AN EXAMINATION OF PROPERTY RELATIONSHIPS IN THE CANADIAN MACHINE STRESS RATED LUMBER IN-GRADE PROGRAM

By

ANNIE HELEN GRIFFIN

B.Sc.(Hons), Carleton University, 1979
B.Sc.F.E., The University of New Brunswick, 1983

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER'S OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Faculty of Forestry)

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

September 1994

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

(Signature)

Faculty ~~Department~~ of Forestry

The University of British Columbia
Vancouver, Canada

Date Sept. 14th, 1994

DE-6 (2/88)

ABSTRACT

The Canadian lumber industry undertook two large-scale test programs for the verification of lumber design properties of Canadian species combinations. The visual lumber in-grade test program was begun in 1983 (with a prior program undertaken in 1975), while a similar program for machine graded lumber (MSR lumber) was undertaken in 1988. Some of the results of the MSR lumber in-grade test program are examined in this thesis. Stiffness and strength results from the visual lumber in-grade program are used for comparison, as are values from the MSR lumber standard.

The importance of differences in methods of testing properties, particularly Modulus of Elasticity (MOE), is shown. Differences in results occur due to changes in the test span to depth ratios, measurement techniques and location of defects.

The importance of knots as a cause of failure in both bending and tension is examined. The high incidence of lumber failures initiating at points where no defect was visible to the human eye is also studied.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF NOTATIONS AND ABBREVIATIONS

ALS - American Lumber Standards Board of Review

ASTM - American Society of Testing and Materials

CLSAB - Canadian Lumber Standards Accreditation Board

CLT - Continuous Lumber Tester

COV - coefficient of variation

CSA - Canadian Standards Association

cusum - cumulative sum quality control procedure

E - modulus of elasticity

EI - bending stiffness

eqn. - equation

F_b - allowable bending stress

Hem-Fir - Hemlock and Fir species combination

I - moment of inertia

ILMA - Interior Lumber Manufacturers' Association

MC - moisture content

MMFBM - million board feet

MOE - modulus of elasticity

MOE_{D198} - ASTM D198 MOE

MOE_{Ingr} - In-grade MOE

MOE_{Lab} - Lab MOE

MOE_{Mill} - Mill MOE

MOR - modulus of rupture in bending

MSR	- Machine Stress Rated
MSRD	- maximum strength reducing defect
NLGA	- National Lumber Grades Authority
psi	- pounds per square inch
S-P-F	- spruce, pine and fir species combination
SPS-2	- Special Products Standard for Machine Stress Rated Lumber
SS	- Select Structural
UCS	- ultimate compression strength
UTS	- ultimate tension strength
VQL	- visual quality level
XLG	- X-ray Lumber Gauge

ACKNOWLEDGEMENTS

The support and guidance of my supervisor, Dr. J.D. Barrett in the execution of the research work and the preparation of this thesis was invaluable.

I would like to thank the Canadian Wood Council's Lumber Properties Steering Committee for allowing the use of the Canadian Visual In-grade Data (1983) and the Canadian MSR In-grade Data (1988) in this thesis.

The financial support of Forintek Canada Corporation in providing a Forintek Fellowship is gratefully acknowledged.

1. MACHINE STRESS RATED LUMBER

1.1 INTRODUCTION

This thesis examines some of the results from two large-scale test programs undertaken by the Canadian lumber industry to determine stiffness and strength properties of Canadian commercial lumber species and grades. The focus is on the results of the test program on machine stress rated (MSR) lumber, but the results of the test program on visually graded lumber are also used for comparison.

1.2 LUMBER GRADING PRINCIPLES

The grading of lumber for structural end-use involves the use of non-destructive means to estimate strength and stiffness properties. Visual grading of structural lumber uses knot size and location, slope of grain, size of splits (cracks) and other visible characteristics to predict the strength and stiffness of a piece. Grading is usually done in the lumber sawmill, most often as the lumber moves along the chain prior to the sorting bins and packaging area. The grader checks the four faces and both ends of the piece as it passes a grading station and a visual grade is assigned based on the grader's assessment of the severity of the visible characteristics in accordance with the grading rules. For structural lumber, each grade has a design modulus of elasticity (MOE) and associated design strength values (e.g. tension, bending and compression) assigned to it. These design properties allow engineers to choose the grade, species and cross-sectional size of lumber required for structures to be capable of resisting the loads imposed on them.

1.3 MSR LUMBER GRADING PRINCIPLES

In the 1960's an alternative to visually grading structural lumber was developed that combined the use of a machine with visual grading. This system lead to the development of machine stress rated (MSR) lumber and its associated structural grades. The machine is used to non-destructively measure a property of the lumber. The most commonly used property of lumber is the bending stiffness. The stiffness (EI) is the product of the modulus of elasticity (MOE or E) and the cross-sectional moment of inertia (I). The moment of inertia can be calculated using the standard (nominal) width and thickness of members, therefore the MOE can be directly related to the member stiffness. The grading machines measure the bending stiffness of lumber on the flat over a span of between 36 to 48 inches (depending on the manufacturer of the machine) using centre point loading.

For structural lumber, there is a correlation between the MOE and strength. The quality of the correlation will vary depending on the failure mode tested (e.g. bending, tension or compression). Generally MOE has been shown to be a good strength predictor. In MSR lumber the MOE is correlated to bending strength. However, since the measured average or minimum stiffness will be relatively insensitive to wane, knot location in the cross-section, splits and appearance characteristics, it has been found useful to incorporate a post-machine visual grading override. The visual grading improves the strength sorting (particularly for end-uses where the lumber is used on edge) and ensures the maintenance of visual quality requirements established for MSR lumber.

1.3.1 MOR - MOE RELATIONSHIP

Common MSR grades and selected associated mechanical property requirements are given in Table 1.

The product standards for MSR lumber require that the mean MOE for the lumber in each grade selected at a mill meet or exceed the mean grade MOE specified for the grade. The fifth percentile value for the MOE (minimum MOE, see Table 1) and the fifth percentile of Modulus of Rupture (MOR) in bending must also equal or exceed those prescribed for the grade. The quality control program which is part of the MSR production process provides the basis for measuring compliance to the above requirements (and allows for acceptable variability). The MSR grade names are given in terms of the allowable extreme fibre stress in bending and mean MOE. The MOR (Table 1) is the fifth percentile of short term strength. The allowable bending stress (F_b), as used in Allowable Stress Design Codes, for the grade is the grade fifth percentile of short term strength divided by a factor of 2.1 to account for safety and normal load duration. Thus an MSR lumber grade of 1650f-1.5E has a fifth percentile MOR of 3,465 psi[1] (1650 x 2.1) and a mean MOE value of 1,500,000 psi.

1.3.2 QUALITY CONTROL

Since the MSR lumber grading machine sorts by stiffness properties only, the machine will be insensitive to changes in the underlying strength-stiffness relationship for wood. Since these relationships can vary with wood source, species and many other factors, the MSR lumber industry uses an on-going quality assurance program to verify product conformance with specifications. The results of the quality control program are

[1]pounds per square inch

used as a feedback mechanism to adjust the grading machine for optimum lumber product value recovery.

As the MSR lumber grading machine simply measures the stiffness and assigns a stiffness grade category based on preset grade boundaries, it is necessary to have a quality control program for MSR lumber production. In fact, MSR lumber is only as good as the quality control program implemented. If, for example, the kiln schedule is changed to produce drier lumber which is run through the MSR lumber machine, the machine will probably assign the pieces to a higher grade. Lumber stiffness increases with decreasing moisture content, and the MSR lumber grading machine would interpret the stiffer lumber as being stronger. Accordingly, mills drying to lower moisture contents can gain an advantage if the planed size stays constant as there will be more wood fibre in the cross-section. However, as the moisture content is reduced, drying defects increase and the pieces become more brittle and may not have the required strength. The optimum moisture content for running MSR has to be selected to be in balance.

The "output-controlled" system which is used in Canada and the U.S.A. has significant benefits over the "machine-controlled" systems used elsewhere in the world. In machine-controlled systems, the grade boundaries are fixed at levels sufficiently high that the grading system will accommodate all natural variation anticipated in the lumber supply and still produce grades with the specified properties. With this method on-going quality control is not required. For this reason machine-controlled systems are inherently less efficient than the output-controlled systems used by the North American industry. Machine controlled systems are best suited to situations where lumber is obtained from a wide variety of sources, such as is the case in the U.K. Output controlled systems are best suited to optimizing yield from a fairly narrow wood source, as is found at an individual sawmill.

In the output controlled system the quality control system used is based on the cumulative sum (cusum) process. Five piece random samples are required to be pulled from post gradestamped lumber for each MSR grade produced during every four hours of production. These pieces are tested for MOE and proofloaded in bending. The samples must meet requirements for average MOE, minimum MOE and bending. As well as meeting set levels within the five piece sample, the results of the samples are added to the results of previously sampled five piece lots in a cumulative sum. This process monitors the immediate results from a five piece sample and the long term trends by use of the cusum process.

1.3.3 VISUAL QUALITY LEVEL

After the lumber has been E-rated and assigned to an E-grade category, it undergoes a visual inspection. The most important characteristic checked is the visual quality level (VQL). The VQL is the maximum fraction of the net cross-section of the lumber that can be occupied by a strength reducing characteristic such as a knot, knot hole, burl, distorted grain or decay that occurs at or partially at the edge of the wide face [19]. The maximum fraction permitted varies with the MSR lumber grade - the higher the grade the smaller the fraction. If a VQL is found that exceeds that permitted in the grade, the grade of the piece must be dropped to the first lower grade that permits the measured VQL. In this way, the visual grading inspection in MSR lumber can lower but never raise the E-grade assigned by the grading machine. Table 2 summarizes the VQL levels and compares them with visually graded structural light framing grades [18].

Defects are restricted on the edges of MSR lumber because MSR lumber grading machines test the lumber on the flat whereas most lumber for structural use in bending is used on edge (e.g. floor joists and roof trusses). Knots on the edge of lumber subjected to bending stresses (in an on-edge use) have more severe affects on strength than knots of the same size at the centerline. For this reason MSR lumber has a visual override to control the maximum size of edge knots.

A restriction is also applied to each end of the pieces where they are not fully tested by the grading machine (due to the distance between the load head and support rollers). This limits the size of knots, other than edge knots, and other strength reducing defects to the size of the largest knot in the tested section or the size of edge knot in the next lower grade if that is greater. The slope of grain is also restricted at the ends. This override is to prevent weaker sections at the ends of the boards, as in use the boards may be spliced together to develop longer lengths (as occurs in many roof trusses).

1.3.4 MACHINE TYPES

Over the years a number of different types of MSR lumber grading machines have been developed. The most common type of machine measures bending stiffness. At the time of the MSR lumber in-grade test program (1988) all MSR machines in use in Canada were of this type. These machines measure stiffness in one of two ways, either by applying a constant load and measuring the resulting deflection or by applying a constant deflection and measuring the load. Some of these machines are designed to operate at the same speeds as the planer mill of a sawmill, therefore they can be placed in-line at a mill. Other machines operate at slower speeds so that the lumber must be fed through separately from the main mill operation. In Canada, four different MSR lumber grading machines are currently approved for use. Most sawmills use the CLT Continuous Lumber Tester produced by Metriguard. Mechanically graded lumber is, however, not limited to machines that directly measure stiffness. Grading machines that measure specific gravity are currently entering the market, such as the Newnes X-ray Lumber Gauge (XLG). This machine uses an x-ray to measure specific gravity which is correlated to strength and stiffness properties.

1.4 MSR LUMBER STANDARDS

In Canada the product standard governing MSR lumber is written by the National Lumber Grades Authority (NLGA). NLGA also produces the *Standard Grading Rules for Canadian Lumber* [18], the lumber grading rule used in Canada. These rules are approved and enforced by the Canadian Lumber Standards Accreditation Board (CLSAB) and the American Lumber Standards Board of Review (ALS). This approval by CLSAB and ALS provides a basis for acceptance of Canadian lumber by Canadian and American building codes.

MSR lumber is produced under *NLGA Special Products Standard for Machine Stress Rated Lumber* (SPS-2) [19]. The standard contains two sections, Part A: Product Specifications and Part B: Qualification and Quality Control Requirements. Part A sets out the grades and their mechanical properties, standard sizes, visual grading requirements, mechanical property requirements and how to evaluate them, and grade stamping requirements. Some of the most common grades recognized by the NLGA standard are listed in Table 1. Not all these grades are produced simultaneously at a sawmill. Market price and demand,and the recovery rates for each grade from the available raw material determines the grading practice. In Canada most sawmills will produce only two grades in combination, although a few may select as many as five grades simultaneously.

The design property values used for engineering design in wood in Canada are given in the *Code for Engineering Design in Wood* (CSA O86) [5] published by the Canadian Standards Association. It provides that the design values are only for use with lumber graded under NLGA rules and grade stamped by an association or independent grading agency in accordance with CSA O141 [6]. There is an equivalency clause that allows certain US species combinations to be used. CSA O86 is referenced under Part 4 of the National Building Code of Canada [17] for engineering design of structures. Thus, only NLGA graded lumber can be used for engineered design in wood in Canada (or those US graded equivalents). Part 9 of the

Building Code, which provides for construction of smaller buildings (e.g. houses) built using a prescriptive method, only permits use of NLGA graded lumber with the appropriate stamps.

The use of lumber graded under NLGA rules ensures that lumber used in construction meets a minimum standard and has published strength and stiffness values approved by a national consensus standard. This code system provides protection for the producer, user and consumer.

1.5 MSR LUMBER PRODUCTION

Canadian MSR lumber production is a small proportion of the Canadian lumber industry's 2-inch dimension lumber production (i.e. 2x4, 2x6, etc.). However, machine grading provides an opportunity to make more efficient use of wood products through provision of increased strength values and increased dollar value recovery over visual grades.

There were 18 sawmills producing MSR lumber in Canada at the time the MSR lumber in-grade test program began in 1988. Of these, 15 mills were in British Columbia and three were located in Alberta. The number of MSR mills has expanded since then to include some mills in Eastern Canada. In 1986 Canadian

MSR lumber production was estimated to exceed 650 MMFBM[2] [10] out of a total Canadian softwood lumber production of 22,000 MMFBM [8]. Therefore MSR lumber production represents only a very minor portion (3%) of total Canadian production although it is growing.

1.5.1 MARKETS

MSR lumber is used in any application where more controlled strength properties are advantageous. It competes against visually graded lumber in the marketplace as it is simply another way to grade lumber for structural use. MSR lumber has an advantage over visually graded lumber in that the grades cover a much narrower and controlled range of strength and stiffness values. For example where visual Structural Light Framing grade rules will segregate the lumber into Select Structural (SS), #1, #2 and #3 grades, each with their own strength values, MSR lumber grading will divide this same population into many grades. The greatest marketing advantage for MSR lumber lies in the fact that machine grading allows selection of products with substantially higher design properties than with the visual grading system. For marketing reasons no sawmill will produce the full range of possible grades simultaneously. Mills will produce only those for which

[2] a million board feet

there is a demand, and which best match the stiffness and strength properties of their wood supply. Mills will also limit the number of grades they produce to ensure that marketable volumes of each grade are obtained.

At present, most MSR lumber is used in products which are engineered under strict quality control, such as trusses for residential and commercial applications, glulam beams and specialized products such as I-joists. These components are designed for more demanding structural requirements than many of the usual dimension lumber applications. Therefore, it can be an advantage to be able to purchase lumber with more precisely controlled stiffness and strength values that can be matched to component performance requirements. Since MSR lumber sells for a premium over visually graded lumber, it will only be used in applications where the selling price of the final product is sufficient to justify the added costs.

1.6 MSR LUMBER POTENTIAL

Machine stress-rating has the potential to cope effectively with problems of changing timber quality and supply that will become increasingly important in Canada and other countries as the old growth timber supply is replaced by trees from younger and managed forests. The processing of young second growth trees will tend to increase the proportion of low quality juvenile wood in lumber grades. MSR lumber has the potential to make more efficient use of our future forest resource by directly evaluating the stiffness properties (or other non-destructively measured characteristics) and allocating each member to its best structural use.

1.6.1 JUVENILE WOOD

Juvenile wood is the wood associated with the tree's early growth. It is typically defined as the first 20 growth rings from the pith [3]. As increasing numbers of trees are harvested from natural second growth stands or from managed plantations, the amount of juvenile wood in structural lumber products will significantly increase. These trees are harvested at a smaller diameter and shorter rotation ages than is common in old growth stands. This means the lumber produced from them will be more likely to contain juvenile wood.

Juvenile wood has characteristics different from the wood put on later in a tree's growth cycle. Two wood quality indicators - longitudinal shrinkage and specific gravity - can be significantly different between mature wood and juvenile wood. Greater longitudinal shrinkage can cause difficulties in kiln drying, resulting in increased drying degrade. In structures, the differential longitudinal shrinkage between members can also result in poor performance of trusses and truss uplift when juvenile wood is used for building trusses. Truss uplift over internal walls has been attributed to differences in temperature and humidity conditions between the top and bottom truss chords in an attic. Equilibrium moisture content differences combined with high longitudinal shrinkage in members can result in the bottom chord shrinking thereby causing the truss to bow upwards [11]. In mature wood fibre this shrinkage is usually not sufficient to cause a problem as longitudinal shrinkage in mature wood is small (0.1%).

