures are virtually unknown. This admirable record is due to several interacting factors:

(1) design floor loads are rarely imposed upon a structure; (2) parts of the structure such as sheathing, subflooring, and interior partitions contribute significantly to the mechanical integrity; and (3) conventional design methodology contributes a secure margin of safety for the integrated structure. Progress in design efficiency and the need for improved conservation of the wood resource both call for change in the way we regard these three factors of wood use in home design (*18*). The research reported herein focuses on the inherent characteristics (properties) of members as one of the essential factors in efficient design.

A cautionary paragraph is in order at this point. This research used adjustment factors from several referenced sources as a means of amalgamating a diverse sample set. There is no implication that, as a result of utilizing the National Design Specifications (NDS) (*14*), for example, that the results of the research are comparable design advice. On the contrary, the NDS values are established to represent a national perspective toward efficient use of wood and, consequently, are developed with a view toward the use and interpretation by the design audience. This document, on the other hand, represents a limited study developed to explore sampling, testing, and analysis methodology, as well as to provide input data to further research. The results of this study do not constitute design advice.

## Study Design

This study was divided into two basic phases with differing but related objectives:

***Phase I***—Sample joist lumber in serial lots to develop statistical data on joist properties. The goal was to infer the probability of selecting joist lots with explicit characteristics.

***Phase II.***—Examine (a) the effect of time on serial sampling and (b) the relationship of serial sampling to the population of lumber.

This report will examine these phases separately.

## Phase I

### Sampling

The most common use for joist-size lumber is in floors, and the common use recommendation is the National Forest Products Association's span tables of the National Design Specification (NDS) (*14*). In that design recommendation, the modulus of elasticity (E) is the controlling property for almost all species and grades of No. 2 or Better. On this basis, E, dimensions, and MC were chosen as the principal variables to be examined.

Some evidence is found of the distribution of E for visual grades in the literature (*7,11,13*). However, samples reported usually involve a broad survey of a species or region, or a sample from a sawmill, selected for some other purpose. In this study, the concern is for properties as they typically find their way into floors. Therefore, in this study the sample is selected *serially* from inventory of the retail lumberyard, thus simulating actual selection of material by yard personnel for sale as floor joists.

From these considerations, nominal 2 by 8, 12- or 14-foot lumber was chosen to be sampled in stress grades of No. 2 or higher. Polensek et al. (*15*) have shown that a joist in a floor system shares a concentrated load with no more than three neighboring joists on either side. Their research also illustrated that under uniform loads the floor deflection performance could be predicted from the average of joist properties. So, in this study, 10 joists taken consecutively from a pile were considered to represent a realistic floor segment. Lots of 10 joists could be dealt with in terms which could be related to realistic floor design.

Several a priori assumptions were made for this survey. Indiana, while not claimed to be a "typical" state, is a state which contains both industrial and rural segments, shows varieties of use patterns, and consumes lumber shipped from various lumbermills in the west, south, and Canada. It was assumed that 2 by 8 stock in the length sampled fairly represented the quality of dimension lumber reaching the market place.

The population of retail lumberyards was stratified by geographic region within Indiana, credit class of the lumberyard, and the population of the nearest town. This stratification was intended to (1) increase precision of estimation, and (2) facilitate comparison among regions and sizes of towns where lumberyards are located. Retail lumberyards numbered approximately 630 in the State of Indiana based on the Lumberman's Red Book, the reference chosen for names, addresses, and credit ratings used for stratification (*12*).

The state was divided into six geographical regions. The City of Indianapolis was considered a unique market area, being the major metropolitan area in the state, and had enough lumberyards to be delineated as one of the six regions. The balance of the state was divided into five regions of the same approximate area. Within these regions, the cities and towns

were grouped into three population groups: Fewer than 5,000; 5,000 to 25,000; and greater than 25,000. The individual yards in a group were then divided by credit rating into five subgroups. The credit rating was used to reflect yard size and financial resource status. Table 1 summarizes the sampling stratification.

**Table 1. – Strata used to establish retail yard sampling plan**

1. Region—6 geographic regions
2. Population—3 classes
   1. < 5,000
   2. 5,000-25,000
   3. > 25,000
3. Credit rating—5 classes *(12)*
   Class 5 has highest rating
   Class 2 has lowest rating
   Class 1 credit unknown

Yards were selected randomly for actual visitation and testing by the following rule: One site selection for the first 12 yards in a sample cell, two site selections for the cells having 13 to 20 yards, three site selections for cells having 21 to 28 yards, and four sites selected for cells having more than 29 yards. Originally, 104 yards were selected out of the 630 possible yards. As the study progressed, the number of yards actually visited was reduced to 91. For data analysis, these 91 yards produced 96 lumber samples because some yards carried more than one species in the sampled lengths.

For each sampled yard, a minimum of 20 specimens were selected by serially selecting two lots of 10. The total inventory of the 2 by 8's, No. 2 or Better of the length sampled, was also counted. Table 2 summarizes the sample plan. Note that in some cells no samples were drawn. This occurred for various reasons, including the discovery of no eligible lumber at the site (e.g., hardwoods only, no dimension, no 2 x 8), yard out of business, incomplete sample (e.g., less than 40 pieces, wrong grades, different species), or the yard declined to participate. (Yards refusing to participate totalled less than 8 pct.) These problems both reduced the total to 91 and caused analysis difficulties because of voids within the sample cells.

The total lumber sample in phase I was 2,020[3] pieces of 12-and 14-foot dimension. Table 3 summarizes this sample together with the indicated MC at time of manufacture, the length, and the species. Totals in table 3 differ slightly from those reported in an early report of the sampling and testing procedure after final screening of yards and specimens (*17*).

Before a site was visited, a contact was made with the yard manager for permission to sample the stock and to ascertain if enough material was present to permit a proper sampling to be made. (Interestingly, this initial contact indicated some confusion about lumber grading and the term "stress grading*' among retail lumber dealers and yard personnel; as a consequence, some trips were unproductive.) Upon arriving

[3] Some of the figures in this report include only 2,000 of the 2,020 specimens. This is due to the fact that for 20 specimens in 1 yard the moisture meter malfunctioned. Rather than discard all of the information on those specimens, we chose to include them except for the variables that were adjusted for MC.

**Table 2. –Summary of strata used and the number of retail yards selected per strata**

| Region | Credit | Population 1 | | Population 2 | | Population 3 | |
|---|---|---|---|---|---|---|---|
| | | $N_h$[1] | $n_h$[1] | $N_h$[1] | $n_h$[1] | $N_h$[1] | $n_h$[1] |
| 1 | 1 | 1114191 | | | | | |
| | 2 | 61 | | | | 1031 | |
| | 3 | 101 | | 21 | | 31 | |
| | 4 | 13 | 2 | 11 | 1 | 15 | 2 |
| | 5 | 31 | | 21 | | 61 | |
| 2 | 1 | 40591 | | | | 51 | |
| | 2 | 91 | | 11 | | 00 | |
| | 3 | 213 | | 31 | | 41 | |
| | 4 | 213 | | 61 | | 51 | |
| | 5 | 91 | | 31 | | 21 | |
| 3 | 1 | 20261 | | | | | 91 |
| | 2 | 21 | | | | 1000 | |
| | 3 | 182121 | | | | | 10 |
| | 4 | 223 | | 81 | | | 91 |
| | 5 | 61 | | 51 | | | 31 |
| 4 | 1 | 222121 | | | | | 51 |
| | 2 | 111 | | | | 0000 | |
| | 3 | 25 | 3 | 10 | 1 | | 11 |
| | 4 | 192 | | 30 | | | 81 |
| | 5 | 21 | | 61 | | | 51 |
| 5 | 1 | 202132 | | | | 91 | |
| | 2 | 121 | | 21 | | 00 | |
| | 3 | 24261 | | | | 71 | |
| | 4 | 101 | | 71 | | 41 | |
| | 5 | 11 | | 21 | | 00 | |
| 6 | 1 | | | | | 13 | 2 |
| | 2 | | | | | 11 | |
| | 3 | | | | | 31 | |
| | 3 | | | | | 20 | |
| | 5 | | | | | 61 | |

[1] $N_h$ = number of yards in each stratum h.

$n_h$ = number of yards sampled in stratum h.

at a yard and selecting a pile of lumber for testing, the first 10 pieces from the pile were discarded to reduce any effect of "picking over." The next 10 members were chosen for testing, another set of 10 was discarded, and a second set of 10 chosen for testing to yield the sample size of 20. When time permitted, the sample size was increased to 30 pieces; this required a total of 60 pieces in stock.

## Measurements

### Variables Measured

The American Lumber Standard (ALS) PS 20- 70 describes several aspects of product quality in softwood dimension lumber. Certain properties and some related characteristics were chosen for study. Since the stock was to be replaced after inspection and testing, only those properties that could be evaluated by nondestructive means were investigated.

1. Moisture content (MC). —The ALS relates lumber size to MC at time of manufacture and recognizes three degrees of drying: S- green, S-dry, and MC-15. (A KD designation, which is limited to southern pine, is comparable to MC- 15 in other species.) A 2 by 8 stamped S-GRN denotes that it was surfaced in the "green" state, defined as having an MC above

**Table 3.–Sample summary of 2 by 8 dimension lumber in a 1972 lumberyard survey in Indiana**

| Species group[1] | Moisture content[1] | Lumber length | Number of specimens |
|---|---|---|---|
| | | Ft | |
| Douglas Fir | S-GRN | 12 | 60 |
| | | 14 | 40 |
| | S-DRY | 12 | 110 |
| | | 14 | 20 |
| Douglas Fir-Larch | S-GRN | 12 | -- |
| | | 14 | 20 |
| | S-DRY | 12 | -- |
| | | 14 | -- |
| Southern Pine | S-DRY | 12 | 200 |
| | | 14 | 40 |
| | KD | 12 | 410 |
| | | 14 | 40 |
| Spruce-Pine-Fir | S-DRY | 12 | 410 |
| | | 14 | 120 |
| Hem-Fir | S-DRY | 12 | 310 |
| | | 14 | 70 |
| Western Hemlock | S-DRY | 12 | 20 |
| | | 14 | 70 |
| Ponderosa Pine | S-DRY | 12 | 60 |
| | | 14 | 20 |
| | | Totals | 2,020 |

[1] **As indicated on the grademark.**

19 percent. A 2 by 8 marked S-DRY denotes surfacing in the "dry" state–at a maximum MC of 19 percent. The rules governing lumber manufactured in Canada for importation to the United States are identical to United States grade rules. Moisture restrictions are summarized in table 4.

**2. *Lumber dimensions.*–** The ALS states that a 2 by 8 marked S-GRN shall be a minimum of 1-9/16 inches thick and a minimum of 7-1/2 inches wide (except for permissible wane) at time of manufacture; S-DRY and MC-15 minimum dimensions are 1-1/2 by 7-1/4 inches.

**3. *Modulus of elasticity (E).*–** The degree to which the loaded floor joist deflects depends upon the E of the material of which the joist is made. Higher E values result in smaller deflections when loaded. In addition, member "stiffness" (EI)–the product of E times moment of inertia (I)–is often the limiting factor for joists in residential construction where allowable deflections are more limiting than strength considerations. Thus the E values assigned to each lumber grade by the agencies which write grade rules and the EI values were both studied.

**4. *Density and specific gravity (SG).*** –Although density, specific gravity, or weight are not properties claimed in either ALS or in the grade rules, density was included in this study to provide information on actual dead load values, and because density is an indicator of mechanical properties. In particular, SG was computed from density to relate SG to E and to relate average species SG values to those of the survey lots. SG was calculated as ovendry weight and volume at 12 percent MC. For dead load information, density was computed as weight (pounds) calculated at 12 percent MC per unit volume (cubic feet) of wood corrected to 12 percent MC.

**5. *Lumber surface temperature at time of test.*** –Surface temperature was taken to permit temperature compensation for moisture meter readings. Since the ambient temperature at the time of test varied from about 40° F to more than 90° F, temperature corrections were deemed necessary.

**6. *Grade stamp legibility.*** –Each stress-graded, grade-stamped joist in the American Standard system is required to have legible, specific information: (a) Grading agency symbol or identification, (b) species or species grouping code, (c) lumber grade (grade name and/or "f rating"), (d) MC at time of surfacing (S-DRY, S-GRN, MC-15), and (e) producer mill number. For classification purposes, if any one item on a grade stamp was definitely illegible, the stamp was declared not legible. However, illegibility is caused by many things other than manufacturing errors; dirt and water stains were common causes of illegibility. Most pieces came from a lumber packet; thus, stamps only partially legible could usually be deciphered through association with like pieces within the packet.

**7. *Method of lumber storage.*** –Lumber which is stored under roof in most parts of the United States will rarely pick up much moisture from the atmosphere. Lumber so stored will generally tend to equalize at some MC below the PS 20- 70 MC at which it was manufactured and shipped. On the other hand, lumber which is stored in an area open to the rain and weather can change MC appreciably. Method of lumber storage, therefore, can have a practical effect upon the size and MC of the lumber. In general, most lumber was stored under roof; that which was stored in the open was usually paper wrapped and nearly always kept off the ground by sleepers.

**8. *Lumberyard inventory.*** –Information about the normal stocked inventory was obtained from the yard managers or foremen. Yards which might normally have had a substantial inventory, but which had less than 40 pieces in stock at the time the yard was contacted, were not sampled.

**Table 4.–Moisture content related to ALS grade stamp moisture designation**

| Grade stamp marking | Average moisture content of lumber in a lot[1] | Maximum moisture content of any piece in a lot[2] |
|---|---|---|
| | Pct | Pct |
| S-DRY | 15 | 19 |
| S-GRN | NA | NA |
| MC-15 | 12 | 15 |

[1] Industry practice acknowledges an approximate relationship between the maximum MC of any piece within a kiln charge and the average of a representative reading from all pieces within a charge (*20*). ASTM D 245 uses the average MC of the lot as the basis of property adjustments for dryness (*1*). Lots labeled S-GRN have no anticipated MC by industry practice.

[2] American Lumber Standard PS 20-70 (*19*).

**9.** ***Species.*** –The following commercial species or species combinations were tested: Douglas Fir, Hem-Fir, western hemlock, Douglas Fir-Larch, Ponderosa Pine, Southern Pine, spruce-pine-fir. Douglas Fir and Douglas Fir-Larch are assigned identical allowable design properties and were combined for analysis purposes even though the grademarks distinguished between the two classifications. Similarly, for some analyses, Hem-Fir and western hemlock were combined.