Juvenile wood will sometimes have lower strength properties possibly due to differences in cell wall structure and/or cell wall component organization [13]. These differences can not be detected in visual grading. In Structural Light Framing grades rate of growth criteria apply only to Douglas Fir and Western Larch in Select Structural, #1 and #2 grades. For these grades, rate of growth is limited to *medium grain* which is an average of approximately four or more annual rings per inch. This rate of growth limit has not been shown to be an effective criteria for rejecting lumber with juvenile wood [3]. Also, since not all juvenile wood shows lower strength properties, it would be wasteful to reject it all for structural uses [3].

Machine stress-rating is a method that shows potential for assessing the structural capability of lumber containing juvenile wood. It enables each piece of lumber to be tested for stiffness and assigned a strength value. Whether the piece has juvenile wood or not is irrelevant. Only the mechanical properties are of concern in MSR lumber production. This, however, does not eliminate the problem of drying degrade which occurs before the lumber reaches the MSR lumber machine or those problems arising due to moisture changes in service (e.g. truss uplift).

1.7 IN-GRADE TESTING

Starting in the late 1970's there was a move in North America towards in-grade testing of lumber. This involves testing full-size pieces of lumber sampled by grade from sawmill production. The major advantage over mechanical property values developed from small clear specimen tests is that the in-grade lumber samples represent the lumber currently being produced. This is important since over the years the nature of the forest resource has changed. For example, there are and will be increasing numbers of second growth trees being cut in North America. These trees are cut at a younger age and typically at smaller diameters than was previously the case. The lumber produced from these trees is more likely to contain juvenile wood which can behave differently (see Section 1.6.1).

1.7.1 VISUAL LUMBER IN-GRADE TESTING

Prior to 1984 the design values in CSA O86 were based on small clear specimens. The original tests were done in Canada and the U.S.A. beginning in the 1920's and 1930's using specimens of wood which were clear, straight-grained, free of decay and other defects. Each commercial species was tested for strength and stiffness properties following American Society of Testing and Materials (ASTM) D143 test procedures and D2555 procedures to establish the clear wood values [1]. To determine strength and stiffness values that applied to commercial grades of structural material (e.g. #2 Structural) the small clear values were multiplied by a strength ratio. The strength ratio is the anticipated strength remaining in a piece of lumber after making allowance for the effect of the maximum permitted defect sizes (e.g. slope of grain or knot size and location) allowed in the grade as set out in ASTM D245. In #2 structural grade the bending strength ratio was set at 45% (see Table 3). Therefore a piece of #2 lumber would have 45% of the bending strength of a defect-free piece of the same species. The strength and stiffness values were also adjusted to account for other factors such as duration of load and moisture content. A factor of safety was also applied. The design values for a species combination were based on the weakest species in the combination for each property.

In-grade testing looks at full-size lumber taken from mill production. In this method it is not necessary to account for growth characteristics as the lumber is already sorted into the visual grades. It is only necessary to test large enough samples across the growing region to ensure the strength and stiffness values are truly representative of the grade. This method also requires that the testing be repeated at intervals if it is suspected that the nature of the forest resource is changing.

The first stage of the in-grade testing program undertaken by the Canadian industry was started in 1975 [16]. Mostly 2x8 lumber of D.Fir-L[3] , Hem-Fir[4] and S-P-F[5] species combinations was tested in bending and tension at the sawmill sites. Overall, some 70,000 specimens were tested using proof-loads designed to break 10-15% of the specimens. The results of

---

[3]A species combination of Douglas Fir and Western Larch.

[4]A species combination of Western Hemlock and Amabilis Fir.

[5]A species combination of Spruces (all except Coast Sitka Spruce), Pines (Jack and Lodgepole) and Firs (Alpine and Balsam).

this first program showed that the design values derived from small clear specimens were too high for D.Fir-L while those for S-P-F were too low. It was also found that there was no significant differences in strength and stiffness between #1 and #2 structural grades. The results of this in-grade program were used to review the design properties for dimension lumber in the 1984 edition of CSA O86.

In 1983, a second in-grade program was undertaken by the Canadian industry (the Visual Lumber Properties Test Program) to acquire data on Canadian species for use in developing design values for North American codes [12] [14]. The U.S. industry had undertaken an in-grade study of their own lumber. The methodology used in the U.S.A. was sufficiently different from that used in the 1975 Canadian study that the Canadian industry undertook the second program to ensure that Canadian design values would be accepted on an equal basis in the U.S. The second Canadian in-grade program was more extensive than the first. All major commercial species combinations (D.Fir-Larch, Hem-Fir and S-P-F) and most minor species[6] were tested in bending, tension and compression (see Tables 4-6). Specimens were tested to destruction rather than using a proof-loading method. All pieces were run through a Cook

[6]Eastern Hemlock, Western Red Cedar, Pacific Coast Yellow Cedar, Red Pine, Eastern White Pine, Sitka Spruce, Western White Pine, Ponderosa Pine, Northern Aspen and Norway Spruce

Bolinders stress grading machine. This test provides flatwise bending MOE values at approximately 4-inch (10 cm) intervals along each specimen. Edgewise bending MOE's were measured at a 17:1 span to depth ratio for all pieces. The samples were then tested to destruction in either bending, tension or compression. Visual characteristics and failure types were recorded for each specimen, providing an extensive bank of additional information. The results essentially confirmed those obtained in the first round of in-grade testing in the 1970's although the D.Fir-L values had been too severely reduced in the 1984 CSA O86. These new results were incorporated into the 1989 edition of CSA O86.

The current edition of CSA O86 (1989) is a reliability-based limit-states code to conform to those used in steel and concrete design. The information on sample populations derived from the second in-grade program were used to develop the information needed for the code. As similar information was not available for MSR lumber, its competitive advantage over visually graded structural lumber could have been eroded. An in-grade test program for MSR lumber allows the existing MSR lumber design properties to be verified and provides sample population information for reliability design.

The results of the second visual lumber in-grade test program are used in this thesis for comparison to the MSR lumber in-grade test data and are referred to as the visual lumber in-grade program results.

1.7.2 MSR LUMBER IN-GRADE TESTING

The Canadian industry completed in 1988 an in-grade test program for MSR lumber. This involved sampling each of the 18 mills producing MSR at this time for each of the grades in production. Packages from the mill yards were sampled randomly and 20 specimens pulled from each of three packages for each grade. The samples were evaluated by the lumber agency grader (e.g. a grading inspector from the Interior Lumber Manufacturers Association - ILMA) for grade, VQL knot and location, maximum strength reducing defect and location, slope of grain, presence of pith and rate of growth and tested for MOE according to the SPS-2 quality control procedures. The samples were then shipped to Forintek Canada Corp. in Vancouver where each specimen was checked by a grading supervisor to verify the characteristics recorded at the mill by the agency grader. The material was all 16 foot S-P-F 2x4 MSR lumber in one of five grades: 1450f-1.3E, 1650f-1.5E, 1800f-1.6E, 2100f-1.8E and 2400f-2.0E. Over 2700 specimens were collected of which 2520 specimens were actually tested. Each 20 specimen sample was divided in two to provide ten specimens for bending tests and ten specimens for tension tests.

All the specimens were run through a Cook Bolinders stress grading machine providing flatwise bending MOE values at 3.3-inch intervals along each specimen. Edge bending MOE values were also obtained for all specimens using a testing machine at a 21:1 span/depth ratio, which corresponds to the bending MOE determined by the MSR SPS-2 lumber quality control program at the sawmills. In addition, a sub-sample was tested for bending MOE following the ASTM standard D198 [1]. The bending sample was then tested to destruction at a 17:1 span/depth ratio to obtain a bending MOE and an MOR that corresponds to those measured in the visual lumber in-grade testing program. The tension specimens were broken using a test set-up identical to that used in the visual in-grade program.

Details of the reasons for each bending and tension failure were recorded. Specific gravity and moisture content samples were taken from the bending specimens after failure. The test program did not involve testing any specimens in compression parallel to grain. The compression strengths were required to be developed from comparisons of the visual lumber in-grade test data (which has bending, tension and compression information), and the MSR lumber in-grade test data for submission to CSA 086. Information on other grades and sizes not tested may also be inferred from the results of the testing program.

When the strength and stiffness values are developed, consideration must be given to the way the grades were produced. For mills that were pulling only two grades e.g. 1650f-1.5E and 2100f-1.8E, the 1650f-1.5E grade contains 1650f-1.5E and 1800f-1.6E material. For mills pulling five grades, the material in the 1650f-1.5E grade would represent a "pure" 1650f-1.5E grade.

The MSR lumber in-grade testing program, like the visual lumber in-grade program, provides an extensive bank of data for the Canadian industry. This information not only allows the strength and stiffness properties to be developed for engineering use but also allows other studies to be undertaken. In particular, the extensive information on visual characteristics and failure types will allow assessment of what types of characteristics, particularly what type and size of knots, have the most detrimental effect on strength and stiffness. This research could be used to refine the VQL requirements for MSR lumber.

1.8 THESIS OBJECTIVES

This thesis examines stiffness and strength properties from the MSR in-grade test program and compares the results with both the SPS-2 requirements and the visual grade values obtained from the 1983 visual lumber in-grade test program. It also examines failure types under both bending and tension for the tested MSR grades. The positioning of specimens in the test span with respect to lumber defects in bending is also examined.

2. STUDY OF MOE'S RECORDED IN THE MSR LUMBER IN-GRADE TEST PROGRAM

2.1 INTRODUCTION

Four different test Moduli of Elasticity (MOE's) were determined as part of the MSR lumber in-grade test program. These were measured on the same pieces of lumber, allowing comparison of the effect of test methods on the resulting MOE's.

The MOE of lumber can be determined by testing using a variety of different loading conditions, span/depth ratios, deflection measuring devices and specimen conditions. In order to compare MOE's or to use the values in determining design properties, the values must be convertible to a standard MOE.

The American Society of Testing and Materials (ASTM) publishes standard test methods which allow material properties to be measured on a consistent basis. ASTM D198 [1] gives a standard method of testing full-size lumber to determine MOE. This is done using a yoke or wire deflectometer, which produces a deflection measurement free of specimen crushing and machine deflection. It is measured at the neutral axis in the centre of the test span relative to the reaction points.

The ASTM standard D2915 which provides procedures for evaluating design values for structural lumber grades, suggests that MOE's be standardized to a 21:1 span/depth ratio and an assumed uniform load. It provides a table for converting MOE's from various loading and span/depth conditions to these standard conditions.

The National Lumber Grades Authority (NLGA) in its *Special Products Standard for Machine Stress Rated Lumber* (SPS-2) [19] outlines the quality control procedures for MSR lumber. Although the design values are based on 21:1 span/depth ratio under uniform load and shear free, the MSR quality control is measured with third point loading. If the span/depth ratio used for quality control testing is not 21:1, a conversion factor is used based on ASTM D2915. The readings are adjusted for machine deflection.

In the visual lumber in-grade test program MOE was based on a 17:1 span/depth ratio with third point loading. To obtain design values this data was standardized for a 15% MC and adjusted for machine deflection.

2.2 <u>TEST PROCEDURES</u>

The MSR lumber in-grade test program used four methods for testing MOE. They are as follows:

a) Mill MOE (MOE_{Mill})

The quality control MOE done at each mill, each piece of the sample was tested following the procedure outlined in SPS-2. That is, at a 21:1 span/depth ratio, third point loading with the piece centred in the test span.

b) Lab MOE (MOE_{Lab})

All pieces were tested at Forintek using the same test set-up as that used by the sawmills for the quality control MOE. This provides a comparison to the MOE_{Mill}. It also provides a more consistent MOE, as all the pieces were tested on the same machine rather than pieces being tested on one of 18 mill bending testers. The MOE's produced differed from the MOE_{Mill}'s in that the actual dimensions of each piece were used in the MOE calculations rather than the standard (nominal) dimensions, and no machine deflection adjustment was applied.

c) In-grade MOE (MOE_{Ingr})

All pieces that were designated for the bending sample were tested for an In-grade MOE as was used in the visual lumber in-grade test program. This meant the span/depth ratio was 17:1, six foot test specimens[1] were used with the Maximum

---

[1]In the visual lumber in-grade test program, the test pieces were full length.

Strength Reducing Defect (MSRD) being randomly located in the test span. Individual piece dimensions were used in calculations and no machine deflection adjustment was applied.

d) D198 MOE (MOE_{D198})

A small sample of pieces, a least one 10 piece lot from each mill for a total of 370 pieces, were tested using the ASTM D198 test procedure. The MOE's were calculated using nominal dimensions and the yoke deflection measurement system which eliminates machine deflection from the deflection measurements. The sample sizes by grade are shown in Table 7.

These various MOE's, collected on the same pieces of lumber, allow comparison of the different MOE's used in the industry. The test procedures described above are summarized in Table 8. Before any analysis of the four MOE's was done, further modifications were made to make them as similar as possible. They were modified as follows:

a) MOE_{Mill}

No modifications made.

b) MOE_{Lab}

- MOE recalculated using nominal dimensions
- adjusted for machine deflection at 21:1 span/depth based on Forintek's report *Effect of Span-Depth Ratio on Apparent*

Stiffness of Dimension Lumber [9]

c) MOE_{Ingr}

- MOE recalculated using nominal dimensions
- adjusted for machine deflection at 17:1 based on Forintek report [9]

d) MOE_{D198}

- no modifications made

2.3 RESULTS

2.3.1 COMPARISONS OF MOE'S MEASURED AT A 21:1 SPAN/DEPTH RATIO

Graphing and regression studies were used to relate the various MOE's tested at a 21:1 span/depth as described below. There were 370 pieces which were tested for an MOE_{D198} (in addition to being tested for an MOE_{Mill} and an MOE_{Lab}) and these pieces were used for the comparison.

a) MOE_{D198} versus MOE_{Lab} (Figure 1)

When graphs were produced with the MOE_{Lab} recalculated based on nominal dimensions and corrected for machine deflection there was good agreement between the MOE_{Lab} and the MOE_{D198}. The R-squared (correlation coefficient squared) of the relationship was 97%, showing strong correlation between the two test procedures. The regression equation resulted in an intercept close to zero and a slope such that:

$$MOE_{D198} = -0.009 + 1.015\ MOE_{Lab} \tag{2.1}$$

(the units of MOE are in psi x 10^6)

The purpose of the machine deflection adjustment to the MOE_{Lab} is to offset the deflection measuring errors that may result from not using a yoke type measuring device. The ASTM standard D198 requires that deflections are measured from the neutral axis at the mid span relative to the load points. Ignoring the deflection adjustment produces errors due to factors such as specimen crushing at the supports and deflection of the test frame. The yoke type measuring device was not used in testing all the specimens in the MSR lumber in-grade test program as the test set-up is complex and time consuming to use for large scale test programs. Testing 370 pieces with the yoke allows correlation of the MOE test methods used to the ASTM standard. The machine deflection adjustments were determined by testing three species and three sizes of lumber [2]. This results in a general equation that can be applied to all lumber based on its size. As the intent is to transform an MOE_{Lab} to an MOE_{D198} the MSR lumber in-grade data can be used to determine a specific machine deflection adjustment for 2x4 S-P-F.

A plot of MOE_{D198} against an MOE_{Lab} that was based on nominal dimensions, but not adjusted for machine deflection was prepared. There was still good correlation between the MOE's with an R-squared of 97%. The intercept was slightly negative with a slope such:

$$MOE_{D198} = -0.040 + 1.052\ MOE_{Lab} \tag{2.2}$$

resulting in a larger adjustment being required than in Eqn. 2.1 to compensate for the machine deflection.

b) MOE_{D198} versus MOE_{Mill} (Figure 2)

The MOE_{Mill} is that taken for quality control tests during MSR lumber production. It is therefore important to know how this MOE relates to a standard D198 MOE and the MOE used in derivation of design values.

A plot of MOE_{D198} versus MOE_{Mill} shows a strong relationship, though not as strong as that between the MOE_{D198} and MOE_{Lab}. There is more scatter of the data, probably due to the fact that the MOE_{Mill}'s are measured on one of 18 different machines in different conditions whereas the MOE_{Lab}'s are all performed on a single test machine. The R-squared for the relationship is 94% with an intercept that is slightly positive and a slope of 0.976. This equation, shown below, gives an indication of the adjustment that would be necessary to adjust MOE_{Mill}'s to MOE_{D198}'s.

$$MOE_{D198} = 0.061 + 0.976\ MOE_{Mill} \qquad (2.3)$$

c) MOE_{Lab} versus MOE_{Mill} (Figure 3)

The regression equations for the relationships discussed already indicate that the MOE_{D198}'s lie between the MOE_{Mill}'s and the MOE_{Lab}'s. This is confirmed in the plots of MOE_{Lab} against MOE_{Mill}'s. These plots are of the same 370 pieces tested for ASTM D198 MOE so that direct comparisons can be made. The scatter of values on this plot is greater than seen in the previous relationships, although the R-squared is still high at 93%.

The intercept is positive and greater than the other plots. The slope is such that:

$$MOE_{Lab} = 0.107 + 0.939\ MOE_{Mill} \qquad (2.4)$$

This equation shows the variability that occurs when testing on different machines, even if the same testing and calculation procedures are followed. The MOE_{Mill} and the MOE_{Lab} used for the plots were adjusted to provide comparable values, e.g. calculated using nominal dimensions, adjusted for machine deflection, etc.

d) Outlier Values

For the plots discussed above, there were data points that were outliers to the main group of data. A check was done to see if these points belonged to the lumber sampled from a specific mill. Plots of the MOE data identified by mill showed that the outliers came from several mills, with no single mill being the predominate contributor.

2.3.2 COMPARISONS OF MOE'S MEASURED AT DIFFERENT SPAN/DEPTH RATIOS

About half the pieces that were tested for an MOE_{D198} were also tested for an MOE_{Ingr} (170 pieces). The MOE_{Ingr} results at a 17:1 span/depth ratio can be compared to the three 21:1 span/depth MOE's (MOE_{D198}, MOE_{Lab} and MOE_{Mill}) available for the same pieces.

In general, the comparisons of MOE_{Ingr} with the 21:1 MOE's show a much greater scatter than was evident between the various 21:1 MOE data.

a) MOE_{D198} versus MOE_{Ingr} (Figure 4)

Analysis of the data shows an R-squared of 81%, much lower than the R-squared values seen relating the 21:1 MOE's. However, the difference in sample size (170 test pieces compared to 370 test pieces tested at 21:1) could account for the lower R-squared values. The intercept is a positive 0.205 with the slope such that:

$$MOE_{D198} = 0.205 + 0.965\ MOE_{Ingr} \tag{2.5}$$

b) MOE_{Lab} versus MOE_{Ingr} (Figure 5)

The data shows similar results to those between MOE_{D198} and MOE_{Ingr}. The R-squared is 80% with an intercept of 0.227 and a slope such that:

$$MOE_{Lab} = 0.227 + 0.937\ MOE_{Ingr} \tag{2.6}$$

Figure 6 shows a cumulative frequency plot of MOE_{Lab} and MOE_{Ingr} illustrating the lower MOE value produced by the in-grade test method for the same pieces. For this graph the full bending data set of 1280 pieces was used.

c) MOE_{Mill} versus MOE_{Ingr} (Figure 7)

In this case the R-squared is slightly lower at 77% and the intercept is higher at 0.28. The slope is such that:

$$MOE_{Mill} = 0.281 + 0.898\ MOE_{Ingr} \tag{2.7}$$

Figure 8 shows a cumulative frequency plot of MOE_{Mill}, MOE_{Lab} and MOE_{Ingr}. The in-grade test procedure at 17:1 results in a lower MOE, while testing the pieces at a central site (MOE_{Lab}) produces an MOE slightly lower than that resulting from testing at the mills due to differences between testing machines. The full bending sample of 1280 pieces was used for this plot.

One major difference between the 17:1 in-grade MOE's and the 21:1 MOE's is the placement of the test specimens in the test span. The 17:1 in-grade specimens have the Maximum Strength Reducing Defect (MSRD), as identified by the grader located *randomly* in the test span that was cut from the full size piece. The 21:1 MOE's had the full size pieces centred in the test span, thus the MSRD may not have been in the zone tested. It would be logical to expect the presence of the MSRD in the test span of the specimen to result in an overall lower MOE, although the MSRD would not always be in the centre third of the test span, and therefore in the area of maximum stress. This is confirmed in Figures 9 - 14, where the ratio of the MOE_{Lab} to the MOE_{Ingr} has been plotted against MOE_{Ingr} for all MSR grades combined and also for each grade separately. The plots are based on the full bending sample of 1280 pieces. The plot of all grades combined (Figure 9) shows that the difference between the MOE_{Lab} and the MOE_{Ingr} decreases with increasing MOE. The pieces with higher MOE would have fewer defects, therefore the effect of placing the MSRD in the test span would be less and the two test methods should produce more similar results. The graphs of each grade separately show the same trend as the all grades combined. The only exception is that of 1450f-1.3E (Figure 10), but this may be due to two factors - the smaller sample size and that as the lowest MSR grade produced there will be few pieces present without some type of defect.

These results indicate that there is a considerable difference between the MOE's determined by the MSR lumber mill quality control and those determined using in-grade (17:1) procedures. The in-grade MOE procedure was used in the visual in-grade test program to determine design MOE's. The in-grade MOE's from the MSR lumber in-grade test program were also used to verify the design values currently in CSA O86 for MSR lumber. As Figure 8 shows, at each percentile the MOE_{Ingr} is less than the MOE_{Mill} and MOE_{Lab} so that design values verified using the in-grade MOE will be easily verified using the quality control MOE's.

3. PROPERTY COMPARISONS OF THE MSR LUMBER IN-GRADE TEST PROGRAM

3.1 INTRODUCTION

The visual and MSR lumber in-grade test programs allow comparison of stiffness and strength properties between visual and MSR grades. The 2x4 S-P-F sample of the visual lumber in-grade test program provides data of the same species and size as was tested in the MSR lumber in-grade test program. Within the MSR lumber in-grade test program, stiffness and strength properties of the tested grades can be compared with the requirements for MSR specified in the MSR standard SPS-2. It is also possible to break down the MSR lumber in-grade data by mill to compare grade properties when different combinations of grades are pulled at each mill. It is important though, when doing the comparisons, to consider the different test methods used to obtain the properties so that similarly measured properties are compared, or the differences between the measured properties are recognized.

3.2 RELATIONSHIPS BETWEEN GRADE COMBINATIONS

The MSR lumber collected from the sawmills was sampled in several different grade combinations. The number of grades, and the combinations of grades produced concurrently, are the decision of each producing sawmill. They depend on the stiffness and strength properties of the wood resource that the mill draws from. For example, some mills have access to fibre with high stiffness and strength properties that would allow them to pull a 2400f-2.0E in combination with lower grades on a regular basis. Other mills will not have the fibre to achieve marketable volumes in the highest grades, therefore a 2100f-1.8E grade might be the highest grade pulled. The choice of how many grades to pull in combination, e.g. two, three or five, will depend again on the stiffness and strength properties of the wood resource. Pulling too many grades could mean that yields for some grades will be small. Or, to produce the yields in each grade, the machine boundaries require raising in a higher grade to increase the yield in the grade below. Thus, yield in the upper grade is sacrificed to produce adequate yield in a lower grade.

In MSR sawmill production, grade combinations differ with the species, size and type of stock. In Canada, S-P-F is the predominate MSR lumber species. In the USA, Douglas fir, Douglas fir-Larch, Hem-Fir and Southern Pine are species combinations that are machine graded. The grade combinations used for these species may differ from those used for S-P-F in order to take advantage of the natural strength and stiffness relationships inherent within each species group. Different grade combinations are also used for different sizes, e.g. for natural 2x4 and 2x6 (cut as 2x4 or 2x6 in the sawmill, rather than developed by splitting a larger size) sawmills will often use the same grades. For 2x8 and wider widths, the grades are usually lower as it is found that for wider widths the yields decrease at the higher end of the grade spectrum. In the wider widths, it is more likely that a defect will be present that will either reduce the stiffness, or exceed the visual override requirements.

Many sawmills will have different grade combinations for 2x4 natural and split stock. Split stock is produced by splitting 2x8 stock, usually as it runs through the planer. Splitting 2x8 tends to produce a 2x4 with spike knots which can take up a larger proportion of the cross-section than round knots. This results in a lower stiffness, because of the associated grain distortion, compared to 2x4 natural stock with its more usual round knots. Therefore, mills may use a 2100f-1.8E and 1650f-1.5E grade combination for their natural 2x4, and an 1800f-1.6E and 1450f-1.3E for their split 2x4. In all decisions regarding sizes and grade combinations produced by a sawmill, the market demand and price for the sizes and grades plays an important role in making the final decision on production options.

The grade combinations sampled at each of the 18 MSR sawmills in the MSR lumber in-grade test program are shown in Table 9. All the combinations shown are ones that the mills pull in a single run. There were three mills which produced only a single grade during a run, although the grade itself differed with each mill (a 2100f-1.8E, an 1800f-1.6E and a 1650f-1.5E). Half the mills produced two grades during a 2x4 run (a 2100f-1.8E and a 1650f-1.5E). Four mills produced three grades during a run and two mills produced five grades in a run.

3.2.1 DATA SOURCES

To compare the grade combinations pulled, the MOE_{Lab}'s were examined. The MOE_{Lab} was determined on the same basis as the SPS-2 quality control MOE (MOE_{Mill}) except that it uses individual piece dimensions rather than nominal dimensions. As the testing was performed at a central facility (Forintek), rather than on one of 18 different bending proofloaders, the between mill variation in MOE due to equipment effect should be eliminated. The bending and tension MOE samples were combined to maximize the sample size, thus the results are based on 2581 pieces.

3.2.2 RESULTS

Statistics for the grades produced at each mill are given in Table 10. The average Coefficient of Variation (COV) for all grades from all mills combined is 9.2% which is less than the 11% COV assumed for MSR grades in SPS-2. There are some individual mill-grades which have a COV over 11% but most are well under the 11% specification. Observation of the COV's shows that in 13 out of the 15 mills which pull two or more grades in a single run, the lowest grade in the combination has the highest COV. An explanation of this would be that the lower tails of the upper grades are artificially curtailed by the presence of a grade below. The lowest grade in a combination would have a larger COV as the tail can extend further provided the mean and minimum MOE's of the grade are met.

The average of the mean MOE's for all mills in each grade exceeds the grade mean required by SPS-2 as shown in the Notes below Table 10. The mean and 5th percentile MOE of each individual mill-grade sample does not necessarily exceed the grade requirements. Of the 1450f-1.3E mill samples, all mean and 5th percentile values exceed the grade requirements. In the 1650f-1.5E, 1800f-1.6E, 2100f-1.8E and 2400f-2.0E, all but one mill-grade sample meets the fifth percentile requirement. For the mean MOE's, there are some mill-grade samples, particularly in the 1650f-1.5E and 2100f-1.8E, that do not meet the mean grade MOE requirement. The lowest mill-grade mean is 94.6% of the required grade mean. SPS-2 allows the mean of a 60 piece sample used for grade qualification at a sawmill to be acceptable if it equals or exceeds the grade MOE minus 0.258 the sample standard deviation - this allows for sampling variability [19]. The samples pulled at the sawmills were of this size range, therefore similar variability could be anticipated and still be acceptable. For example, the 1650f-1.5E grade from Mill M has a mean MOE of 1.469 and a standard deviation of 0.150. The mean of the sample would be acceptable if it were 1.461 or greater. Of the 43 mill-grades sampled all but five meet this sampling criterion.

Graphs of the cumulative frequencies of the grade combinations at each mill, and for each grade of a combination across the mills, were done - a representative group of these are shown under Figures 15 - 23. The individual grades tend to be similar in COV (Table 10) and range of MOE values when compared. There are some differences which would be expected as the grades are not necessarily optimized - some have mean MOE's and 5th percentiles well over that required for the grade.

Figures 15 - 18 show plots of the grade combinations pulled at individual sawmills. Figure 15 is for a mill that pulls only a single grade, in this case a 2100f-1.8E. The graph in Figure 16 is for a mill that pulled two grades in combination. For the mill shown, it is a 2100f-1.8E pulled with a 1650f-1.5E - a very common grade combination (pulled by half the sawmills in the test program). Figure 17 is of a mill that pulled 3 grades in combination, while Figure 18 shows the MOE's for a mill which pulled five grades in the same run. Comparing Figures 15 and 16 shows that the lower tail is cut off at virtually the same point for both 2100f-1.8E grades which would be expected as the minimum MOE requirement (1.476×10^6 psi) would define the cut off of the lower end. For the single grade of 2100f-1.8E pulled, the MOE values are slightly lower at the same percentiles. With no lower grade being pulled, the pieces selected by the MSR grading machine can have more variability provided they meet the mean and minimum MOE's required for the grade.

When Figure 17 (which adds a 2400f-2.0E pulled with a 2100f-1.8E and a 1650f-1.5E) is compared with Figure 16 it can be seen that the 1650f-1.5 COV is similar for both graphs which would be expected as in both cases there is a higher grade being pulled. The 2100f-1.8E in Figure 17 has less variability than that of Figure 16 as pieces with a higher MOE have been taken into the 2400f-2.0E grade.

When Figure 18 which has five grades pulled in combination is compared against Figure 17, it can be seen that the variability of each grade (other than the lowest grade) is restricted in order to divide the sample into five rather than three grades.

For Figures 19 - 23, a single grade has been selected for comparison. In Figure 19, the 1450f-1.3E grade from the three mills where it was sampled has been graphed. For one mill (Mill C), the 1450f-1.3E was pulled with two higher grades, for the other two mills (Mills A and B) it was pulled with four higher grades. It can be seen that for one of the mills with four higher grades the variability in the 1450f-1.3E is less than where fewer grades are pulled above. As 1450f-1.3E is the lowest grade selected, pulling more grades above will not necessarily restrict the variability as the lower tail can extend down as long as the average and minimum MOE's are met.

In Figure 20, 1650f-1.5E from three mills has been graphed, in all cases a 2100f-1.8E grade was pulled above. The variability of the MOE's differ as again this is the lowest grade pulled. The MOE's for one mill (Mill L) are higher, the mean MOE for this mill is 1.594, well above the 1.5 required for the grade. In this case the mill is losing potential MSR yield in the 1650f-1.5E grade. The mean MOE for the 2100f-1.8E pulled by the Mill L is 1.803, which is what is required for the grade.

In Figure 21, the 1650f-1.5E plotted for the three mills has two higher grades pulled with it. Like Figure 20, the variability of the 1650f-1.5E lines differ. Two of the mills have mean MOE's higher than that required by the grade.

For Figure 22 the 2100f-1.8E from the same three mills as Figure 20 have been plotted. The variability of Mills L and O are similar. Mill G has a lower COV, this mill also has a high mean MOE (1.891) which could account for the lower variability.

Figure 23 shows the 2100f-1.8E for the same mills as Figure 21, here the COV for all mills is low as 1650f-1.5E is pulled below. The mean MOE's vary for each mill.

In the graphs described above where the mean MOE is above what is required for the grade it is possible that a higher MOE was necessary to maintain the MOR for the grade. However, usually S-P-F MSR is MOE controlled, that is, if the mean and minimum MOE is maintained for a grade the MOR will also meet the grade requirements. Sawmills may choose not to optimize their grades to avoid going out of control in the quality control procedure, this could also account for the MOE's at some mills being well above the grade requirements. Falldown from a higher grade into a lower grade because of the visual overrides, e.g. for VQL edge knots could also result in higher MOE's in lower grades.

3.3 COMPARISON OF MSR STIFFNESS AND STRENGTH PROPERTIES

The stiffness and strength properties of the MSR grades can be compared between grades and also compared with the stiffness and strength properties of selected grades from the visual lumber in-grade test program. The properties of the visual grades of SS and #2 were chosen for this study because these grades cover approximately the same range of stiffness and strength as the MSR grades.

3.3.1 DATA SOURCES

To compare only between MSR grades, the MOE_{Lab} and 17:1 In-grade MOR could be used. For comparison with the visual lumber in-grade test data, the MOE_{Ingr} (measured at a 17:1 span/depth) should be used rather than the 21:1 MOE_{Lab}. The MSR in-grade properties can also be compared against those required by SPS-2.

3.3.2 RESULTS

3.3.2.1 MOE COMPARISONS

Cumulative frequency curves were plotted for the MSR lumber in-grade test data using both the 17:1 MOE_{Ingr} and the 21:1 MOE_{Lab}. The 17:1 In-grade MOE was adjusted for machine deflection at the 17:1 span to depth and used for comparison against the visual lumber in-grade test MOE which was also tested at a 17:1 span to depth and adjusted for machine deflection.

Figure 24 shows the In-grade MOE data from the five tested MSR grades, with each grade well spaced except for the 1650f-1.5E grade crossing the 1800f-1.6E at the 95th percentile. Figure 25 adds the cumulative frequency plots from the visual lumber in-grade data for SS and #2 grades. At the 50th percentile the grades of 2400f-2.0E, 2100f-1.8E and 1800f-1.6E exceed the value of the SS grade. The value for #2 grade exceeds only the 1450f-1.3E. The variability of MOE for the MSR grades is much smaller than for the visual grades. This is not surprising because the same population is being divided into 5 grades in MSR production and only 2 or 3 grades in the visual lumber production. Figures 26 - 30 show each MSR grade plotted with the visual grades. The MSR design values for MOE are determined at the 21:1 span/depth while the visual MOE properties are determined at 17:1. Comparing cumulative frequency plots of the MSR grades at 21:1 against the visual grades at 17:1 (Figures 31 - 32) show that at the 50th percentile the MSR values are higher so that the grades of 1650f-1.5E and above exceed the SS value and the

1450f-1.3E value is virtually equivalent to #2. The graphs of the 21:1 MOE's show less variability than those at 17:1 with a narrower range of MOE values for the MSR grades.