## Data Collection and Testing Procedure

A variety of data was required for the analysis. Some items required a rather simple observation; with others, concern with accuracy was required. The following list describes the principal observations:

1. Grade stamp information–ALS species, MC designation, grade, grading agency, mill code.
2. Legibility of the grade stamp.
3. Member weight to the nearest 0.1 pound.
4. MC to the nearest 0.5 percent near one end and at midlength as measured by electric resistance moisture meter.
5. Temperature to the nearest degree as measured by a surface thermometer placed on the lumber as close as possible to the stock being sampled.
6. Member length to the nearest 0.1 inch.
7. Member width to the nearest 1/32 inch measured near one end and at midlength.
8. Member thickness to the nearest 0.01 inch measured near one end and at midlength.
9. Midspan deflection to the nearest 0.001 inch for dead loads of 50 and 250 pounds tested on edge as a joist.
10. Method of storing lumber—underroof, at protected site, or open to the weather.

Midspan deflection was determined for subsequent E calculations. A truck-mounted beam tester (fig. 1) was designed and fabricated at Purdue University. The apparatus was easily demountable so that it could be readily transported from yard to yard. With this system, a 2 by 8 could be tested on edge over a 10- foot span. Loading was at the quarterpoints of the span. Deflection was measured to the nearest 0.001 inch by means of a dial gage located at midspan. A hydraulic jack located beneath the beam at midspan was used to apply the load weight. Lowering the jack a few inches applied a yoke to the quarter-points; the yoke weighed 50 pounds and served to steady the beam and cause an initial deflection. Lowering the jack further applied an additional 200- pound weight to the beam so that the incremental deflection was obtained to permit computation of member E values within the elastic range. Preliminary testing showed that each member had to be preloaded for accurate results; consequently, the loading procedure was followed twice for each beam with the data being recorded only for the second loading.

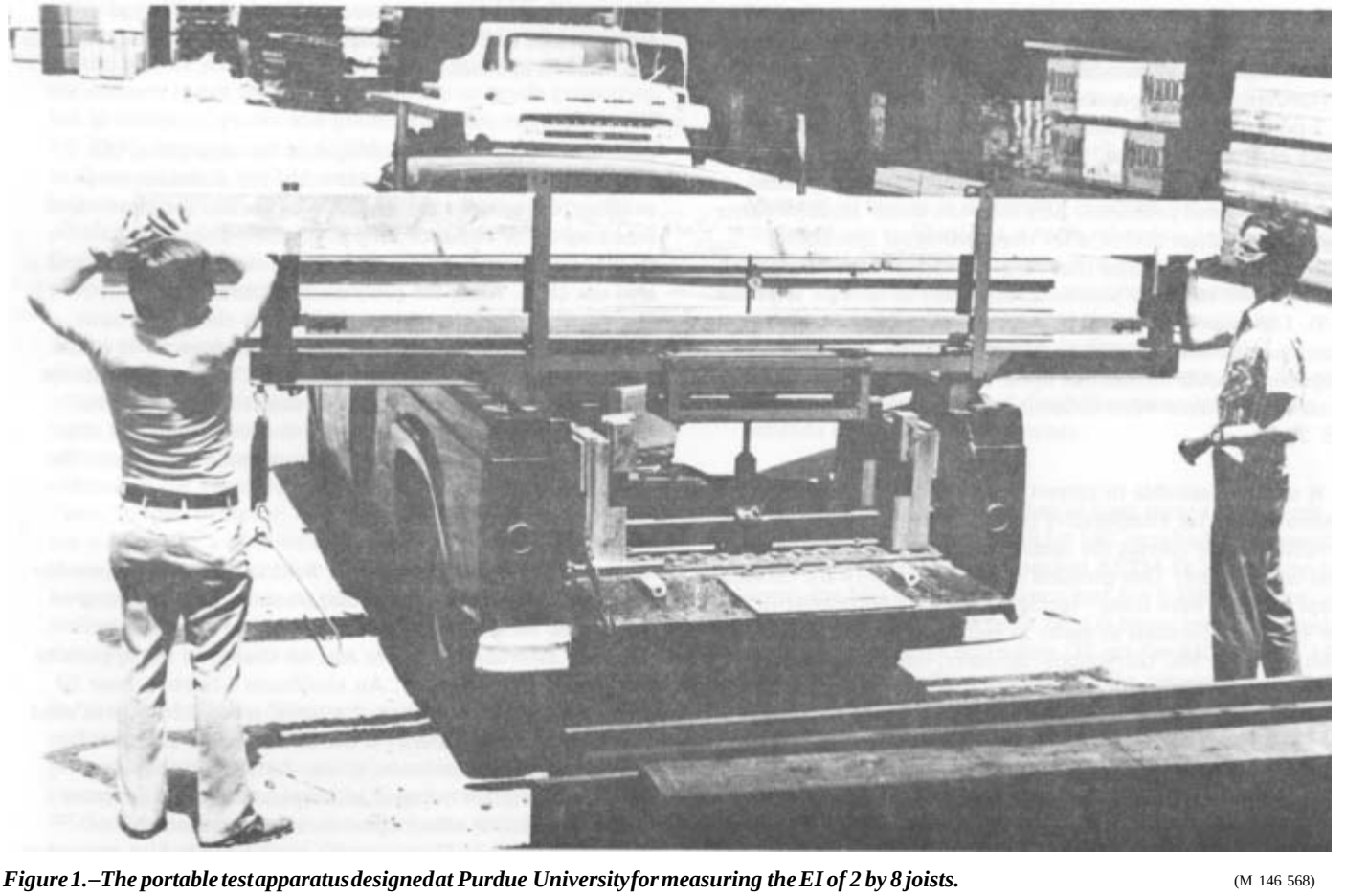

***Figure 1.–The portable test apparatus designed at Purdue University for measuring the EI of 2 by 8 joists.*** (M 146 568)

Each member was examined briefly before being placed in the beam tester. Following recommended construction practice, if any crook was present in a member, the crook was placed "up" for testing. If no crook was observed, the most noticeable defect was placed "down" and within the zone of maximum bending moment for testing. This procedure tended to bias the test results, but was in keeping with ASTM D 2915 (*2*).

Normally, a 2 by 8 will vary in thickness by several hundredths of an inch along its length. For this reason, width and thickness measurements were the average of measurements made at two places on each piece. Localized defects (knots, wane, skips) were avoided when measurements were taken. In some cases, two lengths, 12 and 14 feet, of the same species were tested at one yard.

## Data Adjustments

A field study over a wide geographical area produces problems often conveniently absent in laboratory investigations. These problems concern the use of portable equipment for EI measurement and MC measurement, and also affect observations on lumber conditions as they existed within individual retail yards.

### Moisture Meter Correction

Perhaps the most concern in the study was for measurement of, and eventual corrections for, MC. This complex problem posed dilemmas with no really satisfactory answers. A resistance-type moisture meter was used to measure the MC of each piece at two places along its length. With this type of meter, widely used throughout the industry, accuracy as influenced by species and other characteristics may range to ± 3 percent (*16*). Fluctuations in MC between locations on the piece are to be expected, and gradients in the lumber due to the drying process and subsequent handling in storage can cause additional problems. Any moisture meter tends to better represent average MC of a lot than individual specimens; however, the ALS states that no piece stamped as "dry" shall have an MC above 19 percent at any place at time of shipment (*19*). Likewise, MC-15 and KD designations limit the maximum permissible MC to 15 percent. This obviously imposes difficult restrictions upon the manufacturer and presents problems when collecting MC data referenced to PS 20-70.

It is usually desirable to correct property data to some common MC for comparative purposes. The first step of the procedure is to correct the moisture meter readings for species and temperature. This problem is not straightforward because most samples were from "species groups." Spruce-pine-fir, for example, contains as many as eight species, presumably all with different MC corrections. Actually, corrections were available in the literature in tabular form only for three or four of those species. The same statements could be made about most of the other species groups (e.g., Hem-Fir, Douglas Fir-Larch, Southern Pine). To make species corrections, we chose either "major" species in the species group or a species which tended to have a more conservative MC correction, as long as it was not either an extremely minor species in terms of quantity or an overly conservative correction. We felt that this was a more valid approach than, for example, using only three species out of eight and averaging.

Thus Hem-Fir was corrected on the basis of western hemlock. The Southern Pine corrections were based on short-leaf pine; spruce-pine-fir corrections were based on white spruce; and Douglas Fir-Larch on the basis of Douglas-fir. The latter case is an example of the judgment that must be made. Larch has a bigger correction than Douglas-fir (Douglas-fir actually has zero correction on an electrical resistance-type meter, calibrated on a basis of Douglas-fir) but the quantity of larch present in Douglas Fir-Larch combinations was presumed to be low and it appeared to be more logical to base the correction on Douglas-fir.

Another portion of the moisture meter dilemma is that there is no ASTM standard under which moisture meter calibrations or corrections are made. Thus, it was necessary to use corrections available from a variety of sources. The corrections for Douglas-fir, hemlock, ponderosa pine, and short-leaf pine were from the manual that accompanies the resistance moisture meter. The correction for white spruce was from Bramhall and Salamon (*3*). All moisture measurements were temperature corrected based on the graphical data by James (*10*). A simple linear form was developed from (*10*) to cover the temperature range from approximately 55° to 90° F. Small errors from the linear form were noted at the lower MC's at the lowest and highest temperatures (basically, below 65° F and above 80" F). To correct this error, a second-order term was subtracted at low temperatures and added at high temperatures. All adjustments are listed in appendix A.

### Dimension

Once a corrected MC was computed for each piece, the dimensions themselves were corrected for shrinkage or swelling. Corrections are available by species for clear wood based on either radial or tangential grain directions. Obviously, lumber is not perfectly quarter- or flat-sawn and is also not clear. Also, the problem of accurate species identification appears once again. In this study, the basis chosen for dimension corrections was that prescribed in the American Softwood Lumber Standard: Changes of 1 percent in dimension for each 4 percent change in MC for all but certain high extractive species (*19*). It should be noted that this is an average-type adjustment; appendix B discusses the adequacy of this factor.

### Modulus of Elasticity (E)

Measuring and evaluating E in a field study poses its peculiar problems. The use of a portable, truck-mounted E-tester to travel over the state necessitated the use of a calibration device to ascertain that there was no change in the apparatus that would produce error. An aluminum I-beam, whose EI product was similar to that of a lower grade 2 by 8, was used as a daily reference check on the demountable E-tester. By use of the calibration beam, it was determined that road travel and frequent removal and replacement of apparatus had no discernible effect upon accurate measurement of member deflection. However, the testing resulted in somewhat 'more variability in the data than would be expected in normal,

stringently controlled experimental conditions. Laboratory tests of the apparatus indicated that general deflection measurement varied about ’0.002 inch. Furthermore, with the wide ranges of E values found among the several species and grades tested, an error in deflection measurement of, for example, 0.002 inch could result in from 6,000 pounds per square inch to 60,000 pounds per square inch error in E depending upon EI. The point is that the field studies tended to have larger experimental error factors than laboratory studies. In laboratory tests conducted with field specimens, there was no evidence that variability in measurement due to apparatus used in the field was a function of E; high E pieces had variability in measurement similar to pieces with low E values. Thus, no adjustments were required for the E data.

## Density

Each member was weighed and its MC measured. S-GRN lumber density values were not calculated because many such pieces were over 30 percent MC. Corrections to such member weights depend upon moisture meter readings which are only approximate above 30 percent MC.

## Analysis

A basic premise of this study that affects all data and its’ analysis is that the lumber in the retail yard is basically viewed as acceptable by the builder and, specifically with respect to joist lumber, will be accepted for the conventional house as a satisfactory building material. The presumption is made that the NDS span tables were the basis for floors designed in Indiana in 1972 during the sampling period (14). Because the purpose of the study is to develop a baseline of information on the type of joist material in successful floors in Indiana, the concern is not for individual species or grade properties, but to compare species and grade properties represented under PS 20-70, through use of ASTM standards, and by the NDS to those obtained by field measurements. To provide the basic information needed to analytically describe the successful performance of these joists with respect to other aspects of floor construction, it is necessary to relate measured properties to the design basis.

To compare across classes of species and grade for the variety of material sold in the State, an “idealizing” procedure was adopted. This procedure accepted the NDS as the reference base; the actual measured properties were divided by the NDS reference base. Clearly, a joist with the value exactly as claimed in the standard would have an idealized value of “one.” Note, however, that the NDS reference base for E is the average for a population or perhaps for a large lot. Thus, there is no implication that individual joists are expected to have an idealized value of one for E, and individual joists as well as means of small lots might be expected to deviate from this value.

Before the idealizing procedure could be employed, it was necessary to adjust the data to a common MC base. All properties measured were adjusted to an MC basis of 12 percent. This included both the E and the dimensions. The NDS reference base values for all but the MC-15 lumber assume a 15 percent basis. Thus most NDS values had to be modified to provide an idealized base at 12 percent MC. Whenever possible, adjustment procedures followed the ALS and the ASTM standards D 245, D 2555, and D 2915. Some further interpretations had to be made. All corrections are detailed in appendix A.

## Results–A Histogram Presentation

Histograms are used extensively in this report because they permit visual examination of skewness and comparison of means and near minimums with target values referenced in standards and used in design. The histograms that follow depict 10 specimen lot values. In addition to means, the standard deviation of lot means ($s_{\bar{x}}$) and the average standard deviation of specimens with 10 specimen lots ($\bar{s}_i$) accompany the histogram. [4]

### *Dimensions*

“Nonidealized” or “raw” data for lot average width and thickness are shown by histograms in figures 2 through 5. Figures 6 and 7 show corresponding idealized values. An interpretation of PS 20-70 is that dimensions, including the ideal values based on NDS, are minimums, so that no minus tolerances are acceptable. For example, the “ideal” width for S-DRY lumber adjusted from NDS to 12 percent MC would be 7.196 inches. On that basis, much lumber falls below the anticipated size on the MC adjustment basis used. Note that the average thickness corresponds closely to the idealized value of 1. Another method of presenting this data is to address the probability of occurrence of a dimensionally “acceptable” or “unacceptable” lot by a builder. This concept will be dealt with later in the paper. Note also that individual specimen histograms are not shown. Such histograms might imply a random sample; such was not the case. The study was designed to display lot information. In fact, the study demonstrated significant lack of uniformity between lot specimens, i.e., they do not constitute a “population.”

### *Moment of Inertia (I)*

Moment of inertia is a property in which the width and thickness are combined in a form related to joist stiffness; thus, the resulting histograms are of primary interest. Figures 8 and 9 show histograms of 10-specimen lot averages based on, raw data, and figure 10 idealized data. Although the dispersion of I appears greater in figure 8 than 10, comparison of coefficients of variation of lots (0.03 for raw data and 0.04 for idealized data) illustrates the similarity between raw and idealized values.