3.3.2.2 MOR COMPARISONS

The MOR data of both the MSR lumber in-grade test and the visual lumber in-grade test were based on the 17:1 span testing with the Maximum Strength Reducing Defect, MSRD, randomly placed in the test span. Cumulative frequency plots were done of the data from the MSR grades and the SS and #2 grades (Figures 33 - 39). At the 5th percentile level where the design values are determined for MOR, the values for the 1800f-1.6E, 2100f-1.8E and 2400f-2.0E grades exceed the SS value. The actual number of pieces failing below the 5th%ile required by SPS-2 for each grade is shown in Table 11. All the MSR grades exceed the #2 grade values at the 5th percentile. At the 50th percentile, the value of the #2 grade exceeds that of the 1450f-1.3E grade as the slope of the visual grades is less steep than the MSR grades.

3.3.2.3 UTS COMPARISONS

The ultimate tension strength was determined using the same testing procedure for both the MSR lumber in-grade and the visual lumber in-grade test program. A 12 ft test span was used for all the 2x4 data. As with the MOE and MOR data the MSR grades have less variability than the visual grades (Figures 40 - 42). At the 5th percentile where the design values are determined, the SS value lies below the 1650f-1.5E and higher grades while the #2 grade lies below all the MSR grades. The actual number of pieces falling below the 5th%ile required by SPS-2 for each grade is shown in Table 11. At the 50th percentile, the SS is above the 1650f-1.5E while the #2 still lies below the MSR grades.

3.3.2.4 MOR-MOE

The data can also be used to compare stiffness and strength properties. Figure 43 shows the mean MOR's plotted against the mean MOE's for both the MSR and the visual grades. The MSR grades lie fairly well along a straight line. If a line were to be drawn between the SS and #2 grades it would lie to the right of the MSR line. MSR lumber at the same MOE would have a lower MOR than the visually graded lumber. If the #3 visual values are added in, the line no longer runs parallel, but veers away from the MSR line as the values increase. Figure 44 compares the mean MOE and the 5th percentile MOR, which are the values used for determining design values and includes the

#3 values. The MSR values again lie fairly well on a line and the visual line veers away as the values increase. In Figure 45 the mean MOE values are again plotted against the 5th percentile MOR and the SPS-2 grade values are plotted. This shows that all the MSR grades have strength in excess of the SPS-2 requirement, while the MOE's are below the requirement except for the 1450f-1.3E grade. However the MOE's used are on a 17:1 basis while SPS-2 uses a 21:1 basis.

Table 13 shows the strength of the relationships between MOR and MOE for the total bending sample and for each grade. These can be compared against those from the visual lumber in-grade test program shown in Table 14. These tables show that for the total sample sizes the correlation coefficients are similar between MSR and visually graded lumber. However, the correlation coefficients for individual grades are much lower for MSR than for the visual grades. This could be because the MSR grades are selected by MOE, resulting in a smaller range of MOE within a grade. A regression line fitted to data of this type would have weaker correlation as the data forms a narrow group, rather than being spread out in a more linear form.

If the 5th percentile MOE which is used to determine the minimum MOE's allowed in a grade are plotted against the 5th percentile MOR (Figure 46) the results also show the visual line veering away from the MSR at the higher level. Comparison with the SPS-2 requirements (Figure 47) show that only the 1450f-1.3E grade has sufficient stiffness, although again this is at a 17:1 span/depth.

3.3.2.5 UTS-MOE

Using the 5th percentile UTS values to plot against both the 5th percentile (Figure 48 and 49) and the mean MOE (Figure 50 and 51) for the MOE at a 21:1 span/depth ratio shows that the 5th percentile tension values lie above the grade requirement for all the grades as do the values for both the 5th and mean MOE's. The 21:1 MOE's were taken from the samples used for the tension testing so are the same pieces as are used for the UTS values.

Table 13 shows the strength of the relationships between tension and MOE for the total tension sample and for each grade. These can be compared against those from the visual lumber in-grade test program shown in Table 14. Similar to the bending data, there is a much stronger correlation within the full MSR sample size than within the individual grades. The same explanation as given in Section 3.3.2.4 could apply.

4. MSR LUMBER IN-GRADE KNOT FAILURES

4.1 INTRODUCTION

The MSR lumber in-grade data provides information on the causes of failure of lumber tested in bending (on edge) and in tension. This information is useful in gaining insight as to which defects are more critical to the performances of MSR lumber in bending and tension. These causes of failure can be sorted by species and grade to allow assessment as to whether certain failures are more prevalent in certain species or grades. In MSR lumber grading the results of the machine testing can be overridden by visual criteria, particularly for edge knots. The data collected on failures allows an assessment of the importance of doing this.

4.2 VISUAL RESTRICTIONS ON MSR LUMBER

In the grading of MSR lumber, a visual grading rule is applied after the lumber has been through the stress-rating machine. The visual grading rules are defined in Section 6 of SPS-2. Individual companies may use visual standards more restrictive than those in the grading rule, e.g. tighter wane restrictions, to satisfy customer demands. For the most part, the visual rules are there to produce MSR lumber comparable in appearance to a #2 visually graded structural lumber product. Certain visual restrictions are designed to ensure that the lumber has the stiffness and strength properties of the grade to which the machine has assigned it. One of these restrictions relates to the size of defect allowed at the ends of each piece. With grading machines which measure bending stiffness, there is a system of rollers to support the lumber as the constant deflection is being applied. This is the case with the Continuous Lumber Tester (CLT) which is the most common machine stress-rater used in North America. The beginning and end of lumber pieces are not tested as they can not span the rollers over the load heads. Therefore, graders check each piece of lumber to ensure that any knots, slope of grain or other defects do not exceed the restrictions laid down in SPS-2.

The other visual check to ensure the grade strength and stiffness properties are met relates to the size of edge knots allowed in each grade. The edge knot size is referred to as the Visual Quality Level (VQL) and is defined as a fraction of the cross-section of the wide face of the piece. This is based on the fact that while the grading machines measure the stiffness of a piece on the flat, the predominate use of structural lumber is on edge. A knot on the edge, particularly on the tension edge will be more likely to cause failure in bending than a centreline knot. To take this into account, limits are placed on the size of knots allowed on the edge of pieces even though the piece has been accepted by the machine as meeting the grade. Machine grading rules in other countries do not necessarily put a restriction on the size of edge knots, e.g. the UK machine grading standard BS4978 [4] has no restrictions on the size of edge knot, provided the piece is accepted by the grading machine.

The MSR in-grade test program allows examination of the causes of failure for machine graded lumber for both bending and tension test specimens. The lumber used in the MSR in-grade program was divided into two groups for testing to failure. Half the pieces were tested to failure in bending, while the other half were tested to failure in tension. For each piece the cause of failure was recorded. The Forintek knot code was used to categorize failures due to knots and the Madison knot code was adopted for failures other than knots (*MSR In-grade Testing Data Report - Appendix VII* [15]). These codes can consist of up to 10 digits allowing the type of knot or other defect to be reconstructed in size, orientation and location. A copy of the knot codes and accompanying knot sketches appears in Appendix C. The first two digits of the coding provides enough detail to determine if the failure occurred in clear wood, at a knot (and whether the knot was a tension or compression edge knot and its class) or at a defect other than a knot. If the failure was at a knot, the first two digits provide classification of the knot into one of 11 types (with the first 9 classes being subdivided into tension or compression edge knots). Thus by sorting the pieces by the first two digits of the failure code substantial detail on the cause of failure can be found. A listing of the meaning of the first two digits is shown in Table 15.

For lumber tested to failure in tension the location of the knot in the cross-section does not have the same importance as it does in bending. For the tension test piece the load is assumed to be applied evenly across the cross-section.

The failure codes were sorted first for the combined S-P-F data for each of the bending and tension samples. Then each group of data was further subdivided into failures by MSR grade and by species (pine, spruce and fir) for the grades combined.

4.3 RESULTS

4.3.1 SPECIES MIX

The predominate species in the bending and tension samples is pine (see Tables 16-18). This is to be expected as the MSR grading machine sorts by stiffness and in most of the regions sampled the pine is Lodgepole Pine (*Pinus Contorta*) which has higher MOE's than spruce and fir. There is very little fir (Alpine Fir) in the samples which is also expected. The fir tends to have lower MOE's than the pine and spruce. Also many mills have a practice of either excluding fir from their MSR or dropping it one grade below the grade that it was graded by the machine. This is done by the sawmill graders as it comes past them on the grading chain. As fir is less stiff than pine or spruce it can pull the MSR quality control results out of control for average MOE or minimum MOE if two or three pieces appear in a five piece sample. There is no reason that fir can not be in MSR grades, but its tendency to be at the low end of the stiffness for each MSR grade means that sawmills would have to raise the grade boundaries on the MSR machines to accommodate it. As fir is usually a small percentage of the MSR production, it makes more sense economically to exclude it, or drop it a grade and increase the MSR grade yield.

The percentage of each species is almost identical between the bending and tension samples. The samples were not chosen by species, rather they were randomly chosen by package row from grade stamped lumber units at each mill.

4.3.2 TYPES OF FAILURE

Of the 2580 pieces tested to failure in the MSR in-grade program, there were no failures attributed to defects other than knots. This emphasises the importance of knots, and the grain distortion surrounding them in determining the failure strength of lumber. There was also a large percentage of pieces that failed with no visible defect appearing to be the cause of failure.

The knot class responsible for failure in the MSR grades has been graphed in Figures 52 - 60 for bending failures and Figures 61 - 69 for the tension failures. In bending for all the data combined (Figure 52), over a quarter of the pieces failed with no visible defect as the cause. Tension edge knots caused more failures than compression edge knots. Knots in the same cross-section (Class 10 and 20 knots) accounted for over 35% of failures for all MSR grades combined. Although using the first two digits of the failure code does not give an idea of the size of knots, it does indicate that more than one knot in the same cross-section has a high risk of causing failure. This is most likely due to the more extensive grain distortion that would be associated with several knots occurring in the same vicinity.

The graphs bending failures by grade show that the percentage of pieces failing where there is no visible defect increases with the MSR grade. The higher grades will have more restrictive edge knot requirements. The restrictions on non-edge knots though is no more restrictive than for lower grades as these are judged by the machine except for the untested portion of the ends. It is reasonable to assume that in the higher grades, the number and size of defects will generally be smaller than in the lower grades as they are the higher stiffness and strength pieces. Also, the number of pieces failing where there is no visible defect is much lower in the 1450f-1.3E and 1800f-1.6E grades. In these grades there were fewer samples (Table 17), which could be a factor.

Sorting the bending sample by species shows spruce is less prone to fail due to knots in the same cross-section than pine. This can be attributed to the more scattered knots in spruce. In pine, the branches often grow in whorls which result in clusters of knots. As there were only 21 pieces of fir it is not possible to draw any conclusions.

In the tension sample, as there is no difference between knots on the compression and tension edge the knot classes have been combined together to simplify the results. There are fewer failures attributable to no visible defect than in the bending sample (19% versus 27%). Unlike the bending sample, the tension sample doesn't show an increase in failures at no visible defect with the increase in grade. The percentages are fairly constant across the four lower grade with only 2400f-2.0E showing an increase. The tension samples also show that knots other than cluster knots are more of a factor in failure than bending testing. This could be attributed to the fact that in tension testing, knots anywhere in the cross-section should be equally likely to cause failure, whereas in bending, knots on the tension edge are more likely to cause failure (either singly or in knot clusters).

The sorting of the tension failures by species again shows the pine more prone to failure due to knots in the same cross-section.

The results of this study on causes of failure shows the predominance of knots over any other visible defect as the cause of failure in both bending and tension. It is also interesting to note that a large number of pieces fail where there is no visually detectable defect.

5. LOCATION OF THE MAXIMUM STRENGTH REDUCING DEFECT IN THE BENDING TEST SPAN

5.1 INTRODUCTION

Use of different test methods and procedures can make a difference to the results of test programs. This is certainly true in the case of bending test results. The span to depth ratio for testing can be varied as has been seen in this thesis where the in-grade MOE and MOR are determined at a 17:1 ratio while the MSR SPS-2 quality control is done at 21:1. In other countries, such as many European countries, the standard is 18:1. The positioning of the piece in the test frame can also affect the results. The test pieces could be randomly placed in the test frame without consideration of the location of defects - this is how the in-grade MOE and MOR were tested. The test piece could also be positioned so that the worst defect is in the centre third of the test span where the bending moment is highest which is how the MSR SPS-2 quality control is done for bending. This should increase the chance that pieces will break at a lower load resulting in a lower MOR. The most onerous testing should be if the worst defect was positioned on the tension side in the centre third as has been done in some European testing [7].

The differences in results due to differences in test procedures can be critical. A good example of this is in the current efforts in Europe to harmonize codes and standards for use in the European Community. Where different test procedures have been used from those agreed for use in Europe, the resulting test data must be adjusted to reflect the differences. Canada has had to adjust data resulting from our visual in-grade program to the European test format to provide data for design of Canadian species in Europe.

In this chapter, the difference in test results due to positioning of the worst defect in the centre third of the test span will be examined using data from the in-grade test program.

5.2 DEFECT LOCATION IN TESTING PROCEDURES

In the quality control procedure of SPS-2 for MSR lumber, the bending test is done on edge with the maximum strength reducing defect (MSRD) in, or as close to the centre third of the test span as is feasible. The maximum strength reducing defect, MSRD, is the defect judged to be the most likely cause of failure during the bending testing. When the MSRD is placed in the centre third, it is in the zone of maximum moment (Figure 70) - thus the piece is more likely to fail at a lower load than if the MSRD was placed outside of the centre third of the test span. In the SPS-2 quality control procedure, the MOE and MOR measurements are done at a 21:1 span to depth ratio (the depth being the nominal piece depth i.e. 3.5" for a 2x4). The MOE measurements are done with the piece centred in the test span with the grade stamp always in the same orientation, e.g. to the operator's left and facing up. This provides a random orientation of defects with respect to being on the tension or compression edge in bending. Then when the piece is proofloaded in bending, the piece is moved in the test span so that the MSRD is in the centre third of the test span. The position of the grade stamp is maintained so that the MSRD is random with respect to the tension or compression edge. Where the position of the MSRD does not allow it to be moved into the centre third, i.e., it is too close to the end of the piece, it is moved as close to the centre third as is possible. In the MSR quality control procedure the sample pieces are not tested to failure, but are proofloaded to a stress which is 2.1 times the assigned allowable bending stress for the grade. The determination of the MSRD is done visually by the operator and therefore is dependent on the operators experience in judging the most critical defect under bending.

In the MSR In-grade program, the MSRD was randomly located in the total test span. The MSRD of each piece was preselected by the grading supervisor during the visual re-grading done at

Forintek on every test piece in the in-grade program. Thus the MSRD for each piece was selected by the same person - a very experienced grading supervisor. The pieces were oriented in the same position as they had been at the mill when the MOE_{mill}'s were measured i.e. grade stamp to the operator's left and up. The placement of the MSRD in the test span was determined in the in-grade test program by generating a random number during the earlier MOE testing. The destructive bending test was done on a 17:1 span to depth ratio. This is different from the 21:1 bending proofloading done under SPS-2, but is the same span to depth used for the destructive bending testing in the visual in-grade program. An MOE (MOE_{ingr}) was also measured before the piece was loaded to failure. This allows comparison of the MOE's and MOR's achieved between the two in-grade programs without adjustment for different span to depth ratios or positioning of the MSRD. The random number generated during the earlier MOE testing was used to determine the position of the MSRD from the mid-span of the 17:1 test span. The method of determining this is laid out in a flow chart in *MSR Lumber In-grade Testing Data Report* [15]. To avoid overhanging of the bending specimen, the 16' long specimens were cut to a 6' long specimen with the MSRD located in the 6 feet as determined by the random number. The same position of the grade stamped end was maintained.

In the Visual In-grade program the destructive bending tests were done on a 17:1 span to depth with the grade stamped end to the operator's left and facing up as in the MSR In-grade program. The MSRD was also determined by the grading supervisor for each test piece. The MSRD was randomly placed in the test span based on a generated random number.

Differences in the testing procedures of MOE are summarized in Table 8, while those for MOR are summarized in Table 12.

As the position of the MSRD in the test span for the bending tests is known for both in-grade test programs this allows comparison of the MOE's and MOR's resulting from the positioning of the MSRD in the centre third of the bending span against the MSRD randomly placed in the whole test span. Although the MSR In-grade data could be sorted to determine the difference between the placement of the MSRD in the test span, the Visual In-grade data was used as the sample size is larger. As the data must be sorted to extract those pieces with the MSRD in the centre third, the larger the sample size the more accurate the results.

5.3 SORTING THE VISUAL IN-GRADE DATA

The 2x4 S-P-F Visual In-grade data was chosen for this study as it is a match in species and size to the data used in the

MSR In-grade program. All grades of Structural Light Framing and Light Framing were sorted. However, only results for the higher Structural Light Framing grades are analyzed as they are a closer match to the MSR grades. Data from the lower visual grades, e.g. Utility, could bias the results as they allow larger visual characteristics, such as knots, than would be in MSR.

In the Visual In-grade Program the full piece length was used. A random number was generated and the MSRD was placed that distance from the centre of the test span. If the piece did not rest on the bending supports it was moved to the closest practical position. The position of the piece in the test frame was then recorded under the heading 'Location in Frame'. The precise definition of this value was checked with the technologist at Forintek who was responsible for the measurement during the Visual In-grade program. Location in Frame was measured from the grade stamped end to a position on the far side of the first support (Figure 71). This position was measured and found to be 4 cm (taken as equivalent to 2" for the purposes of the data which is all in imperial units) to the left of the centre of the support. For 2x4, the test span was 59.5" (17 x 3.5"). So the pieces in the middle 20" would be in the centre third of the test span. Using the Location in Frame these pieces can be determined by the equation below.

a = Location in Frame + 20" - 2"

b = Location in Frame + 40" - 2"

a < MSRD in centre third < b

There were some anomalies in the Visual In-grade data that were checked with the Grading Supervisor before the data sorting was done. Where the MSRD code was equal to 0 it meant that there was no identifiable MSRD on the piece. In some cases there was an MSRD location given for these pieces, but this was considered to be a recording error. Where the piece was essentially clear of edge knots the VQL was still recorded as 1/6 (the smallest level of VQL). In these cases there was often no VQL location listed as there was no knot worth measuring and recording. If the VQL was 1/6 and the MSRD was 0, this was because the edge knot was either non-existent or so small it was not considered to be a strength reducing defect. If the VQL was recorded as 1/4 and the MSRD as 0, it was likely to be an error in data recording as the knot would be of a size considered to be strength reducing. These anomalies were all checked and verified prior to the data sorting.

A program was written to combine the relevant data from the S-P-F 2x4 bending data files and sort into a separate file those pieces which had the MSRD in the centre third as defined above. Pieces where the MSRD was 0 were deleted as they had no visible MSRD even though they had an MSRD location recorded. Including them in the sample would bias the results as they should have higher MOR's. The data was then sorted, analyzed and the results plotted. The MOE's and MOR's used were at 15% MC.

5.4 RESULTS

Cumulative relative frequencies were plotted for MOR and MOE for all the grades - see Figures 72 - 79. These graphs show that the MOR's and MOE's for the pieces with the MSRD in the centre third lie consistently to the left (lower in value) of the cumulative frequencies for the total populations. When the MOR data was graphed in Figures 80 - 83 using the ratio of the MSRD centre third MOR over the full data MSR and plotted against the full data MSR, the MSRD centre third data is lower as the line is almost always less than one. The data for all grades combined is plotted in each case along with that for each grade. The graphing for all grades combined (Figure 80) shows the MOR for pieces with the MSRD in the centre third is lowest at the 10th percentile - about 79% of the total population MOR. At the 5th percentile where strength values are determined, the ratio is approximately 82% - giving an 18% difference between the two methods of positioning the test specimens in the span. As the 'all grades combined' includes the lower grades such as #3 and Utility with their larger knots and lower strengths, it is reasonable to assume that the lower grades will influence the lower strength ratios. The results at the 5th percentile of SS and #2 would be closer predictors of the differences due to positioning in MSR grades. In these two grades, the ratio is 87 - 88%, giving a 12% difference between the two methods of positioning.

The ratio rises with increasing MOR value until at the 99th percentile it is 96% of the total population value. It is reasonable to assume the ratio will be closer to one at the upper percentiles. The pieces at the top end should have fewer defects that cause failure, therefore whether the selected MSRD is in the centre third or not should be less important.

This shows that the test positioning can have a great effect on the end result. The design values in CSA O86 were verified for MSR based on the MSR In-grade results, yet the on-going quality control for MSR under SPS-2 is done with the MSRD in the centre third. The results of the above study show that as the MSR quality control procedure requires the lumber to meet MOR grade requirements that are based on in-grade values, the MSR lumber must have a higher MOR than required because of the quality control testing procedure.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Results of the MSR lumber in-grade test program have been examined in this thesis. Results of the visual lumber in-grade test program have also been examined for comparison to the MSR, as have the SPS-2 requirements for MSR.

The examination of the different MOE's determined in the MSR in-grade test showed that the method of testing can make a considerable difference to the value of the MOE determined. These differences between test methods are apparent between the MOE's achieved for the on-going quality control of MSR and the MOE's used for verification of the MSR design MOE's.

The MOE's of the MSR grades pulled in the sawmill are influenced by the number and level of grades pulled in combination. The MOE's are also influenced by other considerations such as the need to satisfy MOR grade requirements, amounts of visual falldown and mill decisions to run conservatively. Examination of the stiffness and strength properties found that the values for the tested grades met the requirements of SPS-2 when 21:1 span/depth measured MOE values were used.

A study of the causes of failure in bending and tension for the MSR in-grade test pieces found that many of the failures occurred at no visually detectable defect. Where the failure occurred at a defect, these defects were all determined to be knots (of varying types, as described by the Forintek knot code).

The positioning of the Maximum Strength Reducing Defect in the centre third of the test span had a considerable effect on the resulting values of MOE and MOR. As the positioning of defects in the test span can affect the results, consistent test methods are necessary to allow comparison of results.

6.2 RECOMMENDATIONS FOR FURTHER WORK

The MSR in-grade and the Visual in-grade test programs contain a wealth of information of which only some was examined in this thesis. There is extensive data on visual characteristics and failure types. Although failure types were examined in this thesis, a more extensive analysis of the type and size of knots causing failure could be of use in refining the VQL edge knot requirements for S-P-F.

7. REFERENCES

1) American Society for Testing and Materials. 1985. *Annual Book of ASTM Standards*. Philadelphia, Pa., Volume 04.09.

2) Barrett,J.D. 1985. *Machine Deflection Adjustments for Canadian In-grade Modulus of Elasticity Data*. Prepared for CWC Special Project - Lumber Properties. University of British Columbia. Vancouver, B.C., 12 p.

3) Barrett,J.D., and Kellogg,R.M. 1985. *Lumber Quality from Second Growth Managed Forests*. A Technical Workshop: Juvenile Wood - What Does It Mean To Forest Management and Forest Products? FPRS Proceedings 47309. Madison, Wis., pgs. 57-71.

4) British Standards Institution. *Timber Grades for Structural Use*. BS 4978:1973. London, UK.

5) Canadian Standards Association. 1989. *Code for Engineering Design in Wood (Limit States Design) CAN3-O86.1-M89*. Rexdale, Ont.

6) Canadian Standards Association. 1970. *Softwood Lumber O141-1970*. Rexdale, Ont.

7) Coppens, Hugo. Personal Communications. Technisch Centrum Der Houtnijverheid, Brussels, Belgium.

8) Council of Forest Industries of British Columbia. June 8, 1987. COFI STATS: *Apparent Consumption of Softwood Lumber in Canada*. Vancouver, B.C., 1 p.

9) Palka,L.C. and J.D. Barrett. 1985. *Effect of Span-Depth Ratio on Apparent Stiffness of Dimension Lumber*. Prepared for Canadian Forestry Service. Forintek Canada Corp. Vancouver, B.C., 29 p.

10) Fouquet,R.J-M. 1987. *Machine Stress-rated Lumber In-grade Testing Program*. Report to Lumber Properties Technical Committee. 6 p.

11) Gorman T.M. 1985. *Juvenile Wood as a Cause of Seasonal Arching in Trusses*. Forest Products Journal 35(11/12):35-40.

12) Hejja,A. 1987. *Data Base for Bending, Compression and Tension Test Results*. Lumber Properties Steering Committee In-grade Program. Forintek Canada Corp. Vancouver, B.C., 36p.

13) Krahmer,R.L. 1985. *Fundamental Anatomy of Juvenile and Mature Wood*. A Technical Workshop: Juvenile Wood - What Does It Mean to Forest Management and Forest Products? FPRS Proceeding 47309. Madison, Wis., pgs. 12-16.

14) Lum,C. and Varoglu,E. 1987. *Canadian Lumber Properties Program Methods of Testing*. Forintek Canada Corp. Vancouver, B.C., 55p.

15) Lum,C. 1988. *MSR Lumber In-grade Testing Data Report*. Forintek Canada Corp. Vancouver, B.C., 20 p.

16) Madsen,B. 1992. *Structural Behaviour of Timber*. Timber Engineering Ltd. Vancouver, B.C., pgs. 51-109.

17) National Research Council of Canada. 1990. *National Building Code of Canada*. Ottawa,Ont.

18) National Lumber Grades Authority. 1991. *NLGA Standard Grading Rules for Canadian Lumber*. Vancouver, B.C.

19) National Lumber Grades Authority. 1987. *NLGA Special Products Standard for Machine Stress Rated Lumber*. NLGA Standard SPS 2. Vancouver, B.C., 14 p.

APPENDIX A

TABLES 1 - 19

Table 1. Common Grades and Mechanical Property Requirements of MSR Lumber (from SPS-2)

Grade	Mean MOE (psi)	Minimum MOE (psi)	MOR (psi)	Tensile Strength (psi)
1450f-1.3E	1,300,000	1,066,000	3,045	1,680
1650f-1.5E	1,500,000	1,230,000	3,465	2,142
1800f-1.6E	1,600,000	1,312,000	3,780	2,467
2100f-1.8E	1,800,000	1,476,000	4,410	3,307
2400f-2.0E	2,000,000	1,640,000	5,040	4,042

Note: The table of grades in the current SPS-2 contains 15 grades in total.

Table 2. MSR Lumber Visual Quality Levels (from SPS-2)

MSR F_b Classification	Visual Quality Level	Equivalent Visual Grade[1]
2100f and over	1/6	better than SS
1500f to 2050f	1/4	better than #1
950f to 1450f	1/3	better than #2
up to 950f	1/2	#3

[1] as specified in the NLGA grading rules [18]

Table 3. Bending Strength Ratios for Structural Light Framing Grades (from ASTM D245)

Grades	Bending Strength Ratio
SS	67%
#1	55%
#2	45%
#3	26%

Table 4. Visual Lumber In-grade Program Sample Sizes for Major Species

Size	Visual Grade		
	SS	1&btr	#2
2x4	360	360	360
2x8	360	360	360
2x10	360	360	360

Note: This sampling was done for each of the bending, tension and compression components of the program.

Table 5. Visual Lumber In-grade Program Sample Sizes for Major Species in Light Framing Grades

Size	Visual Grade			
	Construction	Standard	Utility	Stud
2x4	120	120	120	120

Note: Samples were collected only for bending tests.

Table 6. Visual Lumber In-grade Program Sample Sizes for Minor Species

Size	Visual Grade	
	SS	#2
2x4	60	60
2x6	60	60
2x8	60	60

Note: This sampling was done for each of the bending, tension and compression components of the program.

Table 7. MSR Lumber In-grade Program - Number of Pieces Measured for ASTM D198 MOE

MSR Grade	Total Number of Pieces	Pieces from Bending Sample	Pieces from Tension Sample
1450f-1.3E	40	20	20
1650f-1.5E	130	40	90
1800f-1.6E	30	10	20
2100f-1.8E	130	90	40
2400f-2.0E	40	20	20
Total	370	180	190

Table 8. MOE's Determined in the MSR Lumber In-grade Test Program

Condition	Mill MOE MOE_{mill}	Lab MOE MOE_{lab}	D198 MOE MOE_{D198}	In-grade MOE MOE_{ingr}
Span/Depth Ratio	21:1	21:1	21:1	17:1
Loading	1/3 point	1/3 point	1/3 point	1/3 point
Specimen Position in Test Span	centred	centred	centred	random MSRD
Selection of Tension Edge	random	same as Mill MOE	same as Mill MOE	same as Mill MOE
Specimen Size	full 16' piece	full 16' piece	full 16' piece	6' piece[1]
Dimensions used in MOE Calculations	nominal	actual	nominal	actual
Moisture Content Adjusted	no	no	no	no
Machine Deflection Adjusted	yes	no	machine deflection free	no
Sample Size (number of pieces)	2580	2580	370	1280

[1]Piece selected with maximum strength reducing defect randomly located in the bending test span.

Table 9. Mill-Grade Combinations for MSR Lumber In-grade Data

Number of Mills	1450f-1.3E	1650f-1.5E	1800f-1.6E	2100f-1.8E	2400f-2.0E
1				X	
1			X		
1		X			
9		X		X	
3		X		X	X
1	X	X		X	
2	X	X	X	X	X

Note: Each mill-grade sample consists of 30 pieces for testing in bending and 30 pieces for testing in tension.

Table 10. Statistics on MOE_{lab} for Individual MSR Grades Produced by Each Mill

Mill	Grade	Mean	Standard Deviation	Median	COV
A	1450f-1.3E	1.393	0.133	1.385	0.095
	1650f-1.5E	1.473	0.104	1.467	0.071
	1800f-1.6E	1.583	0.126	1.559	0.080
	2100f-1.8E	1.767	0.102	1.784	0.058
	2400f-2.0E	1.963	0.135	1.939	0.069
B	1450f-1.3E	1.432	0.174	1.425	0.122
	1650f-1.5E	1.498	0.114	1.517	0.076
	1800f-1.6E	1.641	0.121	1.646	0.074
	2100f-1.8E	1.778	0.139	1.796	0.078
	2400f-2.0	2.005	0.154	1.979	0.077
C	1450f-1.3E	1.403	0.131	1.380	0.093
	1650f-1.5E	1.662	0.171	1.626	0.103
	2100f-1.8E	1.963	0.137	1.967	0.070
D	1650f-1.5E	1.501	0.154	1.499	0.103
	2100f-1.8E	1.804	0.127	1.815	0.070
	2400f-2.0E	2.040	0.154	2.028	0.075
E	1650f-1.5E	1.560	0.209	1.568	0.134
	2100f-1.8E	1.703	0.116	1.724	0.068
	2400f-2.0E	2.028	0.182	2.013	0.090
F	1650f-1.5E	1.619	0.183	1.623	0.113
	2100f-1.8E	1.764	0.105	1.769	0.060
	2400f-2.0E	1.999	0.177	1.989	0.089
G	1650f-1.5E	1.492	0.143	1.493	0.096

Mill	Grade	Mean	Standard Deviation	Median	COV
	2100f-1.8E	1.891	0.166	1.916	0.088
H	1650f-1.5E	1.630	0.156	1.634	0.096
	2100f-1.8E	1.939	0.172	1.923	0.089
I	1650f-1.5E	1.545	0.197	1.555	0.128
	2100f-1.8E	1.902	0.220	1.882	0.116
J	1650f-1.5E	1.530	0.146	1.534	0.095
	2100f-1.8E	1.898	0.161	1.908	0.085
K	1650f-1.5E	1.551	0.177	1.549	0.114
	2100f-1.8E	1.777	0.128	1.745	0.072
L	1650f-1.5E	1.594	0.130	1.587	0.082
	2100f-1.8E	1.803	0.194	1.783	0.108
M	1650f-1.5E	1.469	0.150	1.459	0.102
	2100f-1.8E	1.736	0.152	1.730	0.088
N	1650f-1.5E	1.716	0.173	1.714	0.101
	2100f-1.8E	1.992	0.195	1.952	0.098
O	1650f-1.5E	1.522	0.178	1.477	0.117
	2100f-1.8E	1.790	0.180	1.754	0.101
P	1650f-1.5E	1.555	0.194	1.558	0.125
Q	1800f-1.6E	1.864	0.198	1.844	0.106
R	2100f-1.8E	1.828	0.164	1.792	0.090

Notes: The COV assumed in SPS-2 for calculating the 5th percentile is 0.11, i.e., the 5th percentile MOE allowed is 0.82 grade MOE.

The average COV for all the grades above combined is 0.092.

Mean MOE's for the grades above:

1450f-1.3E = 1.409 2100f-1.8E = 1.833

1650f-1.5E = 1.557 2400f-2.0E = 2.007

1800f-1.6E = 1.696

Table 11. Number of Pieces Falling Below the MSR SPS-2 5th Percentile MOR and UTS Value

Test	Grade	Total Number of Pieces	Number of Pieces Below 5th %ile	Percentage
Bending	1450f-1.3E	90	1	1%
	1650f-1.5E	480	5	1%
	1800f-1.6E	90	0	0%
	2100f-1.8E	470	5	1%
	2400f-2.0E	150	2	1%
Tension	1450f-1.3E	90	0	0%
	1650f-1.5E	480	7	1%
	1800f-1.6E	90	0	0%
	2100f-1.8E	490	12	2%
	2400f-2.0E	150	4	3%

Note: Number of pieces below the 5th %ile were taken from the MOR-MOE and UTS-MOE plots, therefore they are approximate.