### *Moisture Content (MC)*

MC of the sampled lumber has at least three target levels on a lot average basis. An average lot MC required for property adjustments is assumed to employ ASTM D 245. Figure 11 shows the MC data of specimen lots for S-DRY lumber, and figure 12 for MC- 15. The D 245 (*1*) target levels assumed for mechanical property correction (12 pct for MC-15, and 15 pct for S-DRY) are indicated. Many of the lot averages exceed the D 245 targets. Because this sampling was subsequent to manufacture, one might expect MC to be different from the production site target. Yet there was little evidence of exposure to rain in storage and although the MC’s are high,

[4] The standard deviation of lot means ($s_{\bar{x}}$) is an estimator of the variability of lot means. The average standard deviation of specimens within the lots ($\bar{s}_i$) is the arithmetic average of the standard deviation of specimens calculated in each lot.

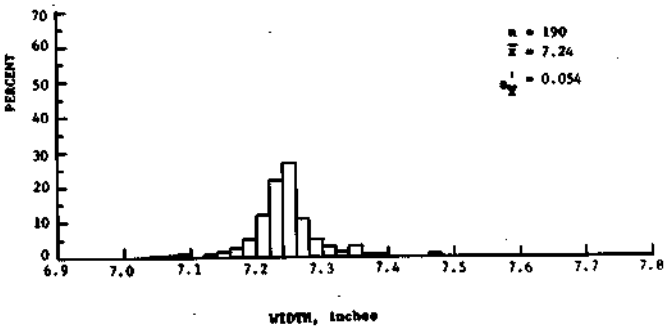


*Figure 2.–Width of S-DRY and MC-152 × 8 joists presented as the average of 10-specimen lots, as measured in the lumber yards. No adjustments for moisture have been made. (The symbol n denotes number of lots; x̄, the mean; and $(s'_{\bar{x}})$, the standard deviation of lot means.)* (M 146 445)

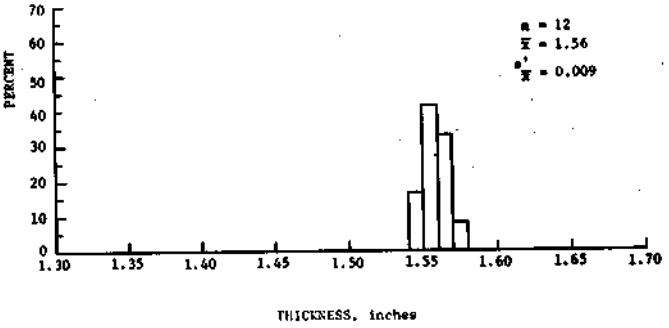


*Figure5.–Thickness of S-GRN2 × 8 joists presented as the average of 10-specimen lots, as measured in the lumber yards. No adjustments for moisture have been made. (The symbol n denotes number of lots; x̄, the mean; and $s'_{\bar{x}}$, the standard deviation of lot means.)* (M 146 466)

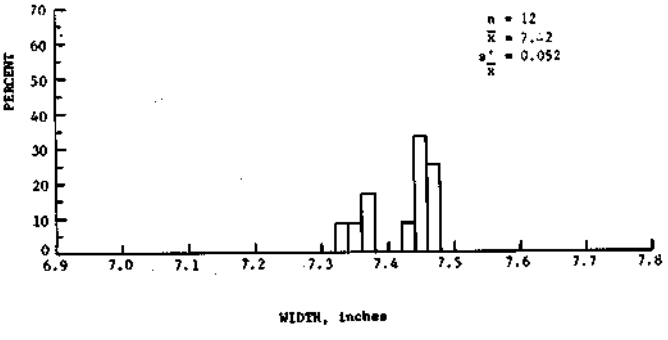


*Figure 3.–Width of S-GRN2 × 8 joists presented as the average of 10-specimen lots, as measured in the lumber yards. No adjustments for moisture have been made. (The symbol n denotes number of lots; x̄, the mean; and $(s'_{\bar{x}})$, the standard deviation of lot means.)* (M 146 455)

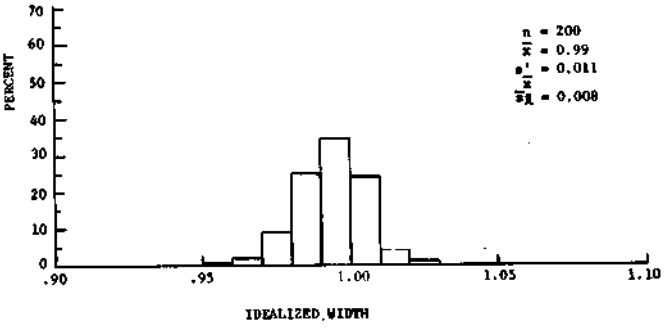


*Figure 6. –Width of the 2 x 8 joists sampled, presented by lots on an "idealized" basis. All values are the quotient of the measured value and the NDS target value, both adjusted to 12 percent MC. (The symbol n denotes number of lots; x̄, the mean; $s'_{\bar{x}}$, the standard deviation of lot means; and $\bar{s}_1$ the mean standard deviation of specimens within lots.)* (M 146 467)

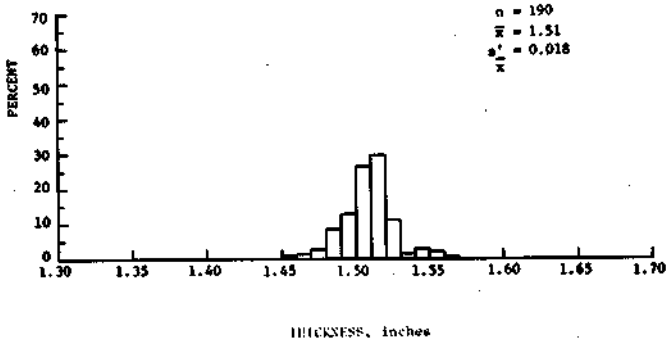


*Figure 4.–Thickness of S-DRY and MC-152 × 8 joists, presented as the average of 10-specimen lots, as measured in the lumber yards. No adjustments for moisture have been made. (The symbol n denotes number of lots; x̄, the mean; and $s'_{\bar{x}}$ the standard deviation of lot means.)* (M 146 465)

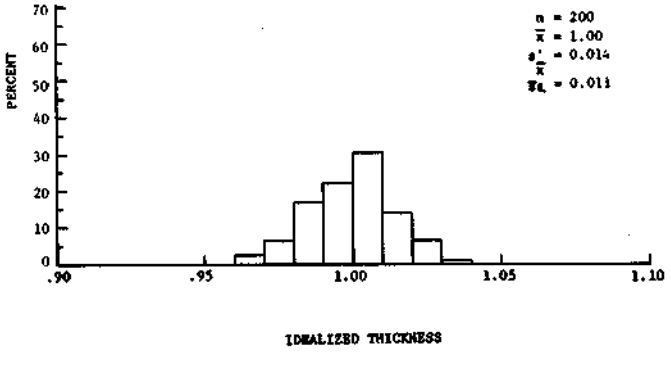


*Figure 7.–Thickness of the 2 × 8 joists sampled, presented by lots on an "idealized" basis. All values are the quotient of the measured value and the NDS target value, both adjusted to 12 percent MC. The symbol n denotes number of lots; x̄, the mean; $s'_{\bar{x}}$, the standard deviation of lot means; and $\bar{s}_1$, the mean standard deviation of specimens within lots.)* (M 146 468)

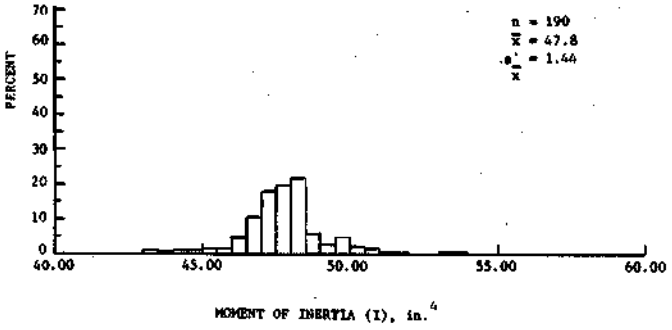


*Figure 8.–Moment of Inertia (I) of a joist based on measurements, unadjusted–for lots of S-DRY and MC-15 joists only. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the standard deviation of lot means.)* (M 146 446)

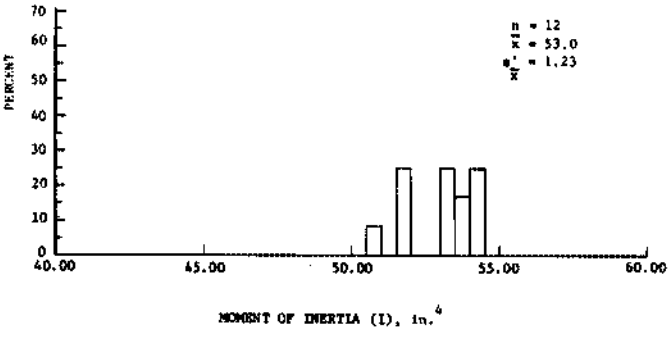


*Figure 9. –Moment of Inertia (I) of a joist based on measurements, unadjusted–for lots of S-GRN joists only. (The symbol n denotes number of lots; x̄, the mean; and $s_{\bar{x}}$, the standard deviation of lot means.)* (M 146 447)

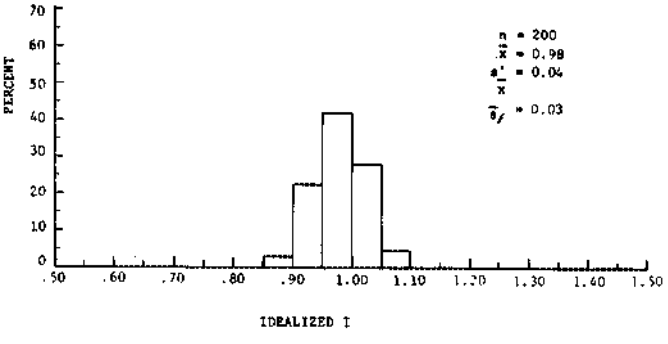


*Figure 10.–Moment of Inertia (I) for 10-specimen lots where all data have been corrected for MC and idealized to an NDS "target" base. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the the standard deviation of lot means; and $\bar{s}_i$, the mean standard deviation of specimens within lots.)* (M 146 448)

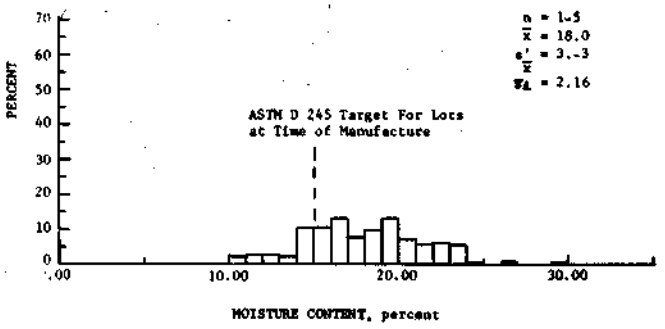


*Figure 11.—Lot average MC at time of sampling for lumber designated by the grade stamp as S-DR Y. The moisture meter was corrected for species and temperature. The ASTM D 245 lot average target at time of manufacture is shown. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the standard deviation of lot means; and $\bar{s}_i$, the mean standard deviation of specimens within lots.)* (M 146 449)

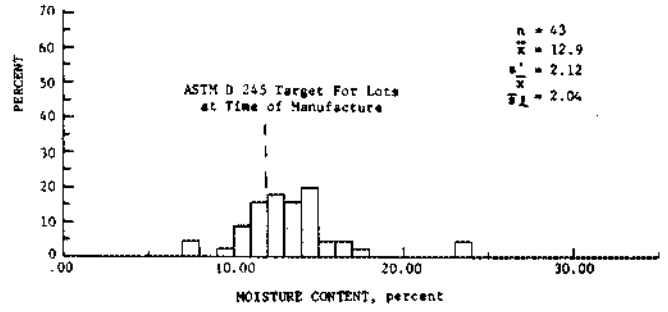


*Figure 12.–Lot average MC at time of sampling for lumber designated by the grade stamp as MC-15. The moisture meter was corrected for species and temperature. The ASTM D 245 lot average target at time of manufacture is shown. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the standard deviation of lot means; and $\bar{s}_i$, the mean standard deviation of specimens within lots.)* (M 146 450)

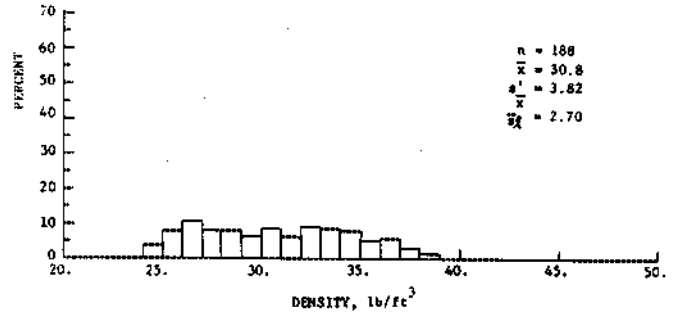


*Figure 13.–Density of 2 × 8 joists in lb/ft³ where weight and volume are on a 12 percent MC basis. Only S-DRY and MC-15 joists are represented. AN species and grades are combined. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the standard deviation of lot means; and $\bar{s}_i$, the mean standard deviation of specimens within lots.)* (M 146 451)

the dimensions at time of sampling were not excessive (see figs. 2-5).

No actual S-GRN MC's are shown because the moisture meter was not sufficiently accurate above 30 percent. All meter readings above 30 percent were indicated as 30.

***Density and Specific Gravity (SG)***

It would be desirable to observe the density of the specimen lumber on an idealized basis. It is difficult, however, to establish an idealizing base because some of the commercial grades contain several species. As a consequence, the density and SG results (figs. 13 and 14) serve as a record of the variation only in lumber which was marked S-DRY, MC-15, or KD. Density (in lb/ft$^3$) is on the basis of weight and volume corrected to 12 percent MC; SG is at ovendry weight and volume at 12 percent MC.

***Modulus of Elasticity (E)***

Lot E values idealized with the NDS values are generally lower than the ideal value of one. Figure 15 shows the lot histograms that describe the results for E. The NDS values are intended to be averages of lots; yet, the figure 15 lot average is less than this target by approximately 9 percent.