Table 12. Test Protocol for In-grade MOR and SPS-2 MSR MOR

Condition	In-grade MOR	SPS-2 MSR MOR
Span/Depth Ratio	17:1	21:1
Loading	1/3 point	1/3 point
MSRD Position in Test Span	random in test span	random in centre 1/3 of test span
Selection of Tension Edge	random	random
Specimen Size	full	if full, corrected for overhang
Dimensions used in MOR Calculations	actual	nominal

Table 13. MSR Lumber In-grade Program Correlation Coefficients for MOR-MOE and UTS-MOE

Property	MSR Grade	Number of Pieces	Correlation Coefficient r
Bending	All	1280	0.73
	1450f-1.3E	90	0.56
	1650f-1.5E	480	0.55
	1800f-1.6E	90	0.72
	2100f-1.8E	470	0.62
	2400f-2.0E	150	0.51
Tension	All	1300	0.66
	1450f-1.3E	90	0.40
	1650f-1.5E	480	0.48
	1800f-1.6E	90	0.36
	2100f-1.8E	490	0.41
	2400f-2.0E	150	0.35

Table 14. Visual Lumber In-grade Program Correlation Coefficients for MOR-MOE, UTS-MOE and UCS-MOE for S-P-F 2x4

Property	Visual Grade	Number of Pieces	Correlation Coefficient r
Bending	All	2364	0.76
	SS	441	0.72
	#1	123	0.72
	#2	440	0.77
	#3	180	0.79
	Construction	190	0.74
	Standard	190	0.78
	Utility	170	0.72
	Standard	172	0.74
	1&Btr	458	0.75
Tension	All	1456	0.71
	SS	440	0.67
	#1	114	0.63
	#2	444	0.73
	1&btr	458	0.68
Compression	All	1482	0.78
	SS	440	0.77
	#1	131	0.69
	#2	441	0.81
	1&btr	470	0.75

Table 15. Failure Coding Used for In-grade Testing

First Two Digits	Corresponding Defect
00	failures not associated with a defect
01	tension edge knot Class 1
02	tension edge knot Class 2
03	tension edge knot Class 3
04	tension edge knot Class 4
05	tension edge knot Class 5
06	tension edge knot Class 6
07	tension edge knot Class 7
08	tension edge knot Class 8
09	tension edge knot Class 9
10	boxed pith with one or more knots in same cross-section
11	compression edge knot Class 1
12	compression edge knot Class 2
13	compression edge knot Class 3
14	compression edge knot Class 4
15	compression edge knot Class 5
16	compression edge knot Class 6
17	compression edge knot Class 7
18	compression edge knot Class 8
19	compression edge knot Class 9
20	knots in cross-section with pith on surface or pith not present
21 - 70	Madison Knot Code for defects other than knots

Table 16. MSR Lumber In-grade Bending and Tension Sample Size by Species

Species	Bending Sample Piece Number	Tension Sample Piece Number
Spruce	245 (19%)	261 (20%)
Pine	1012 (79%)	1023 (79%)
Fir	21 (2%)	16 (1%)

Table 17. Species Mix By Grade For MSR Lumber In-grade Bending Sample

Species	1450f-1.3E	1650f-1.5E	1800f-1.6E	2100f-1.8E	2400f-2.0E
Spruce	19 (53%)	98 (39%)	17 (29%)	95 (28%)	16 (13%)
Pine	68 (39%)	367 (55%)	71 (69%)	372 (72%)	134 (87%)
Fir	3 (8%)	15 (6%)	1 (2%)	2 (0%)	0 (0%)
Total	90 (100%)	253 (100%)	59 (100%)	342 (100%)	119 (100%)

Table 18. Species Mix By Grade For MSR Lumber In-grade Tension Sample

Species	1450f-1.3E	1650f-1.5E	1800f-1.6E	2100f-1.8E	2400f-2.0E
Spruce	13 (14%)	119 (25%)	14 (15%)	89 (18%)	26 (17%)
Pine	73 (81%)	349 (73%)	76 (84%)	401 (82%)	124 (83%)
Fir	4 (5%)	12 (2%)	0 (0%)	0 (0%)	0 (0%)
Total	90 (100%)	480 (100%)	90 (100%)	490 (100%)	124 (100%)

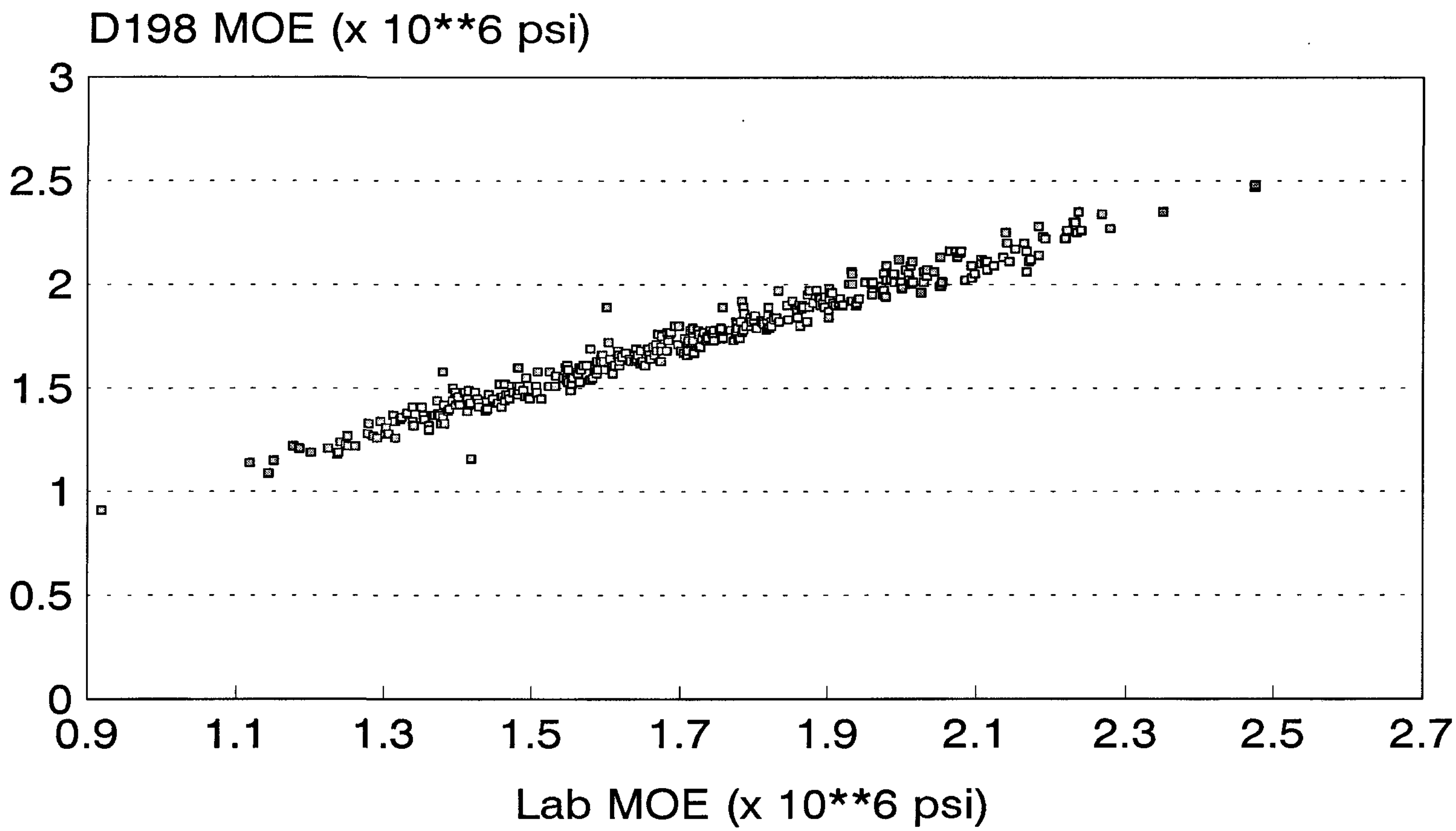
Table 19. Sample Sizes for Full Visual Lumber In-grade Data and for the Data with the MSRD in the Centre Third

Visual Grade	Full Data Set	MSRD in Centre Third
All	2364	341
SS	441	57
#1	123	15
#2	440	72
#3	180	27
Construction	190	35
Standard	190	22
Utility	170	20
Stud	172	32
1&btr	458	61

APPENDIX B

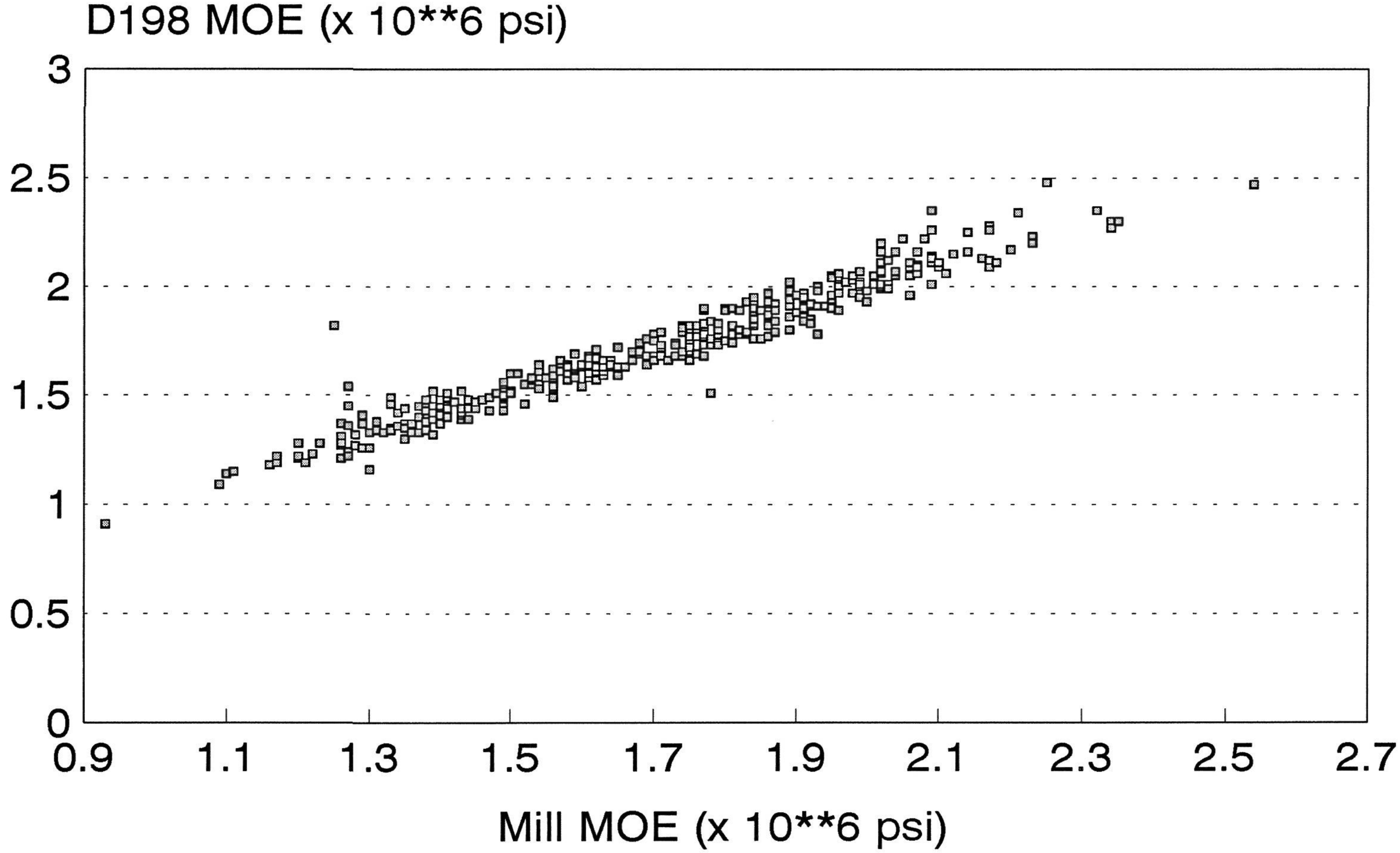
FIGURES 1 - 83

Figure 1. D198 MOE vs Lab MOE
MSR Lumber In-grade Data at 21:1 span/depth



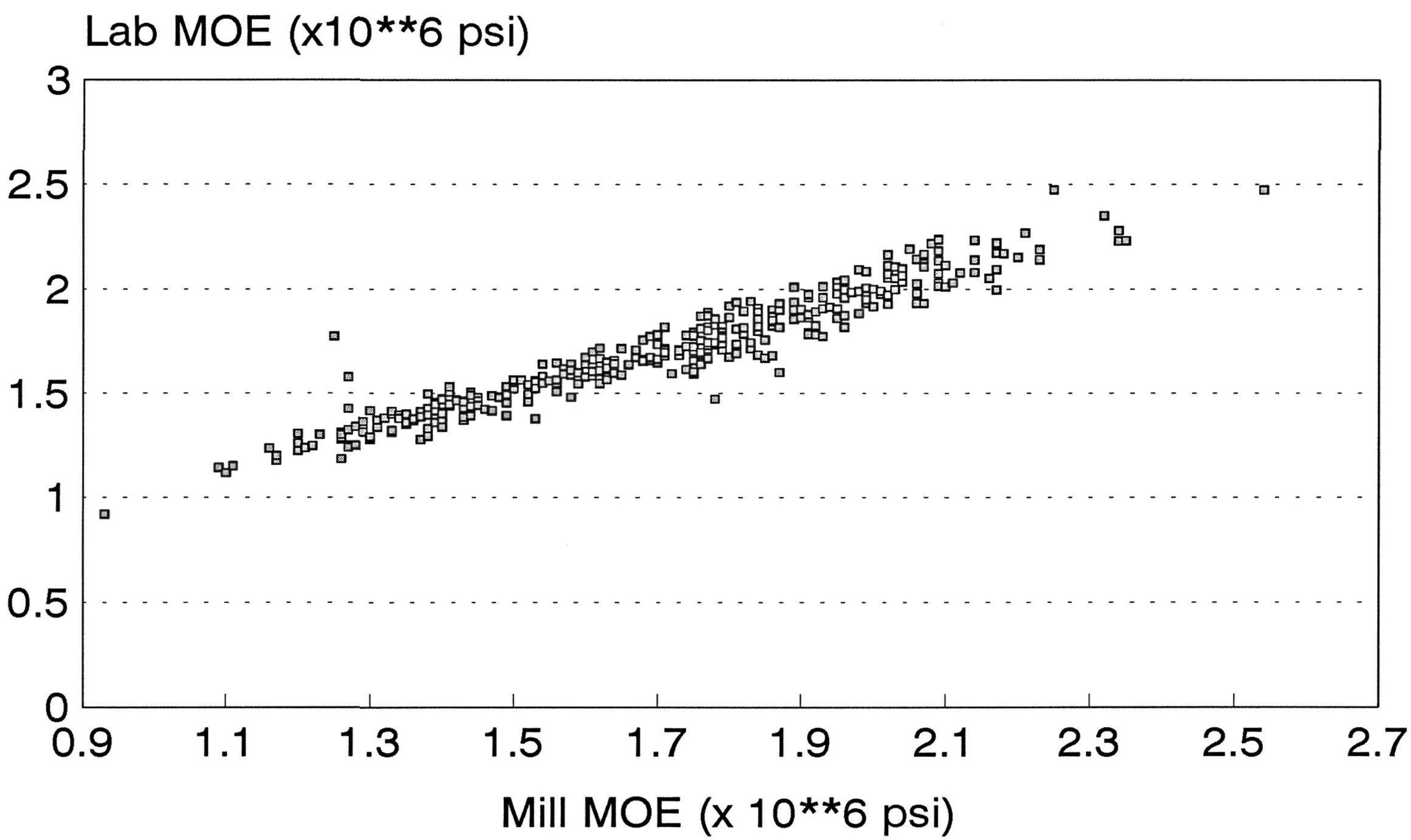
Lab MOE based on nominal dimensions and mach. defl. adjusted