For comparison, figure 16 illustrates E values for S-DRY and MC-15 lumber based on raw data (no corrections to a common span-to-depth ratio loading, MC (*2*), or for temperature), idealized by the NDS-listed E values to adjust for species. Figure 17 provides S-GRN E values idealized by NDS values adjusted for green conditions.

One possible criticism of this analysis might be made. The study included seven species marketing groups, six of which had different assigned E values, with additional differences by grade level. Supposing, for example, that one particular species or species-grade combination could be primarily responsible for either superior or inferior performance (i.e., the idealized values are on either the *far* right or *far* left of one). Then the probabilities of purchasing a particular quality level by a customer may be misleading if many retail yards do not carry that particular grade or species combination. To examine for extreme bias, idealized histograms were observed (but not shown here) by species-marketing combinations even though some of these groups contained far too few specimens to make probabilistic statements on the basis of a single species alone.

Review of these histograms suggests that there is only a slight potential for bias; two of the seven species groups adhered to the NDS claim within 3 percent (i.e., the mean of the histogram is within 3 pct of the idealized value of 1.0). The mean values of other species are approximately 10 percent lower in corrected E values. The two species within 3 percent both comprised only 8.4 percent of the total specimens.

A similar analysis of MC was made by species. In this case, only in one species of very limited sample size did MC values agree closely with ASTM production targets.

Values determined by individual species and grade level were examined in the study only subjectively. The sampling plan was oriented to determine the probability of properties obtained by the customer. Thus the data base was not designed to give a good measure of individual species and grade performance; necessary statistical procedures for sample selection were not developed for species and grade identification.

***Stiffness (EI)***

Stiffness values are not listed in most design manuals; nevertheless, the ALS suggests that the dimensions are minimums, and D 245 (*1*) implies that the E is the mean value of a lot. The ideal target value, therefore, should be a mean value. It is possible, then, to develop an idealized EI value against which survey data can be compared. Figure 18 illustrates, as suggested from the individual E and I information, that the mean of the distribution did not meet the desired value of 1.0. The overall mean EI was 0.88. For comparison, figure 19 illustrates EI based on "raw" data. Note in figure 18 that, overall, 5 percent of specimen lots had average EI values as low as approximately 65 percent of the assumed value based on NDS; approximately 70 percent were less than the assumed value.

A discussion of the procedures for "idealizing," which considers variability in the histograms on thickness, width, and I, is found in appendix B.

## Results—Property Relationships

***Specific Gravity (SG) as a Predictor of E***

Specific gravity is known to be related to E in clear, straight-grained wood. It is not well related to E for lumber containing natural characteristics such as knots and slope of grain. Nevertheless, for some types of potential grading systems, such as species-independent systems which might be applied to tropical forests, there may be some value in examining these relationships. Further, no study at the consumer level has examined the results of the SG versus E relationship across species and grade combinations. Figure 20 illustrates this relationship for all specimens graded as S-DRY, MC-15, or KD in this study. SG and E are both corrected to bases of 12 percent MC as explained previously.

***Variation of E by Grade***

ASTM D 245 (*1*) requires that the E for No. 2 grade be assigned 10 percent lower than for No. 1 and Select Structural. This reduction is applied to the mean value for the grade. Histograms which represent the idealized species E values can be examined for the adequacy of this D 245 adjustment. Idealized E values for all species Select Structural and No. 1 were combined for comparison with No. 2 and No. 2 MG in figure 21. If the adjustment is adequate, the means ($\bar{x}$) for the two groups should be equal. It is noted that the adjustment (reduction) for No. 2 may be 3 percent too small. Note that this difference is also statistically significant at the 5 percent level.

Likewise, D 245 allows a 5 percent increase in E for density. Figure 22 is a histogram comparison of the adequacy of the adjustment in E for density, where Select Structural and No. 1 are compared with Dense Select Structural and Dense No. 1. Similarly, figure 23 compares No. 2 and No. 2 MG with Dense No. 2. The comparison suggests that the D 245 adjustments for No. 1 and Select Structural, based on the

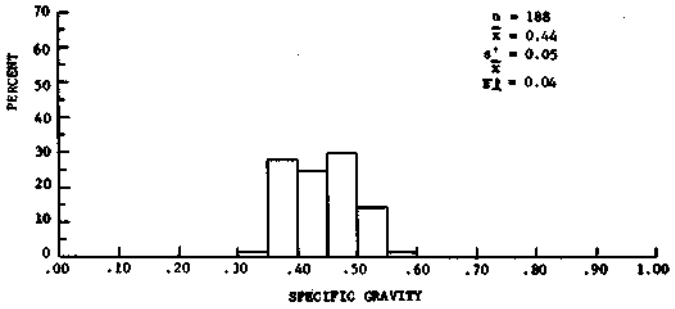


*Figure 14.–Specific gravity of 2 × 8 joists on the basis of ovendry weight and volume at 12 percent MC–S-DRY and MC-15 joists only. All species and grades are combined. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the standard deviation of lot means; and $\bar{s}_i$, the mean standard deviation of specimens within lots.)* (M 146 452)

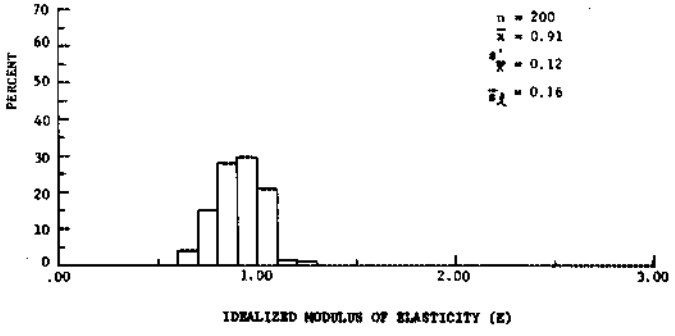


*Figure 15.–Idealized E values by lot for all species and grades sampled. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the standard deviation of lot means; and $\bar{s}_i$, the mean standard deviation of specimens within lots.)* (M 146 453)

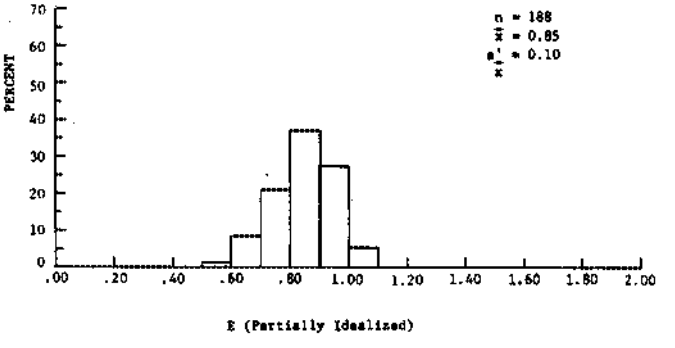


*Figure 16.–Modulus of elasticity (E) of lots idealized only by NDS listed E values to account only for species differences (i.e., no adjustment for span-to-depth ratio, loading, temperature, or MC), S-DRY and MC-15 only. (The symbol n denotes number of lots; x̄, the mean; and $s_{\bar{x}}$, the standard deviation of lot means.)* (M 146 454)

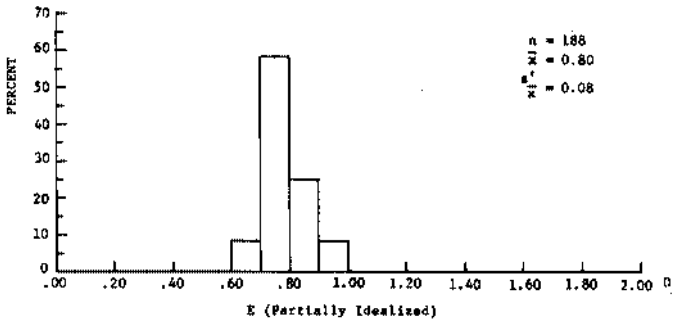


*Figure 17.–Modulus of elasticity (E) of lots idealized only by NDS listed E values to account only for species differences (i.e., no adjustment for span-todepth ratio, temperature, or MC), S-GRN only. (The symbol n denotes number of lots; x̄, the mean; and $s_{\bar{x}}$, the standard deviation of lot means.)* (M 146 456)

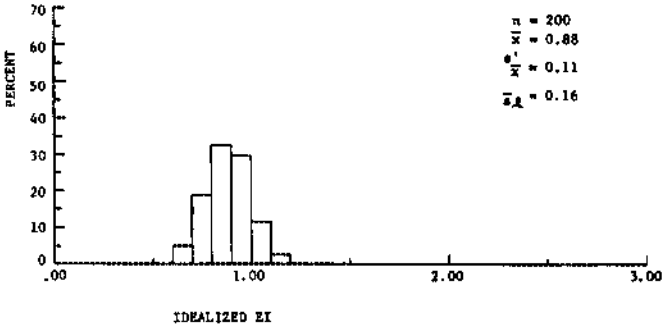


*Figure 18.–Stiffness (EI) of 2 × 8 joists idealized on the basis of NDS (PS 20-70 and ASTM standards) and presented on a 10-specimen lot basis. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the standard deviation of lot means and $\bar{s}_i$, the mean standard deviation of specimens within lots.)* (M 146 457)

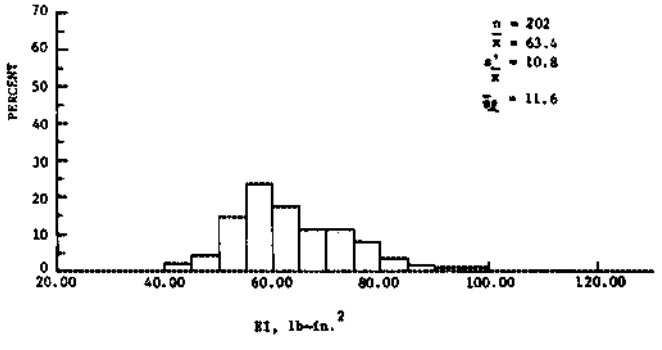


*Figure 19.–Stiffness (EI) of 2 × 8 joists based on the "as sampled" dimensions and E values. (The symbol n denotes number of lots; x̄, the mean; $s_{\bar{x}}$, the standard deviation of lot means; and $\bar{s}_i$, the mean standard deviation of specimens within lots.)* (M 146 458)

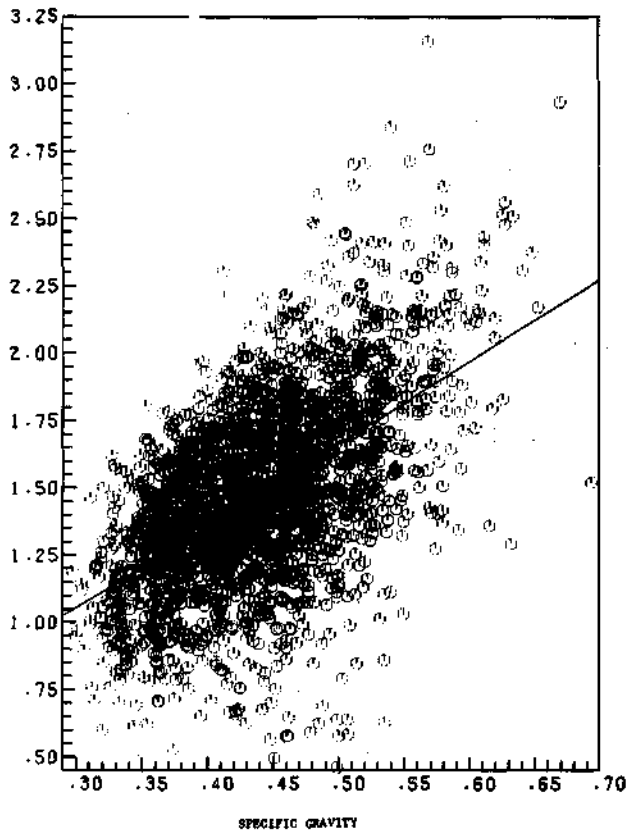


*Figure 20. –The relationship between E and specific gravity for all S-DRY and MC-15 specimens sampled. Specific gravity and E are both corrected to 12 percent.*

(M 146 459)

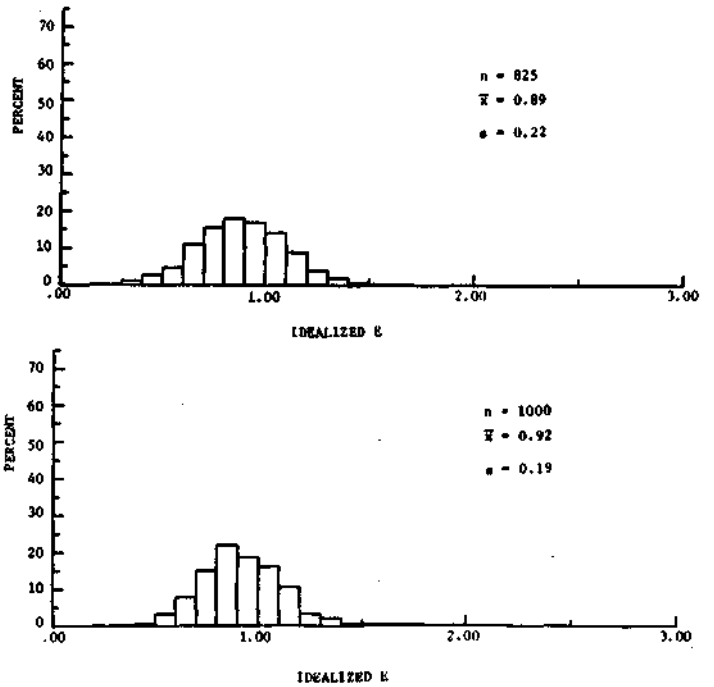


*Figure 21.–A histogram observation of the effectiveness of the ASTM D 245 reduction in E for No. 2 grade level. The top histogram contains No. 2 MG specimens; the bottom, No. 1 and Select Structural. (The symbol n denotes number of specimens; $\bar{x}$, the mean; and s, the standard deviation of specimens.)*

(M 146 460)

mean, are adequate. The comparison for No. 2 level material suggests the increase may not be warranted.

Note also that the selection of lumber by grade level categories (Select Structural and No. 1 versus No. 2) as well as categorizing by density (D 245 growth rate and percent summerwood) has little effect on the variability in E by category.

## Results—Grade Stamping and Market Combinations

The data corrections and property relationships explored in this report depend upon the legibility of the grade stamps on the lumber. Observations on legibility and similar concerns have been reported in the early overview of this study (17). In that report, the essential data on target grades and MC were easily derived from the serial lots even though approximately 14 percent of the specimens had one or more features of the grade stamp that were illegible. On this basis, the authors feel that the data base (the grade stamp information) is sufficiently accurate.

Also of interest is the amount of mixing of species and/or mill origin that occurs in the lumber distribution system. Analysis of the data shows that approximately 93 percent of the 10-piece lots sampled in Indiana in 1972 contained lumber from only one mill source. No lots contained lumber from more than two mills. Similarly, only one lot contained lumber of more than one species-marketing group (Douglas Fir and Douglas Fir-Larch were considered separately for this analysis). Sixty-six percent of the lots contained two grades; 13 percent, three or more. (Density was considered a grade sort in this comparison.) Of the Douglas Fir-Larch and Southern Pine permitted by D 245 to have sorts by density (growth rate and percent summerwood), 9 percent of the lots contained a mix of dense and nondense grades. Fifteen percent contained only dense grades.

Only Southern Pine was furnished in the MC-15 (KD) category; as shown by table 3, 65 percent of Southern Pine was KD. Forty-three percent of Douglas Fir and Douglas Fir-Larch was S-GRN.

## Probability of Obtaining an "Acceptable" Lot

On the basis that a lot of 10 pieces was a reasonable representation of joist performance in a floor, the analysis examined lot properties statistically to develop what proportion of lots in Indiana had a certain attribute. Data collected allowed any attribute to be chosen, but the primary interest was EI.

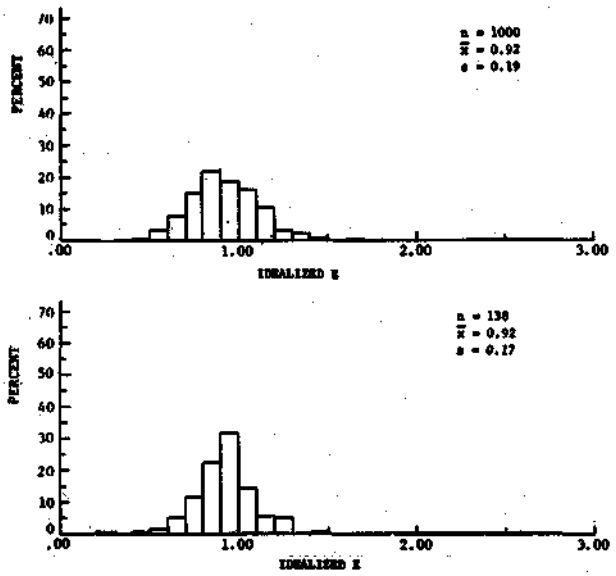


*Figure 22.–A histogram observation of the effectiveness of the ASTM D 245 increase in E for density for No. 1 and Select Structural grade levels. The top histogram represents No. 1 and Select Structural; the bottom, No. 1 Dense and Dense Select Structural. (The symbol n denotes number of specimens; $\bar{x}$, the mean; and s, the standard deviation of specimens.)*

(M 146 462)

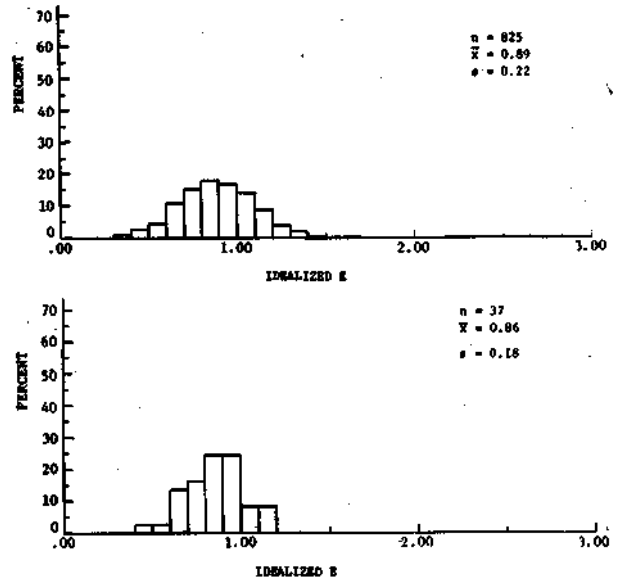


*Figure23.–A histogram observation of the effectiveness of the ASTM D 245 increase in E for the No. 2 grade level. The top histogram represents No. 2 and No. 2 MG while the bottom is No. 2 Dense. (The symbol n denotes number of specimens; $\bar{x}$, the mean; and s, the standard deviation of specimens.)*

(M 146 463)

To use this probability-based analysis to explore the performance of the 2 by 8 joists, it is necessary to define a level of "acceptability." Then, the probability of a randomly selected lot of lumber meeting or exceeding this level can be estimated. This research was to provide a data base for probabilistic floor system design; it therefore *precedes* the analysis that will provide a measure of "acceptability" based on performance. This report, which lacks this design experience, presents the results on the general basis that *if* a percent $P_0$ of NDS-based EI is chosen as "acceptable," the proportion of joist lots meeting or exceeding this level can be estimated. That is, we estimate the proportion of lots whose idealized EI exceeds $P_0$.

The probability estimates in this study are based on a sample design with two stages of sampling. The first stage is yards sampled at random from within each stratum. The second stage is lots sampled from within the selected yards.

In the sample survey jargon, this design is called two-stage cluster sampling with stratification (*4*) where the yards are the clusters (of lots) and the strata are as previously defined. The definition of the estimator, $\hat{p}$ for the proportion (P) of lots meeting or exceeding some standard and the variance of the estimator are given in appendix C. Because many of the cells had very few yards sampled, the credit class strata were pooled to improve estimation of the variance of P. It can be shown that this procedure is conservative and that if the stratification by credit class does have an effect, the procedure overestimates the variance.

***Weighting Versus Nonweighting***

The choice of estimator depends on whether we want to make the assumption that each lot in the population has an equal chance of being selected. In other words, do we want to weight the estimates by the size of the yard?

The practical concern here is, do yards with more inventory sell more lumber than those with less inventory? If, in general, inventory is directly related to sales volume, the yard estimate should be weighted by the size of the yard. This question was not the subject of the study but was anticipated by the statistical design in the provision for weighting or nonweighting of results. Thus, the probability of obtaining certain joist lot properties could be examined under both assumptions. Appendix C provides the statistical statements that express the "weighting" or "nonweighting" options.

Figure 24 represents the "weighted" analysis. For example, *assume* that a lot-average, idealized EI of 0.85 is chosen as acceptable (i.e., $P_0$ = 85 pct). From figure 24, it is then seen that about 66 percent of the 10-specimen lots in the State of Indiana will meet this criterion.

**Results–Proportion of Lots and Pieces with Desired Attribute**

The lot results based on the entire State are shown in tabular form in table 5. The table includes both "weighted" and "nonweighted" results. The procedure for calculating the proportion of total lots with the desired attribute can also be employed for pieces. These estimates and the associated

**Table 5.–State estimates—proportion of lots and pieces with average stiffness greater than or equal to $P_0$ percent of the design stiffness (EI)**

| Estimates | $P_0$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | 100 | 95 | 90 | 85 | 80 | 75 | 60 |
| Proportion (weighting) | 0.132 | 0.256 | 0.443 | 0.655 | 0.759 | 0.840 | 1.0 |
| Standard error | .0361 | .0475 | .0602 | .0650 | .0639 | .0612 | 0. |
| Proportion(nonweighting) | .145 | .315 | .453 | .645 | .758 | .874 | 1.0 |
| Standard error | .0277 | .0424 | .0490 | .0464 | .0423 | .0345 | 0. |
| Proportion(pieces)[1] | .255 | .349 | .447 | .552 | .649 | .762 | .930 |
| Standard error | .0250 | .0302 | .0360 | .0376 | .0358 | .0340 | .0152 |

[1] Here the desired attribute is redefined to be the number of pieces within a lot which meet or exceed $P_0$ percent of the EI.

standard errors for all tabulations also are shown in table 5. To visualize the variability of the data in practical terms, a 95 percent confidence interval is approximately ± two standard errors. Applied to the sample used previously where "acceptability" is defined as lots with at least 85 percent of the NDS-based EI, the probability of a builder obtaining a lot of this level is approximately 66 ± 13 percent with 95 percent confidence.

This analysis could be made as the probability of obtaining a "nonacceptable" lot. In this example, this probability with 95 percent confidence is 34 ± 13 percent. This particular example is not to suggest that "acceptability" should be 85 percent or that 66 ± 13 percent is a reasonable performance. As noted, these decisions must be based on analysis of design adequacy.

Note in table 5 that in the weighted case only 13 ± 7 percent of the lots and 25 ± 5 percent of the pieces meet or exceed the design (NDS-based) EI (i.e., $P_0$ = 100) with 95 percent confidence. The commonly expected proportion here is 50 percent since the design values are based on an average E. All of the lots meet or exceed 60 percent of the design value, but approximately 7 percent of the pieces do not. This table also shows that—at least over the entire State—the question of weighting versus nonweighting for EI is not really important since the estimates are within one or two standard errors of each other.

***Analysis by Strata***

The preceeding analysis can also be made by examining individual regions to determine geographic influences. Table 6 presents these data and shows wide diversity between regions. These regional results are influenced by smaller numbers of lots in the regions and by some statistical difficulties in certain blocks of the analysis such as Region 6. The difficulty was in calculating the variance estimates for substrata because in most cases very few yards were sampled. The same procedure as before, pooling over credit class, was also used here in calculating the variance. An approximation method which can be used to compare various substrata estimates is shown in appendix C, equation (3). This method shows that there are significant differences when comparing regions (see table 6).

Similar analyses by the other stratification variables–population and credit level—are shown in tables 7 and 8. Estimates by population level are more stable than the regional estimates, and none of these population class estimates show significant differences. The estimates by credit level are similar but the standard errors tend to be large. This again suggests that in this study, without additional research, analysis by credit level yields only the conclusion that there is little effect of credit rating on the average, but the variability creates uncertainty in employing the results.

***Sources of Variability***

One of the statistical concerns in sampling is to identify sources of variability, not only for interpretation of results but for subsequent development of similar sampling plans. Comparison of variance within and between lumberyards is shown in table 9 for weighting, nonweighting, and individual pieces. Significantly, the variance between yards is from three to seven times the variance within each yard. Two possible explanations are apparent, because in most retail yards the samples originated at a single lumber mill source. First, each mill turns out a consistent product but the mills differ in property level of the product; or, secondly, all mills are similar but each mill turns out a variable product having "small" within-lot differences and "large" between-lot differences. Obviously, any combination of these two possibilities could also explain the variability. In any case, these differences in variance suggest also that for sampling of this type it is more important to sample sufficient sites than

**Table 6.–Regional estimates—proportion of lots and pieces with average stiffness greater than or equal to 85 percent of design stiffness (EI)[1]**

| Estimates | Region | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Number of yards sampled | 16 | 22 | 16 | 16 | 16 | 5 |
| Proportion (weighting) | 0.923 | 0.332 | 0.731 | 0.833 | 0.447 | 0.064 |
| Standard error | .0446 | .1278 | .1575 | .1054 | .0994 | .0946 |
| Proportion (nonweighting) | .884 | .550 | .662 | .787 | .464 | .261 |
| Standard error | .0603 | .0836 | .1157 | .1170 | .1233 | .3012 |
| Proportion (pieces)[2] | .678 | .400 | .622 | .619 | .428 | .278 |
| Standard error | .0424 | .0853 | .0832 | .0540 | .0562 | .0441 |

[1] Significant comparison (95 pct confidence)–weighting: 1-2, 1-5, 1-6, 2-4, 3-6, 4-5, 4-6, 5-6; nonweighting: 1-2, 1-5, 1-6; pieces: 1-2, 1-5, 1-6, 3-6, 4-6, 5-6.

[2] Here the desired attribute is redefined to be the number of pieces within a lot which meet or exceed $P_0$ percent of the EI.

**Table 7.–Population site estimates of the desired attribute. Proportion of lots and pieces with average stiffness greater than or equal to 85 percent of design stiffness (EI)[1]**

| Estimates | Population | | |
|---|---|---|---|
| | 1 <5,000 | 2 5,000-25,000 | 3 >25,000 |
| Number of yards sampled | 44 | 22 | 25 |
| Proportion (weighting) | 0.625 | 0.775 | 0.596 |
| Standard error | .0974 | .0999 | .1205 |
| Proportion (nonweighting) | .641 | .635 | .669 |
| Standard error | .0643 | .0995 | .0873 |
| Proportion (pieces)[2] | .543 | .551 | .569 |
| Standard error | .0640 | .0525 | .0629 |

[1] *Significant comparisons* (95 pct confidence): weighting, none; nonweighting, none; pieces, none.

[2] Here the desired attribute is redefined to be the number of pieces within a lot which meet or exceed $P_0$ percent of the EI.

**Table 8.–Credit level estimates of the desired attribute. Proportion of lots and pieces with average stiffness greater than or equal to 85 percent of design stiffness (EI)[1]**

| Estimates | Credit rating | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Number of yards sampled | 25 | 9 | 21 | 21 | 15 |
| Proportion (weighting) | 0.731 | 0.724 | 0.564 | 0.628 | 0.620 |
| Standard error | .1224 | .4680 | .1725 | .0964 | .1565 |
| Proportion (nonweighting) | .635 | .807 | .418 | .818 | .664 |
| Standard error | .0875 | .1670 | .0995 | .0812 | .1085 |
| Proportion (pieces)[2] | .572 | .640 | .513 | .531 | .584 |
| Standard error | .0699 | .3181 | .0911 | .0599 | .0939 |

[1] Significant comparisons (95 pct confidence): weighting, none; nonweighting, 2-3, 2-4; pieces, none.

[2] Here the desired attribute is redefined to be the number of pieces within a lot which meet or exceed $P_0$ percent of the EI.

to increase the sample size within the site. Aspects of this issue are addressed further in Phase II of this report.

### Probability Based Histogram Presentation

Note that the histograms (figs. 2 through 19 and 21 through 23) were based on data as collected, i.e., they give percentages of sampled lots. They make no adjustment for the fact that not all lots (i.e., yards) in the the State had an equal probability of being sampled. Histograms could be constructed which would make this adjustment, and these histograms would more accurately describe the results. The construction of such histograms would use the known sampling plan.

Idealized EI was used to illustrate this latter technique. The results are shown in figure 25 for the weighted case, and in figure 26 for the nonweighted. These figures correspond to figure 18. Note that all three histograms are quite similar.