Figure 2. D198 MOE vs Mill MOE
MSR Lumber In-grade Data at 21:1 Span/Depth



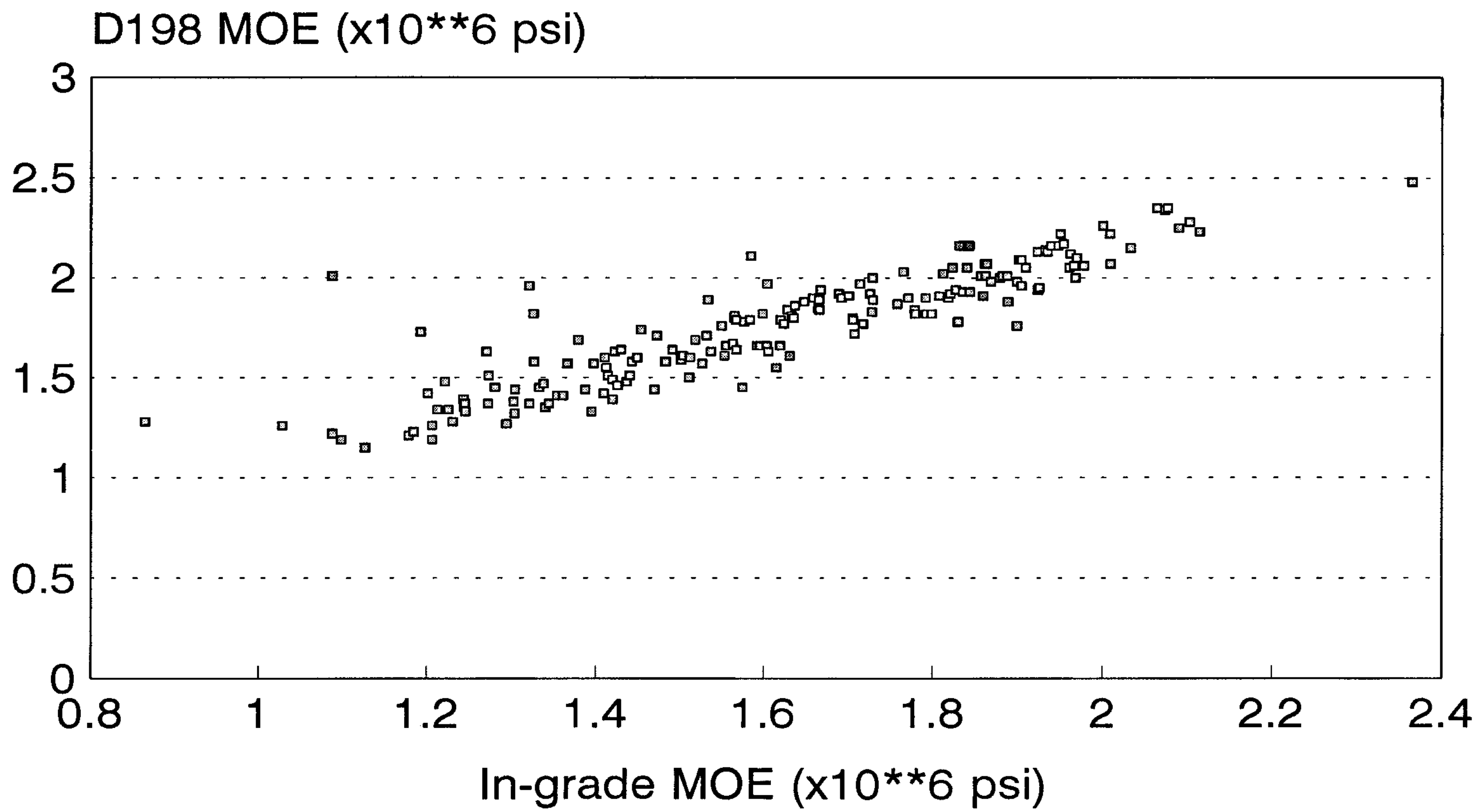
92

Figure 3. Lab MOE vs Mill MOE
MSR Lumber In-grade Data at 21:1 Span/Depth



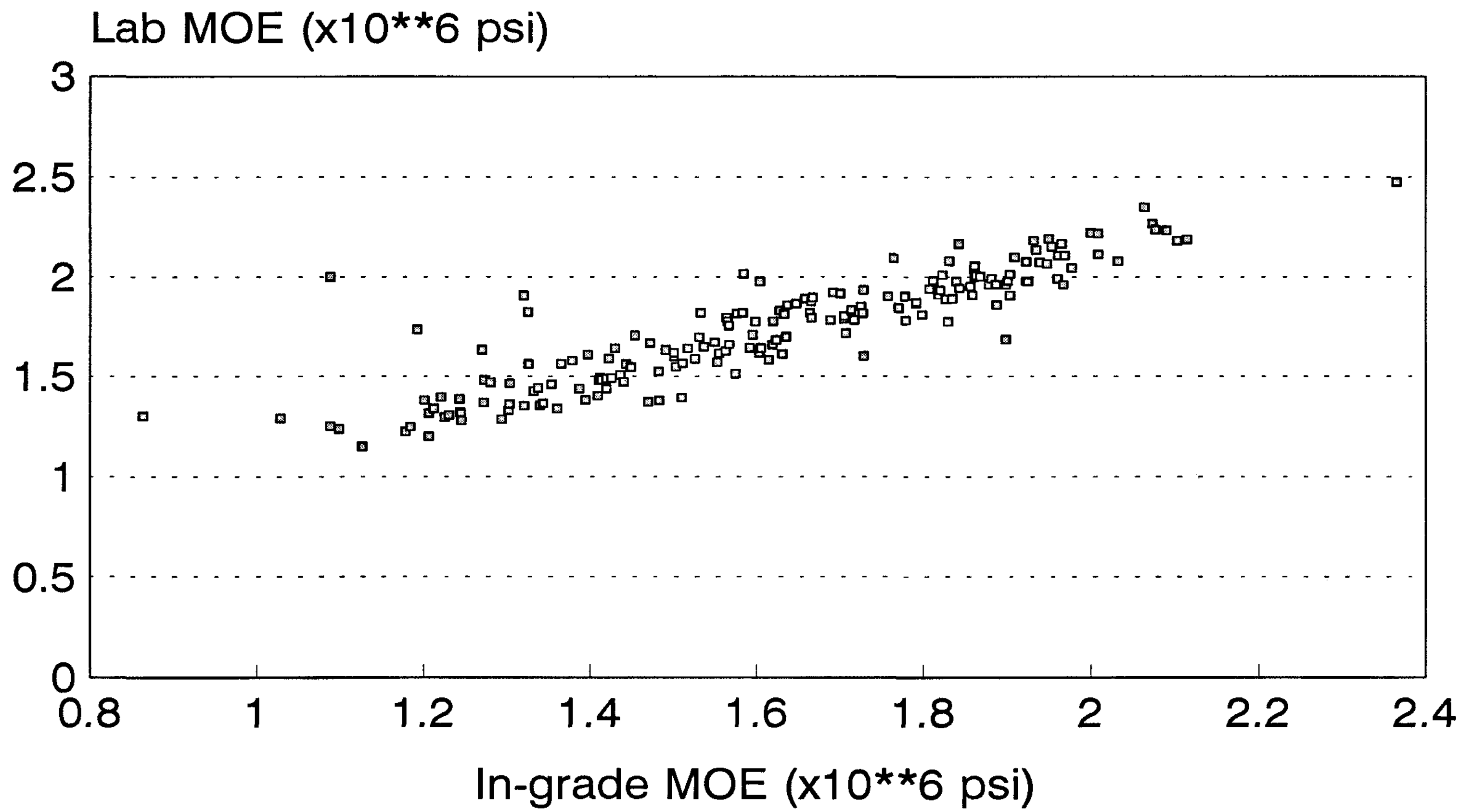
Lab MOE based on nominal dimensions and mach. defl. adjusted

Figure 4. D198 MOE vs In-grade MOE
MSR Lumber In-grade Data



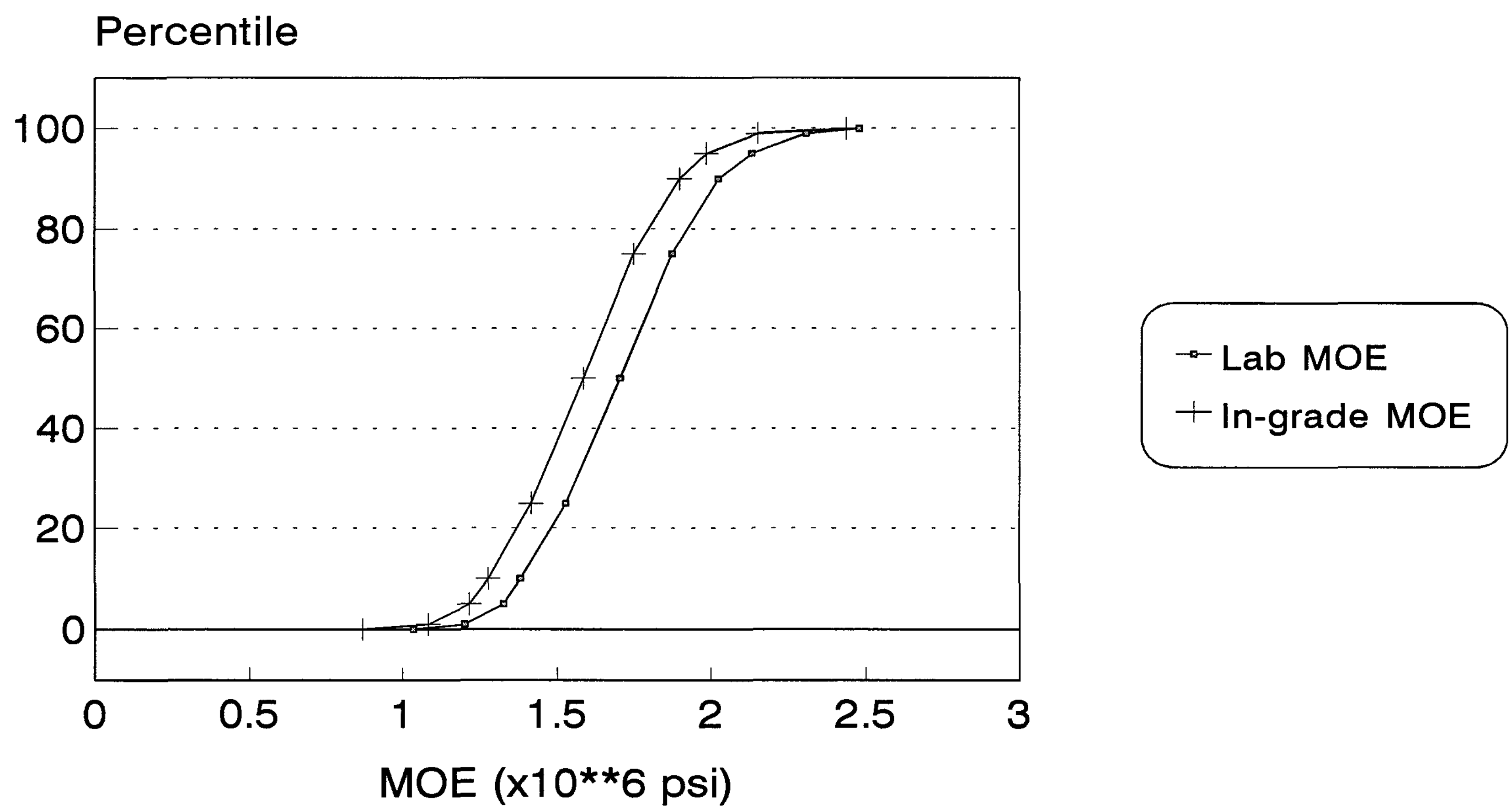
In-grade MOE at 17:1, based on nominal dimensions and mach. defl. adjusted
D198 MOE at 21:1

Figure 5. Lab MOE vs In-grade MOE
MSR Lumber In-grade Data



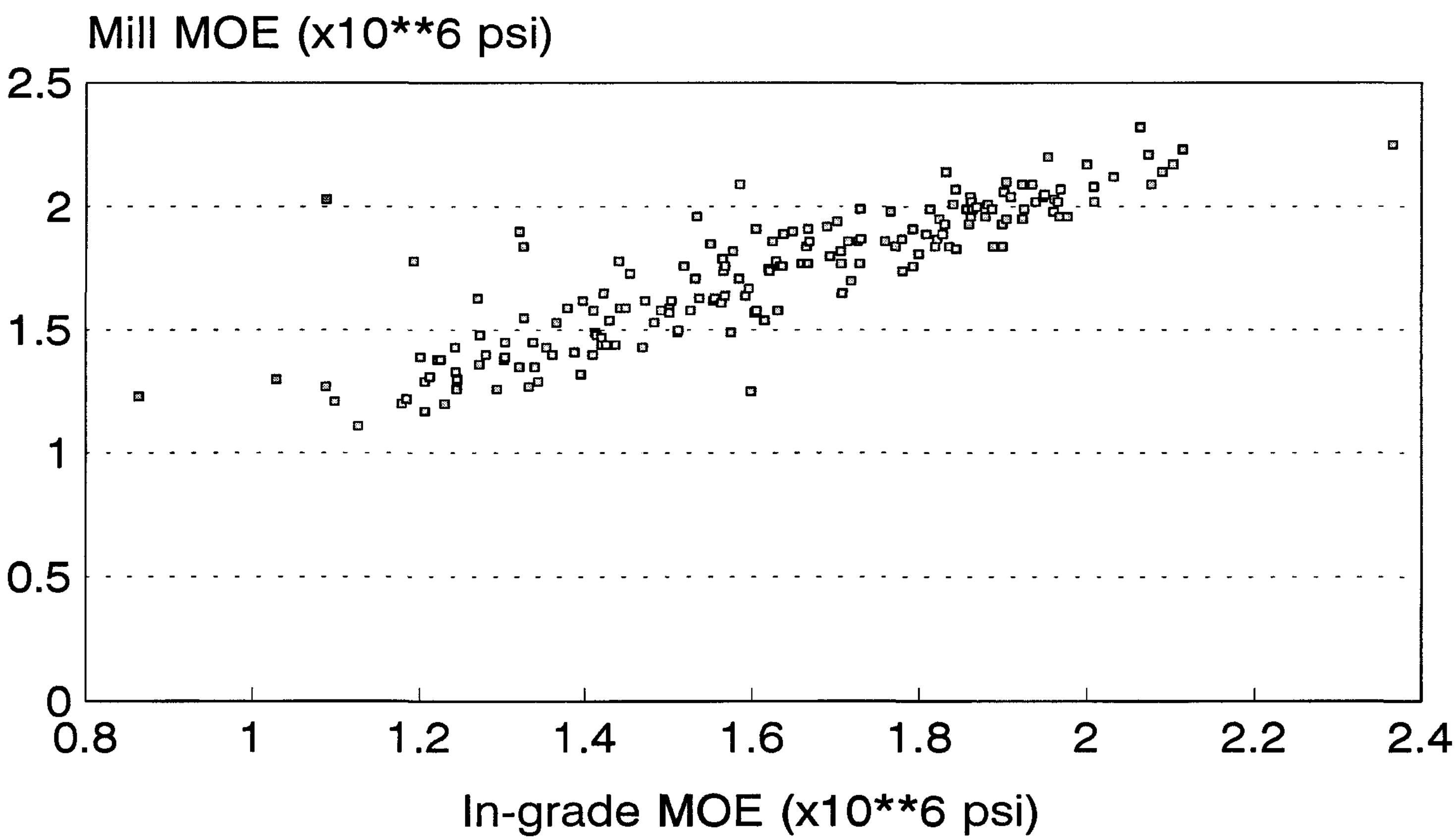
In-grade MOE at 17:1, Lab MOE at 21:1
Both based on nominal dimensions and mach. defl. adjusted

Figure 6. Lab and In-grade MOE Comparison
MSR Lumber In-grade Data



Both Lab and In-grade MOE mach. defl. adjusted

Figure 7. Mill MOE vs In-grade MOE
MSR Lumber In-grade Data



In-grade MOE at 17:1, based on nominal dimensions and mach. defl. adjusted
Mill MOE at 21:1