**Table 9.–A comparison of the variance differences between weighting, nonweighting, and individual pieces, and the contributions to this variance within and between yards[1]**

| | Variance | | |
|---|---|---|---|
| | Total | Within yards | Between yards |
| Weighting | 0.00417 | 0.00052 | 0.00365 |
| Nonweighting | .00207 | .00051 | .00156 |
| Pieces | .00149 | .00023 | .00126 |

[1] All data are based on the assumption of "acceptability" being those lots with an EI equal to or better than 85 percent of an NDS-based EI.

### Further Analysis

The procedure outlined for determining probability of "acceptable" EI by lot can be carried out for the other variables measured in this study. Similarly, analyses can be carried out at different levels of "acceptability."

No further computations have been carried out, however, pending design analysis that will provide guidance. Presumably, the EI data presented herein provide a sufficient example of the potential of the method, and also relate more specifically to probabilistic joist performance in a floor, than any of the other variables.

## Phase II

### Sampling and Measurements

The primary objective of sampling in Phase II was to obtain data on the entire inventory of 2 by 8 joist lumber in retail yards. With this inventory, examination of both serial and population characteristics could be conducted. Representativeness to all yards in the State of Indiana was not an objective; therefore, the nine yards were selected for sampling convenience. In these yards, all 2 by 8 stock of 12- or 14-foot lengths in grades of No. 2 or higher was examined.

Test procedures and measurements were identical to those employed in 1972. Table 10 summarizes the species, moisture designations, and lengths of the 1973 sample; 1972 figures are included for comparison. The 1,313 total specimens in 1973 resulted from sample sizes in the nine yards ranging from 282 to only 30. Phase I rules were followed; this required an inventory of at least 40 specimens to sample. Thus, two yards sampled in 1973 with low inventory were included only for total population observations, not for serial lot properties. Most of the subsequent data analysis is, therefore, based upon seven yards.

### Data Adjustments

The premise of lumber acceptability that formed a basis for Phase I was maintained in Phase II. For consistency between phases and for convenience in relating the diverse grades and species, the "idealizing" and MC correction procedures of Phase I were also employed in Phase II.

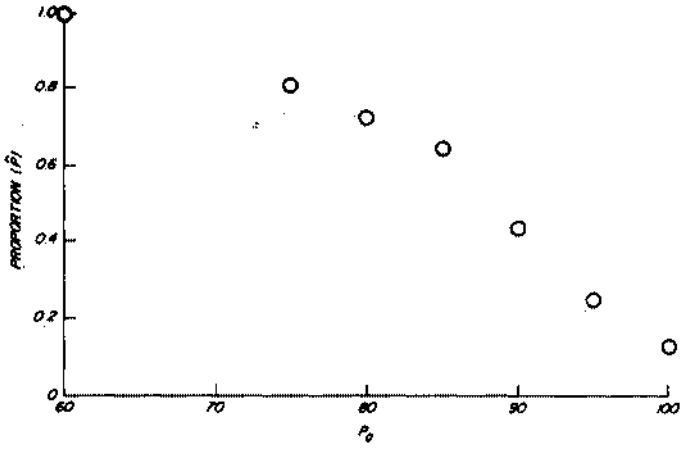


*Figure 24. –Proportion of lots ($\hat{P}$) with the desired attribute $P_0$ where $P_0$ is the percent of the NDS-based design EI.*

(M 146 534)

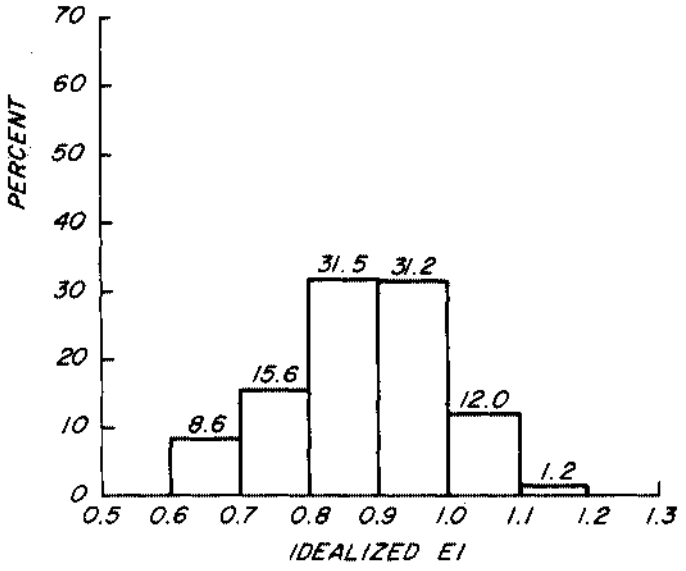


*Figure 25.–Histogram heights represent the estimated proportion of lots in the population that lie between the class boundaries. Estimates are based on the weighted analysis.*

(M 146 532)

## Analysis

Are the results obtained from the comprehensive sampling in 1972 time dependent? That is, would repeat sampling in 1973 produce the same estimates of floor joist lot properties?

Within the funding and time frame of this research, it was not possible to address this question as fully as desired. It also was not possible to repeat the 1972 sampling program and analysis in 1973. This repetition, of course, would have been ideal and would have provided the most adequate answer to

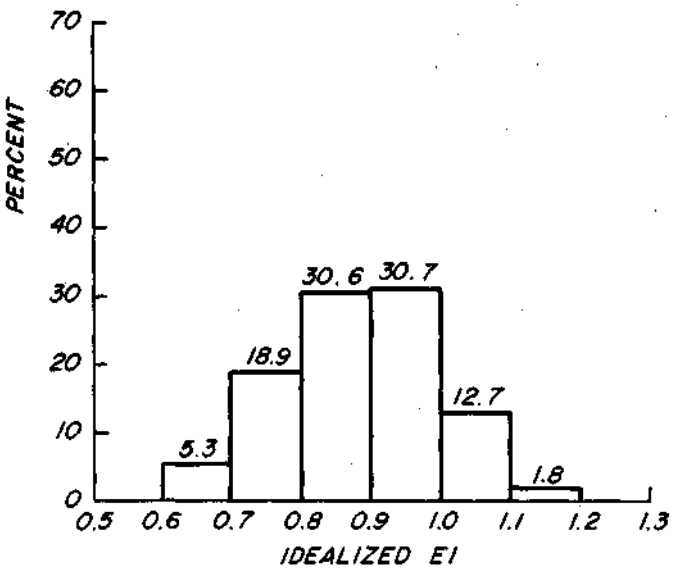


*Figure 26. –Histogram heights represent the estimated proportion of lots in the population that lie between the class boundaries. Estimates are based on the non weighted analysis.*

(M 146 533)

the question. Lacking this comprehensive approach, the nine yard inventory sample was taken. The results, then, are limited to this sample base; Phase I-type statements related to probability of obtaining an acceptable lot in the State of Indiana are not possible. Nevertheless, some insights into serial retail yard sampling are obtained. Only the EI product has been assessed since it is of most interest and provides a suitable example. The questions are answered through analyses based on mean and variance calculations for the different years. These values are tabulated in table 11.

In table 11, "72" denotes the serial samples collected in 1972, "Pop" signifies parameters of the entire 2 by 8 joist population collected in 1973 in the nine retail yards. "73" signifies small serial lots derived by sampling in 1973 (from Pop)—the same number of lots and collected in the same manner as in '72. In all cases, data represent mean and standard deviation of individual specimens based on a single sample. Lot properties are not tabulated because the small number of lots sampled precluded adequate statistical comparisons of lot properties.

### Are the Comprehensive 1972 Results Time-Dependent?

This comparison of the 1972 comprehensive and 1973 limited surveys was made to judge whether repeat sampling would produce similar estimates of floor joist lot properties. That is, are the results obtained from the 1972 comprehensive sampling time-dependent?

***Serial Lots–Yards***

In four of seven lumberyards, significant differences in $\bar{x}$ or s occurred between 1972 serial lots (72) and 1973 serial lots (73). These observations suggest that in these yards, the

**Table 10.–Sample summary of 2 by 8 dimension lumber in retail lumberyard survey in Indiana in 1972 and 1973**

| Species group[1] | Moisture content[1] | Lumber length | Number of specimens 1972 | Number of specimens 1973 |
|---|---|---|---|---|
| | | Ft | | |
| Douglas Fir | S-GRN | 12 | 60 | -- |
| | | 14 | 40 | 50 |
| | S-DRY | 12 | 110 | -- |
| | | 14 | 20 | 148 |
| Douglas Fir-Larch | S-GRN | 12 | -- | -- |
| | | 14 | 20 | 2 |
| | S-DRY | 12 | -- | 130 |
| | | 14 | -- | 232 |
| Southern Pine | S-DRY | 12 | 200 | -- |
| | | 14 | 40 | -- |
| | KD | 12 | 410 | 70 |
| | | 14 | 40 | 299 |
| Spruce-Pine-Fir | S-DRY | 12 | 410 | 107 |
| | | 14 | 120 | 92 |
| Hem-Fir | S-DRY | 12 | 310 | 143 |
| | | 14 | 70 | -- |
| Western Hemlock | S-DRY | 12 | 20 | 40 |
| | | 14 | 70 | -- |
| Ponderosa Pine | S-DRY | 12 | 60 | -- |
| | | 14 | 20 | -- |
| | | Totals | 2,020 | 1,313 |

[1] As indicated on the grademark.

character of the lumber lots had changed. In each yard comparison, there is a 5 percent chance of difference when no real difference exists. Chance occurrence of four or more differences between the 14 total comparisons of 72 versus 73 means and standard deviations would occur less than 1 percent of the time (assuming $\bar{x}$ and s are independent). But, although change occurred, there is no consistent pattern of increase or decrease in sample parameters related to year of sampling.

Remember that the comparisons of standard deviations in table 11 are based on individual specimens in aggregate, not on lot properties. In making the comparisons, no implication of homogeneity of the specimen population is implied. However, the change in specimen characteristics within these nine yards seems to imply a change in lot properties as well. Because lot samples are considered to represent the lumber in floors, a change in the input data by yard for specific floors is implied.

***Lumber Source***

In Phase I, it was shown that most serial samples contained lumber from only one lumber mill. It follows then that the change in lumber characteristics can be related either to change in mill source or to change in lumber quality at a mill. Did significant changes occur in mill source, in species, or in grade mix between the two sample dates?

Based on comparable samples (73 and 72), eight of the nine revisited lumberyards had lumber from a different mill source

**Table 11.–Tabulation of sample size (n), mean ($\bar{x}$), and standard deviation (s), for idealized EI samples from nine retail yards[1]**

| Yard | | "72" | "Pop" | "73" |
|---|---|---|---|---|
| 1 | n | 40 | 282 | 40 |
| | X | 0.9020 | 0.9169 | 0.9012 |
| | S | .1173 | .1929 | .1835 |
| 4 | n | 20 | 138 | 20 |
| | X | .6563 | .8945 | .8725 |
| | S | .2376 | .2151 | .1934 |
| 6 | n | 30 | 228 | 30 |
| | X | 1.0136 | .9703 | ,9959 |
| | S | .1483 | .2045 | .2195 |
| 52 | n | 20 | 199 | 20 |
| | X | .7391 | .8759 | .8925 |
| | S | .1247 | .1660 | .1712 |
| 82 | n | 20 | 226 | 20 |
| | X | .9713 | .8644 | .8998 |
| | S | .1426 | .1756 | .1842 |
| 83 | n | 20 | 30 | |
| | X | .9081 | .8602 | |
| | S | .1901 | .1976 | |
| 84 | n | 20 | 67 | 20 |
| | X | .7988 | .8477 | .7239 |
| | S | .1822 | .2061 | .1619 |
| 89 | n | 20 | 107 | 20 |
| | X | .7549 | .8884 | .8380 |
| | S | .1548 | .1726 | .1346 |
| 95 | n | 20 | 36 | |
| | X | .7711 | .7885 | |
| | S | .1288 | .1416 | |
| All | n | 210 | 1,313 | 170 |
| | X | 0.8499 | 0.8978 | 0.8850 |
| | S | .1540 | .1879 | .1813 |

[1] "72" denotes the serial samples collected in Phase I (1972). "Pop" signifies parameters of the entire 2 by 8 joist population in a retail yard collected in Phase II (1973). "73" properties are derived by sampling from Pop the same number of lots and in the same manner as 72.

in 1973 than in 1972. In 1972, 13 different lumber mills were represented; in 1973, 15 different mills. In 1972, six yards had only one mill source; two had two; one had three. In 1973, only four had one mill source; two had two; one had three; and one had four.

In 1972, eight yards had only one species group represented; one had two. In 1973, seven had one species group; two had two. Between 1972 and 1973, four of the yards changed species; one yard added a species.

Grades available depended upon the species group. In 1972, five yards had two grades per species group; four had three. In 1973, one yard had one grade only; five had two; and three had at least one species group with three grades.

If grades, species, and mills are observed in the total 1973 population, mills represented in yard inventory ranged from one to five; species, from one to two; and grades, from one to three.

It is apparent that the answer to Question 1 is "yes"—many significant changes occurred between 1972 and 1973. Because all data were "idealized" for purposes of comparison and because Phase I suggests no outstanding bias by species-grade combinations, these observations suggest that the changes in yard lot properties can be linked to changes of mill source.

Population Characteristics

Review of the foregoing serial lot and yard observations raises the question of whether the overall population characteristics of lots in the state changed from 1972 to 1973. For example, could a change in lumber demand between 1972 and 1973 result in actual property differences in 1973 floor joist lots? This cannot be directly addressed by citing the yard-by-yard differences that have already been found significant. Further, the 1973 sampling is not judged adequate to address this question comprehensively. However, an estimate of population characteristics can be obtained by comparing the pooled results of all specimens tested in the nine yards sampled in 1973 with the State estimates obtained in 1972 from serial lots.

| | 1972 | | 1973 | |
|---|---|---|---|---|
| | Total serial | State lots | Nine yard "72" | Nine yard "Pop" | Nine yard "73" |
| Number of specimens | 2,000 | 210 | 1,313 | 1 70 |
| Specimen average EI | 0.88 | 0.85 | 0.90 | 0.89 |
| Specimen standard deviation EI | .19 | .15 | .19 | .18 |

We believe that statistical significance tests should not be applied to differences in this tabulation; nevertheless, the trend of the data may be consistent with a shift in the nine yard values between 1972 and 1973.

To further comment on lumber population, the lot data reported in Phase I may be observed as an aggregate of all specimens comprising the lots. An example is figure 27, in which the top histogram reports the "idealized" EI values by specimens while the bottom histogram of lots is repeated from figure 18. Figure 28 displays the same histograms as figure 27 developed by the probability-of-occurrence procedure discussed in Phase I. The same observations may be made for these histograms.

Figures 27 and 28 display the distributions of specimen properties that were nonrandomly sampled. Since the study focused on lots rather than specimens, these specimen data are presented only for general information, such as the range, and should not be used as a random data set.

## Phase II Summary

Properties of specimens in serial lots were significantly different in the 1973 sample from those of the 1972 sample. No consistent trend was evident. There were many changes in mill source, species, and grade in individual lumberyards on the two sample dates. These observations, coupled with Phase I results, suggest changes in lot properties may be traceable to mill source.

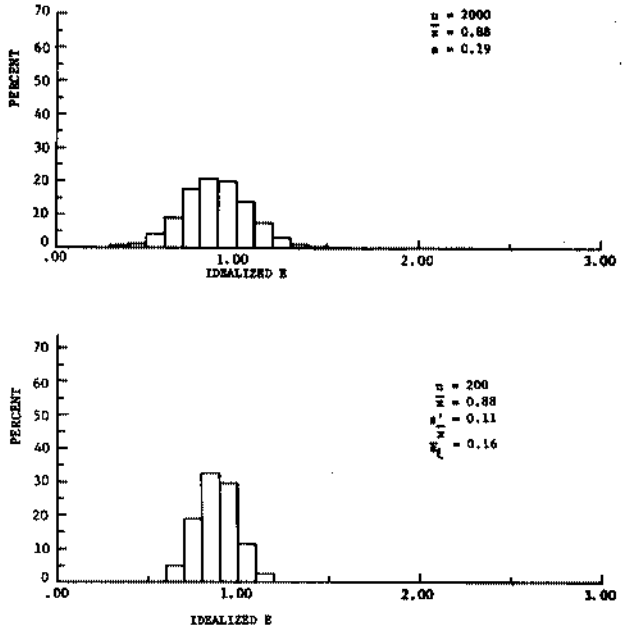


*Figure 27. –A comparison of idealized EI of individual specimens from lots viewed in aggregate (top histogram) with lot properties (bottom histogram). (The symbol n denotes number of specimens; $\bar{x}$, the mean; s, standard deviation of specimens; $s_{\bar{x}}$, standard deviation of lot means; and $s_i$, mean standard deviation of specimens within lots.)*

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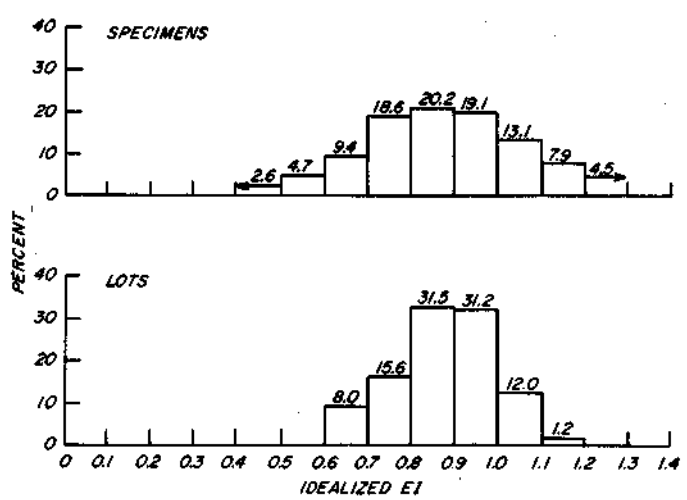


*Figure 28. –Histogram heights represent the estimated proportion of specimens (top) and lots (bottom) in the population that lie between the class boundaries. Estimates are based on the weighted analysis.*

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## Conclusions

### Phase I–1972

Width and thickness dimensions of approximately 50 percent of 2 by 8 joists were less than would be anticipated by ALS PS 20-70, both directly as measured and as adjusted for shrinkage and to a MC basis of 12 percent. MC of many specimens was higher than anticipated by the grade stamp MC. The lot mean MC's for S-DRY joists averaged 18 percent MC. The lot means of MC-15 pieces averaged 13.3 percent MC. Although all measurements were taken at retail yards rather than at the manufacturing site where production standards are directly applicable, it appears many pieces were either too small or the MC was too high at time of surfacing.

E values for the 10-specimen lots of joists, adjusted for MC, averaged approximately 9 percent less than would be anticipated by NDS. The lot mean EI was 0.88 of anticipated. E determinations followed the ASTM D 2915 procedure of placing the most noticeable defect in tension.

Procedures used to make MC adjustment are, at best, approximate but the methods used were based on current ASTM and ALS standards and agree reasonably well with published studies.

The results also suggest the adjustment (reduction) of E for No. 2 grade may be 3 percent too small. Similarly, the 5 percent increase in E for density in No. 2 grade may not be warranted, while that for No. 1 and Select Structural may be adequate.

Most lots contained lumber from only one lumber mill source but represented two or more grades.

The analysis presents estimates of the proportion of lots meeting or exceeding a level of acceptability. For example, if a lot having a mean EI equal to 85 percent of that calculated from NDS is defined as "acceptable," then about 66 ± 13 percent of the lots were acceptable (95 pct confidence). This form of analysis can be extended to other levels of "acceptability," to other variables, and to strata of the sample.

It should be reemphasized that this paper is an initial effort at serial sampling, end-use sampling, and probability-based analysis. The above conclusions are intended for use in probability-based research studies and not as design advice applicable to current deterministic practices, without further review and study expressly for that purpose.

### Phase 11—1973

Sampling repeated in 1973 disclosed that specimen properties in the nine "repeat" yards were different from 1972. Many lumber sources, species, and grades for these yards also changed, suggesting joist lot properties of a lumberyard are significantly influenced by these yard purchasing decisions.

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# Appendix A

## Data Codes and Correction Calculations

For purposes of clarity in handling the data, three segregations were. made—"raw" data, "calculated" data, and "corrected' ' data. Code terminology was employed to simplify handling of these data. Where more than one reading was taken on a specimen, the numbers 1 and 2 indicated the duplicate or sequential readings. Starting with descriptions of the "raw" and "calculated" data, the details of the data corrections are outlined in the following sections.

### I. "Raw" Data

Deflection D1, D2 Compute: $D = D2 - D1$

Width W1, W2 Compute: $W = \frac{W1 + W2}{2}$

Thickness T1, T2 Compute: $T = \frac{T1 + T2}{2}$

Moisture content MC1, MC2 Compute: $MC = \frac{MC1 + MC2}{2}$

Temperature TEMP

$X_w$ = weight wet basis ("raw" basis)

$V_w$ = volume wet basis ("raw" basis)

### II. "Calculated" Data

Moment of inertia Compute: $I = \frac{TW^3}{12}$

Modulus of elasticity Compute: $E = \frac{4.95}{(I)\,(D)}$

$\frac{X_w}{V_w} = \square_w$ = density (raw) basis

### III. "Corrected" Data

MC corrected for temperature: MCT*

$$MCT = MC + [7 - \frac{TEMP}{10}] - \frac{80}{(MC)^2} \text{ when } TEMP \leqslant 55°F$$

$$= MC + [7 - \frac{TEMP}{10}] \text{ when } 55°F < TEMP < 80°F$$

$$= MC + [7 - \frac{TEMP}{10} + \frac{80}{(MC)^2} \quad \text{when } TEMP \geqslant 80°F$$

MC corrected for temperature and species: MCTS*
(from the meter manual and Bramhall and Salamon (3)).

Species

Douglas Fir (D. fir) : $MCTS = MCT$

Douglas Fir-Larch (Fir-Lar) : $MCTS = MCT$

Hem-Fir : $MCTS = -2.41029 + 1.44615\,MCT - 0.01548\,(MCT)^2$

West Coast Hemlock (WCH) : $MCTS = -2.41029 + 1.44615\,MCT - 0.01548\,(MCT)'$

Southern Pine (SYP) : $MCTS = -1.134198 + 1.286074\,MCT - 0.007652\,(MCT)^2$

Spruce-Pine-Fir (SPF) : $MCTS = 0.609404 + 1.141813\,MCT - 0.001993\,(MCT)^2$

Ponderosa Pine (PP) : $MCTS = -2.17899 + 1.46249\,MCT - 0.01430\,(MCT)'$

Width corrected to a specified MC (from ALS):

A. Based on moisture meter reading (MC) corrected for temperature

(MCT): Yields WT

Formulas:

$WT = W[1 - (0.01)\,(\frac{MCT - 12}{4})]$: Corrected to 12 percent

$WT = W[1 - (0.01)\,(\frac{MCT - 15}{4})]$: Corrected to 15 percent

$WT = W[1 - (0.01)\,(\frac{30 - MCT}{4})]$: Corrected to 30 percent where $MCT \leqslant 30$ percent

$WT = W$: Corrected to 30 percent where $MCT < 30$ percent

B. Based on moisture meter reading (MC) corrected for temperature and species (MCTS): Yields *WTS*

Same formulas as in A except substitute MCTS for MCT

Thickness corrected for MC (from ALS):

A. Based on MCT: Yields *TT*

Formulas:

$TT = T[1 - (0.01)\,(\frac{MCT - 12}{4})]$: Corrected to 12 percent

$TT = T[1 - (0.01)\,(\frac{MCT - 15}{4})]$: Corrected to 15 percent

$TT = T[1 + (0.01)\,(\frac{30 - MCT}{4})]$: Corrected to 30 percent where $MCT < 30$ percent

$TT = T$: Corrected to 30 percent where $MCT \geqslant 30$ percent

B. Based on MCTS: Yields *TTS*

Same formulas as in A except substitute MCTS for MCT

*These equations hold if MCT < 30 percent MC. If calculated MCT ⩾ 30 percent, use 30 percent for MCT. The same logic applies for MCTS. See Section IV.

***Moment of inertia*** corrected for moisture content:

A. Based on MCT: Yields *IT*

Use W and T corrected by MCT, namely WT and TT:

Formulas:

$$IT = \frac{(TT)(WT)^3}{12}$$ : Corrected to appropriate MC's

B. Based on MCTS: Yields *ITS*

Use W and T corrected by MCTS, namely WTS and TTS:

Same formula as A except substitute W and T properties corrected by MCTS

*Modulus of elasticity* corrected for $\frac{l}{d} = 21$ and uniform load:

*EU* (from D 2915)

EU = E(1.014)

*Modulus of elasticity* corrected for temperature: *EUK* (interpolated from figure 4-12 of *Wood Handbook,* Agric. Handbook 72, Rev.)

$$EUK = EU[1 - (0.02)\left(\frac{68 - TEMP}{5}\right)]$$: Corrected to 68° F

*Modulus of elasticity* corrected for MC:

A. Based on MCT for E correction: Yields *EUT* (Based on D 245)

Formulas:

$$EUT = \frac{EU}{1.20 - 0.0167\ (MCT)}$$ : Corrected to 12 percent (see Section IV)

$$EUT = \frac{EU}{1.26 - 0.0175\ (MCT)}$$ : Corrected to 15 percent (see Section IV)

$$EUT = \frac{EU}{1.44 - 0.02(MCT)}$$ : Corrected to 22 percent where MCT $\leqslant$ 22 percent

EUT = EU: Corrected to 22 percent where MCT $\leqslant$ 22 percent

B. Based on MCTS for E correction: Yields *EUTS*

Formulas:

Same as for MCT except substitute MCTS for MCT

*Modulus of elasticity* corrected for MCT:

EUKT : Where correction is for MCT plus a temperature correction to 68° F for E.

EUKTS: Where correction is for MCTS plus a temperature correction to 68° F for E.

Same correction formulas as for MC correction alone except use EUK instead of EU.

EI products:

P = EI : Product of E and I as calculated from raw data.

PU = EUP: Product of E corrected for $\frac{l}{d}$ and uniform load and I as from raw data; no MC correction for either E or I.

PUK : Temperature, $\frac{l}{d}$, and uniform correction for E; no correction for E or I. Product of EUK and I.

PUT : Product of EUT and IT

PUTS: : Product of EUTS and ITS

PUKT : Product of EUKT and IT

PUKTS : Product of EUKTS and ITS

$X_{OD}$ = weight ovendry

$V_{12}$ = volume at 12 percent MC

$$D_{OD}\left(1 + \frac{MCTS}{100}\right) = X_w$$

$V_{12} = V_w$ – shrinkage

Let $S_o$ = volumetric shrinkage, fiber saturation to $V_o$ = 12 percent (*Wood Handbook* chosen as basis for all species used)

$$\text{Then } S_w = \left(\frac{MCTS - 12}{30}\right)(12) = (MCTS - 12)(0.4)$$

$$V_{12} = V_w\,[1 - 0.004\,(MCTS - 12)]$$

$$\square_{12} = \square_w \frac{1.12}{\left(1 + \frac{MCTS}{100}\right)[1 - 0.004\,(MCTS - 12)]}$$

$$\text{Specific gravity (12 pct basis)} = \frac{\square_{12}}{(62.4)\ (1.12)}$$

based on volume at 12 percent MC and OD weight.

**IV. Rules for Corrections and Adjustments of Data**

A. Moisture content

Corrections for MC will correct data (1) to target MC indicated by the grade stamp and reflected in the data as follows, and (2) to 12 percent MC, regardless of target MC at time of surfacing. The latter are coded with a 2 appended, i.e., PUKTS2, to signify 12 percent MC.

| Grade stamp | Purdue label | Target moisture content | Code |
|---|---|---|---|
| S-DRY | 15 percent | 15 percent | 0 |
| MC-15 or KD | 12 percent | 12 percent | 1 |
| S-GRN | 25 percent | 30 percent for size<br>22 percent for properties | 2 |

B. Missing data

Several specimens had data voids. These data were supplied by averaging the properties of the serial lot of which they

are a member, e.g., 1 through 10 for No. 7 and 11 through 20 for No. 14.

C. Missing MC data

At one sample site, the moisture meter malfunctioned. The yard was retained as a sample site, but no MC corrections can be made on this yard. MC readings and corrections are to be ignored.

D. MC correction rules

1. Shrinkage: these equations hold if MCT < 30 percent MC. If calculated MCT ⩾ 30 percent, use 30 percent for MCT. The same logic applies for MCTS. The reasoning is that no shrinkage is anticipated above 30 percent MC, the assumed fiber saturation point (FSP). Thus, subsequent use of MCT or MCTS should not include values above 30 percent MC. Exception: Use calculated MCT from equations in Section III to calculate MCTS; then use MCT and MCTS values subsequently at 30 percent if the respective calculated values exceed 30 percent.

2. The rule above applies only to changes for physical properties (size). Historically in the project, after the above rule was adopted it was noted that the size correction for MC was based on a FSP of 30 percent in ALS. but the E corrections for MC were based actually on a FSP of 22 percent in D 245. Thus, using the rule above for E resulted in increases in E of 43 percent in going from S-GRN to 12 percent whereas D 245 says only a 20 percent increase is allowed. After deliberation it was decided to use 22 percent for FSP for E.

3. The result of the preceding decision is to use 22 percent for a FSP "target" for E at an S-GRN condition, 30 percent FSP for W and T (see IV-A). Also, all "ideal" W, T, and E values will be based on these respective "target" bases.

4. Conclusion: MC values over 30 percent are disregarded for corrections of size; MC values over 22 percent are disregarded for corrections of E.

## V. "Ideal" Values

A. Data corrected to "target" values:

When the data are being corrected to their target values (see IV-A), the corresponding "ideal" values are regarded as the following, based on PS 20-70, D 245 and others:

| Grade stamp | Width (IDEALW) | Thickness (IDEALT) | E |
|---|---|---|---|
| S-DRY | 7.25 | 1.50 | NDS rating for species and grade (ERATE) |
| MC-15 or KD | 7.25 | 1.50 | NDS rating for species and grade (ERATE) |
| S-GRN | 7.50 | 1.5625 | (ERATE) (0.97) = IERATE[4] |

[4] It should be noted that the 0.97 factor presupposes a coincident increase in I from moisture gain and is, therefore, an adjustment for stiffness as normally used in NDS rather than solely an "E" adjustment.

B. Data corrected to 12 percent MC:

In order to provide one set of data, all at the same MC, 12 percent MC was chosen. The corresponding "ideal" values are as follows (also see IV):

| Grade stamp | Width (IDEALW) | Thickness (IDEALT) | E |
|---|---|---|---|
| S-DRY | 7.196 | 1.489 | (ERATE) (1.053) |
| MC-15 or KD | 7.25 | 1.50 | ERATE |
| S-GRN | 7.163 | 1.492 | (ERATE) (1.053) |

# Appendix B

## Reflections on the Procedures for "Idealizing"

### Shrinkage

Observations on the variability in the histograms on thickness, width, and I are incomplete unless potential inadequacies in adjustment procedures are recognized. These inadequacies can result from assumptions about the fiber saturation point (FSP) as well as the shrinkage coefficient. Comstock's studies of shrinkage of 2 by 6 Douglas-fir and loblolly pine lumber following rapid kiln drying suggests an effective FSP of 22 percent compared to the 30 percent used in this study (*5*). Comstock found an average shrinkage of approximately 1.14 percent for each 4 percent change in MC for bastard-sawn lumber. This coefficient, used with the 22 percent FSP, yields I values for 20 percent MC joists corrected to 12 percent MC that are approximately 2 percent lower than those used by the authors.

The research of Covington and Fewell (*6*) with European redwood and Canadian hemlock and spruce (based on a FSP of 28 pct–shrinkage values of 0.8 pct for each 4 pct change in MC) suggests I values should be approximately 2 percent higher than used by the authors. Wood and Soltis (*20*) found that coefficients average about 0.86 percent shrinkage in width for each 4 percent change in MC based on careful drying of southern pine, western hemlock, and Douglas-fir. Shrinkage in thickness was less than in width, but the species differed significantly in shrinkage presumably because of differences in growth ring orientation between the samples. A FSP of 28 percent was assumed by Wood and Soltis. In recent unreported studies by Littleford at the Canadian Forest Products Laboratory in Vancouver, green Hem-Fir 2- by 4-, 2- by 6-, 2- by 8-, and 2- by 10-inch lumber dried to approximately 3.6 percent shrinkage (equivalent to approximately 0.9 pct shrinkage for each 4 pct change in MC).

Variability in shrinkage may be as important as average trends. The influence of growth ring orientation reported by Comstock suggests that I values for joist lumber drying from 28 percent to 12 percent MC may be 1 to 2 percent lower for flat sawn than for bastard sawn, while edge-grain lumber can be 2 percent higher. Comstock further notes that adjustments of drying stresses take place under storage, causing additional minor reduction in size. Wood and Soltis also observed significant variability with standard errors ranging from 0.6 to 1 percent; the result would be variability in I of at least ± 2 percent. Littleford notes variations from 2.9 to 4.4 percent in shrinkage.

In this study, the shrinkage basis chosen was that specified by ALS PS 20-70. This basis is midway between the average results of Comstock (*5*) on the one hand and those of Wood and Soltis (*20*), and Covington and Fewell (*6*) on the other, while also close to the observations of Littleford. More important, however, this adjustment must be viewed as of value only "on the average." Lumber ring orientation and piece-by-piece variability in shrinkage suggest possible inaccuracies in predicting I of over 2 percent. Thus, some of the variability in figure 10 can be explained as inability to predict individual joist shrinkage to 12 percent MC. At this time it is reasonable to observe that a designer may be faced with the same dilemma; the ALS provision for shrinkage adjustment is applied to minimum sizes (zero negative tolerance). This provision does not appear to adequately describe the lumber in this study. Because ALS PS 20-70 implies only plus tolerances, an idealized histogram of size should be composed of values over 1.0, or perhaps at least be heavily skewed to the right. This is not the case, as seen in figures 6 and 7. Furthermore, the variability observed here is not unlike that in the other studies referenced where final laboratory-type equilibrium was obtained (*5,6,15*). Thus, the actual "raw" field observations of figures 2 through 5, and the idealized histograms (figs. 6 and 7) illustrate the uncertainty of predicting final size for design purposes.

### Modulus of Elasticity (E)

In view of the variability in E and departure of the lot mean E from a predicted "idealized" value of one, the "standard" ASTM D 245 procedure for correcting "raw" E to 12 percent MC should be compared with other adjustment procedures. "Standards" procedures used to adjust and "idealize" data may not cope adequately with the diversity in properties and the storage conditions of the lumber as it reaches end use. There are other indications of this possibility from different research sources (Gerhards (*9*) and unpublished work by Little ford).

The ASTM D 245 basis is an effective FSP of approximately 22 percent for mechanical properties, regardless of species. A linear relationship from FSP to 12 percent is assumed, yielding an increase in E of 20 percent. By comparison, Wood and Soltis imply that an approximate 28 percent FSP was used in their study (*20*). They plotted a linear trend of log E versus MC below about 22 percent MC and extrapolated a nonlinear function up to about 28 percent MC. Their data suggest increases in E of about 17 to 20 percent between green and 12 percent MC. Thus, the D 245 adjustment of 20 percent may be slightly high by comparison, but the different fiber saturation basis makes direct comparison awkward. Differences in the E-increase between lots of the same species were as high as 7 percent, suggesting an even larger variability in individual specimen changes. Species effects are evident, although density and grain orientation differences between species were compounding factors. The Wood and Soltis data are based on careful drying to equilibrium.

Covington and Fewell (*6*) also provide a reference point for E correction based on a 28 percent FSP and a log E versus MC relationship. They find a large difference in E change by species. When, however, their recommended average coefficient is used in their log relationship, the E change from 20 percent MC to 12 percent MC is close to that obtained by ASTM 245 with its linear relationship. The different average species lot coefficients found by Covington and Fewell would predict E values at 12 percent MC that vary approximately ± 4 percent, again suggesting specimen variation may be

appreciably greater. Covington and Fewell conclude that overall species adjustments are less adequate for E than for dimensions. They also note that moisture coefficients for small clear specimens are 50 percent greater than for full-size joists.

## Stiffness (EI)

Combined EI corrections also have been considered by Wood and Soltis, and Covington and Fewell; however, their conclusions differ somewhat. Wood and Soltis conclude that EI varied little with moisture; Covington and Fewell find that EI averages about 2 percent higher at 15 percent than at green conditions for Canadian hemlock. However, for the spruce, both Canadian and European, EI increased from 6 to 10 percent in drying from green to 15 percent MC. Covington and Fewell also found the coefficient of variation for change of stiffness with MC only 4 to 8 percent for individual specimens.

Comparing these results with the combined ALS PS 20-70, NDS, and ASTM procedures used herein, suggests that these procedures are adequate for most design needs, although the procedures can only be correct by average trends. For example, the NDS adjustment factor of 0.97 to adjust "grade E" for green use is intended to adjust for stiffness decrease to green condition by adjusting E only. This review of the literature suggests this is a reasonable procedure, providing it is understood that actual E value change can be greater.

## Summary

Review of the current literature suggests that the procedures used in this study to make adjustments to E and to dimensions for MC agree reasonably well with similar research. The review also indicates that the variability in properties disclosed in the field measurements and remaining after adjustments to 12 percent MC is typical of that found also in laboratory studies where lumber is equilibrated. Thus, although our procedures cannot adequately predict individual specimen changes in dimensions or E, these average corrections can suitably represent predicted values as they might occur in lumber at a 12 percent MC equilibrated in a home.

# Appendix C

## Statistical Notions

## "Weighted" Versus "Nonweighted" Techniques

Let P be the probability that a lot selected at random from *all* of the lots in the State meets or exceeds the standard (i.e., it is "acceptable"). If we denote the proportion of lots in yard j, stratum h that meet or exceed the standard by $P_{hj}$, then

$$P = \frac{\sum_h \sum_j M_{hj} P_{hj}}{\sum_h \sum_j M_{hj}} \qquad (1)$$

where $M_{hj}$ is the total number of lots in yard j, stratum h. The numerator of (1) is the number of lots in the State that meet or exceed the standard, and the denominator is the total number of lots in the State. Thus, P "weights" the proportions ($P_{hj}$) by the sizes ($M_{hj}$) of the yards. Assuming that sales volume is related to inventory ($M_{hj}$), P takes into account the differential sales of lumber yards in the State.

An alternative "nonweighted" quantity is

$$P^* = \frac{1}{N} \sum_h \sum_j P_{hj} \qquad (2)$$

where N is the total number of yards in the State. This is the probability of obtaining an "acceptable" lot if a yard is selected at random (i.e., each yard has equal probability of being selected), and then a lot is selected at random from the selected yard. Thus, a lot in a large yard will have a smaller chance of being selected than a lot in a small yard.

The above P and P* are both population quantities. That is, we can obtain P and/or P* if we have a complete enumeration of all lots in the State. In most cases this is not feasible, so we then, through proper sampling techniques, estimate these proportions. The remainder of this appendix is devoted to sampling and the resulting population estimators.

## Two Stage Cluster Sampling with Stratification—Definitions and Probability Estimators

Assume that there are L strata, that within each stratum we are sampling lumber yards, and that within each yard we are sampling lots of lumber. Then we let

$N_h$ = number of yards in stratum h (h = 1, 2, ..., L),

$n_h$ = number of yards sampled in stratum h,

$M_{hj}$ = number of lots present in yard (h, j) (j = 1, 2, ..., $n_h$),

$m_{hj}$ = number of lots sampled in yard (h, j),

and we define

$Y_{hji}$ = 1 if the *i*th lot in the (h, j) th yard has the desired attribute
(i = 1, 2, ..., $m_{hj}$)
= 0 otherwise.

The general estimator for the proportion of lots having the desired attribute is given by

$$\hat{P} = \frac{\sum_h \frac{N_h}{n_h} \sum_j M_{hj} \bar{Y}_{hj}}{\sum_h \frac{N_h}{n_h} \sum_j M_{hj}} \qquad (3)$$

where

$$\bar{Y}_{hj} = \frac{1}{m_{hj}} \sum_i Y_{hji}$$

If we wish to estimate the weighted proportion P described previously, this estimator is $\hat{P}$ [equation (3)] exactly as given. If we wish to estimate the nonweighted proportion P* then in equation (3), the $M_{hj}$ are replaced by ones (1) so that the weights are removed.

The estimator for the variance of $\hat{P}$ is given by the following expression

$$\mathrm{var}(\hat{P}) = \frac{1}{\hat{X}_T^2} \sum_h N_h \left[ \frac{1 - f_{1h}}{n_h} \frac{\sum_j M_{hj} (\bar{d}_{hj})^2}{n_h - 1} \right] + \frac{f_{1h}}{n_h^2} \left[ \sum_j \frac{M_{hj}^2 (1 - f_{2hj}) s_{2hj}^2}{M_{hj}} \right] \Bigg\} \qquad (4)$$

where

$$f_{1h} = \frac{n_h}{N_h},$$

$$f_{2hj} = \frac{m_{hj}}{M_{hj}},$$

$$\hat{X}_T = \sum_h \frac{N_h}{n_h} \sum_j M_{hj},$$

$$d_{hji} = Y_{hji} - \hat{P}$$

$$\bar{d}_{hj} = \frac{1}{m_{hj}} \sum_i d_{hji}, \text{ and}$$

$$s_{2hj}^2 = \frac{1}{m_{hj} - 1} \sum_i \left( d_{hji} - \bar{d}_{hj} \right)^2.$$

As before, equation (4) estimates the variance for the weighted proportion. The variance for the nonweighted proportion can be obtained by again replacing the $M_{hi}$ by 1.

If one wants to estimate the proportion of pieces of lumber in the State which have the desired attribute we define

$X_{hji}$ = number of pieces in lot i of yard (h, j) and redefine $Y_{hji}$ to be

$Y_{hji}$ = number of pieces in lot i of yard (h, j) which have the desired attribute.

The estimator for the proportion of pieces is similar to equation (3) except that $\bar{y}_{hj}$ is as redefined here and the the $M_{hj}$ in the denominator is multiplied by $\bar{x}_{hj}$ where

$$\bar{x}_{hj} = \frac{1}{m_{hj}} \sum_i X_{hji}.$$

Similarly, the variance estimator for pieces is equation (4) with the following exceptions,

$$\hat{X}_T = \sum_h \frac{N_h}{n_h} \sum_j M_{hj} \bar{x}_{hj}, \text{ and}$$

$$d_{hji} = Y_{hji} - \bar{P}X_{hji}$$

where $Y_{hji}$ and P are as redefined for pieces.

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U.S. Forest Products Laboratory

Wood Joist Floors: Probabilistic Analysis of Joist Stiffness Measured at Retail Lumberyards, by W. L. Galligan, J. H. Haskell, J. F. Senft, R. L. Ethington, J. F. Sedransk, and D. A. Fergus, Madison, Wis. 1982

29 p. (USDA For. Serv. Research Paper FPL 402).

Paper discusses the philosophy which prompted the study to define "acceptable" performance of dimension lumber in terms of floor system performance, using a composite of current standards and presents results.

Describes a systematic sampling of joist lumber yards over a period of 2 summers.

Keywords: lumber grading methods, machine grading, stress grades, construction practices.

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