Figure 8. Cumulative Relative Frequencies
MSR L.P. Data - 2x4 S-P-F

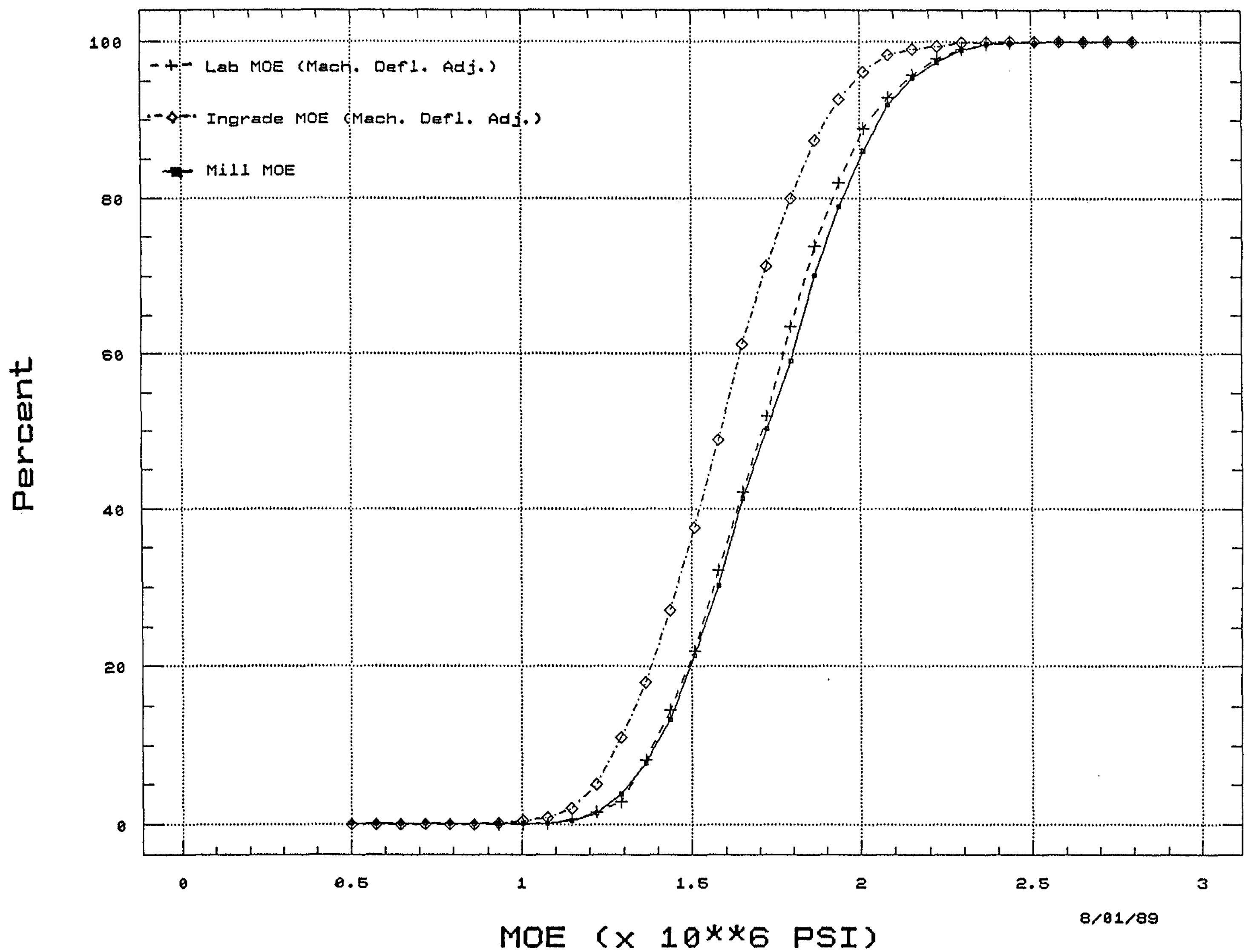
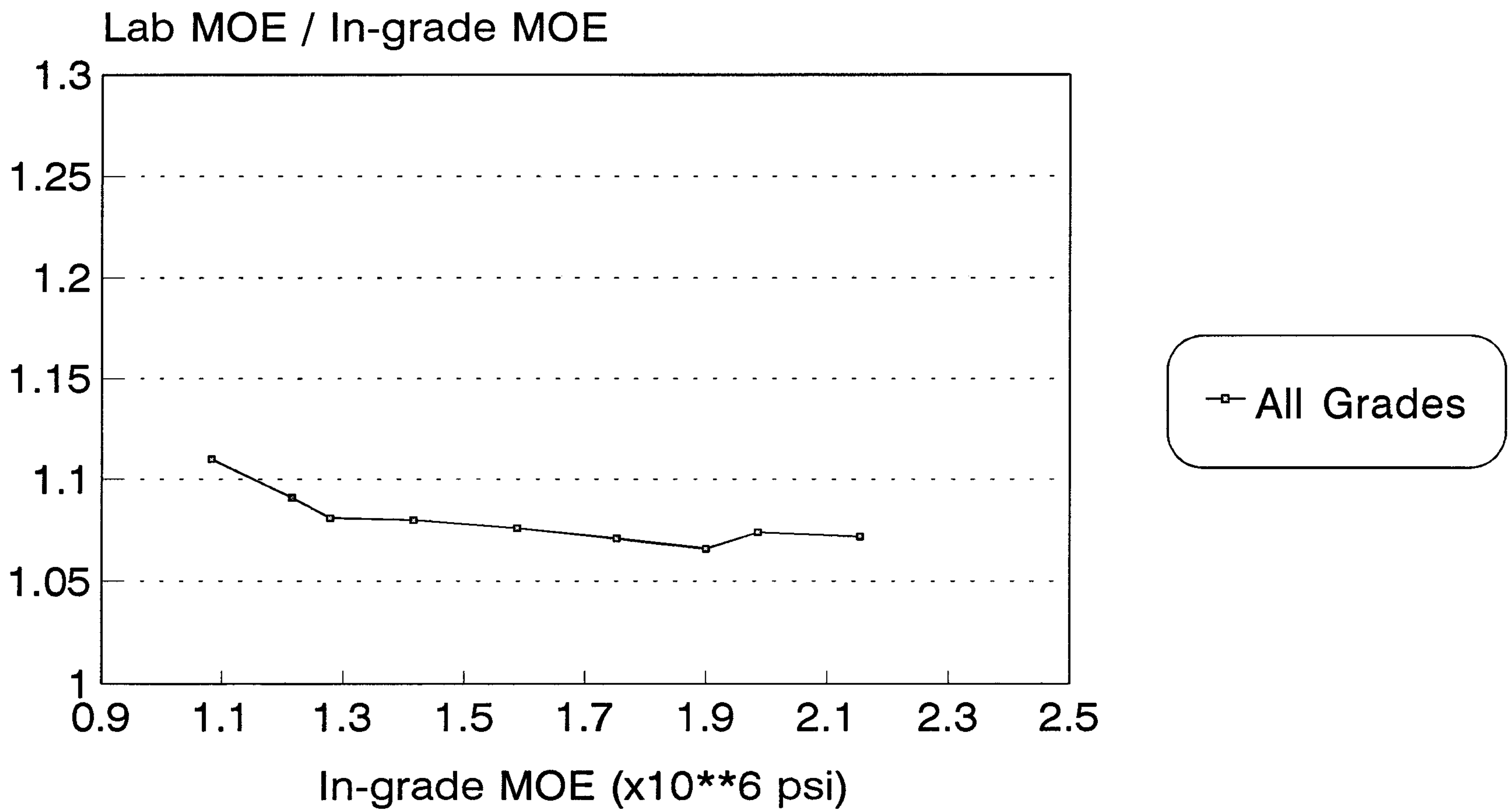


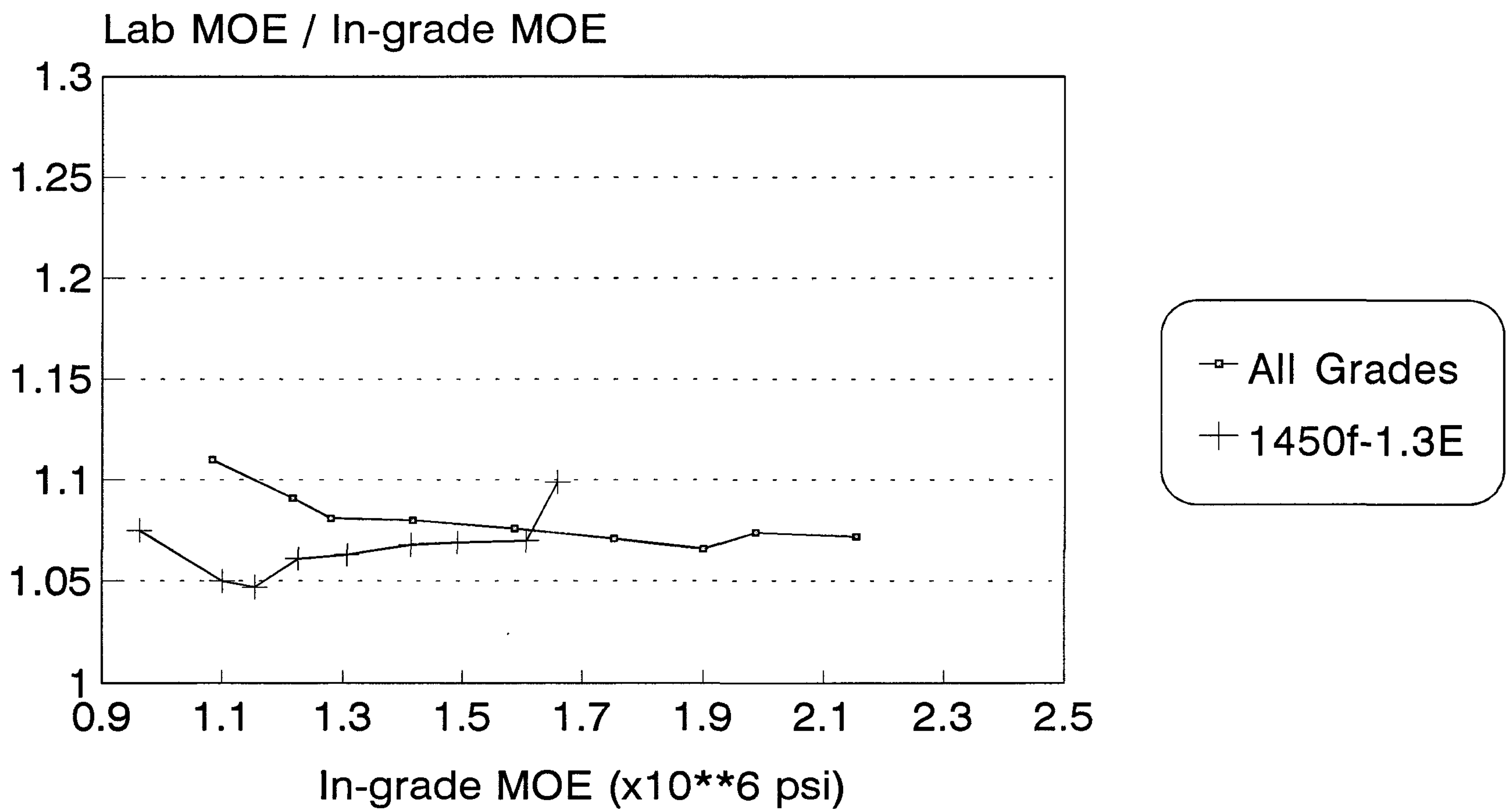
Figure 9. Plot of 21:1 / 17:1 vs 17:1 MOE
MSR Lumber In-grade Data



Both based on nominal dimensions and mach. defl. adjusted

Figure 10. Plot of 21:1 / 17:1 vs 17:1 MOE

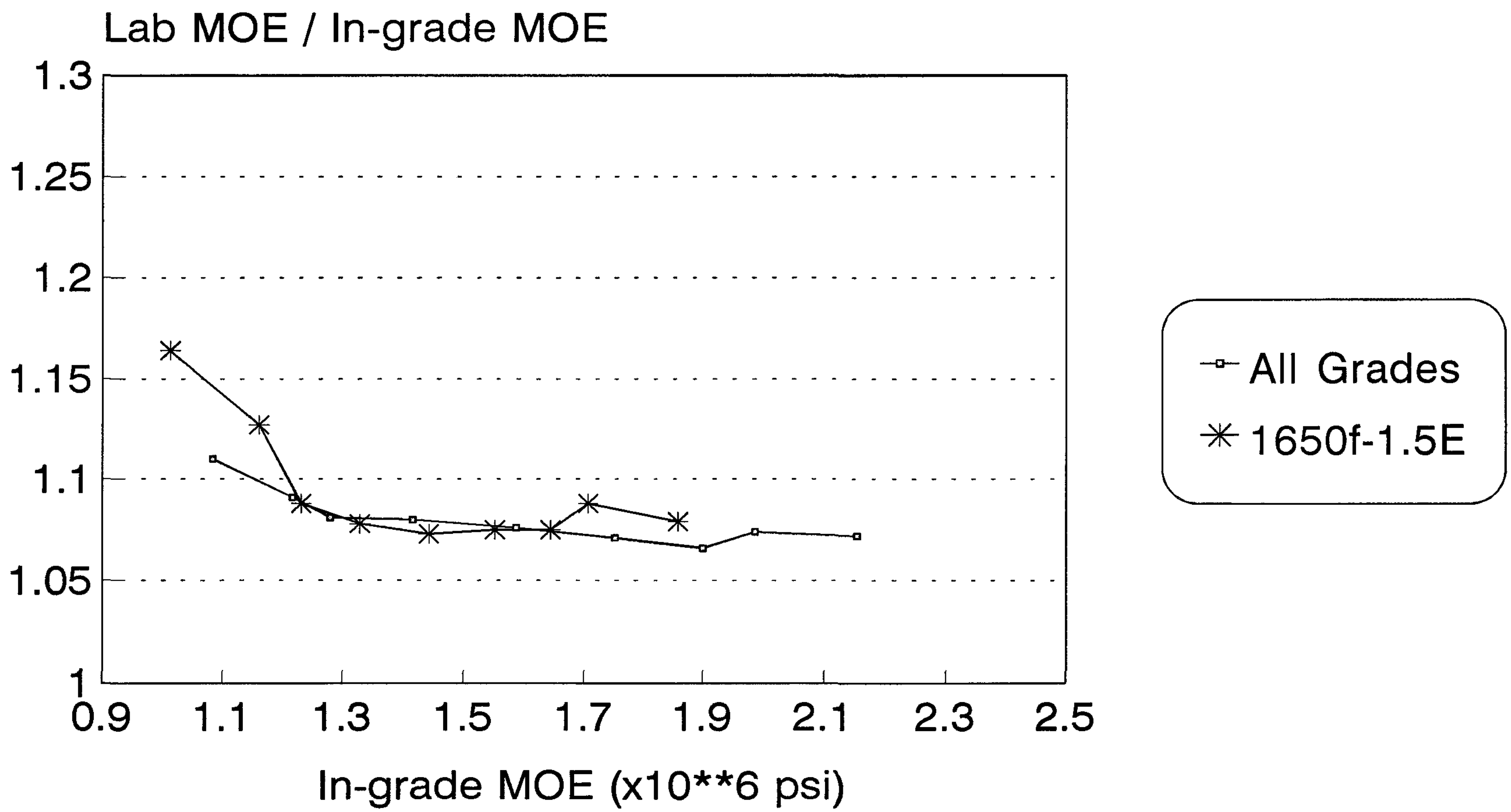
MSR Lumber In-grade Data



Both based on nominal dimensions and mach. defl. adjusted

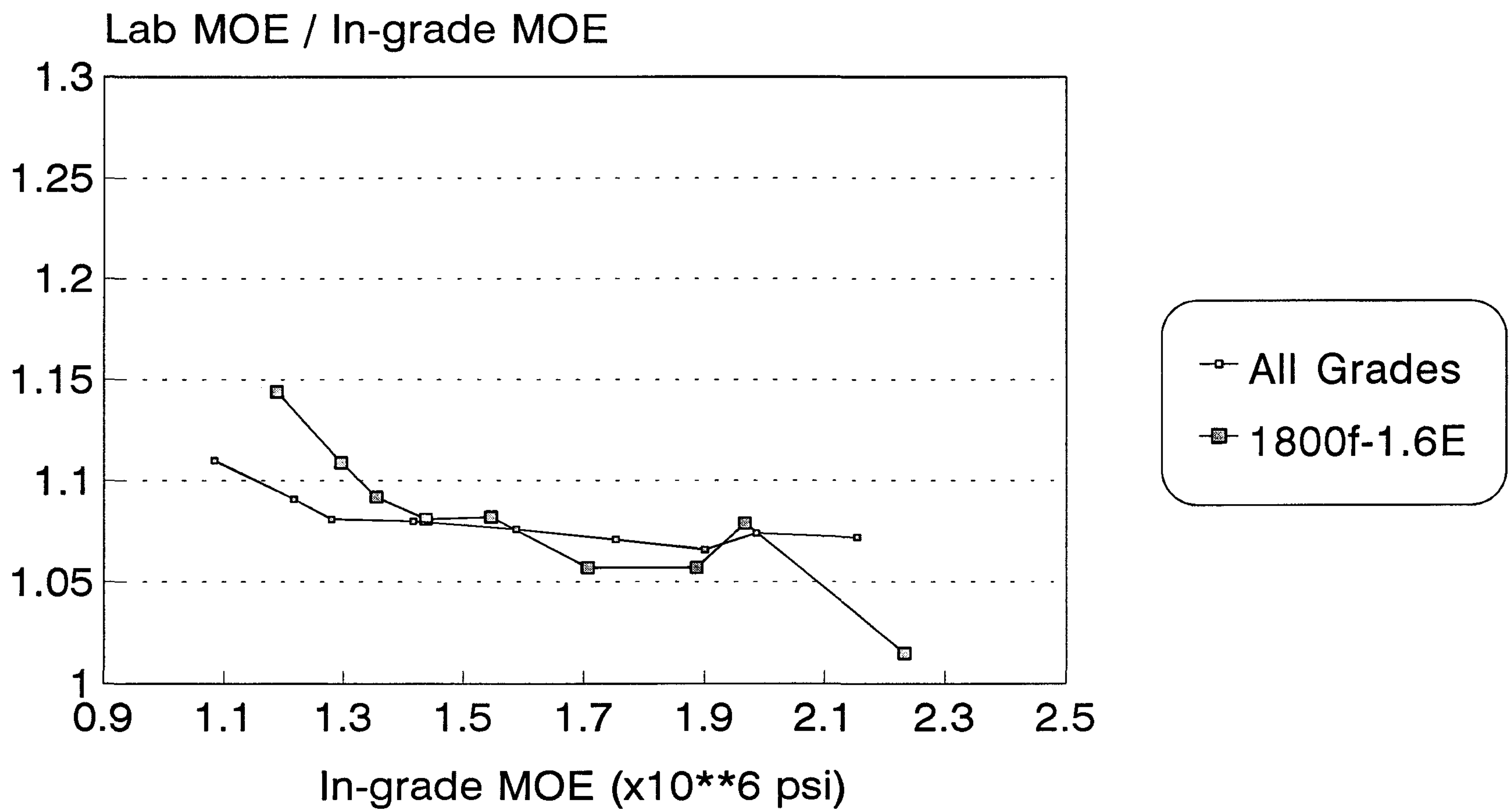
Figure 11. Plot of 21:1 / 17:1 vs 17:1 MOE

MSR Lumber In-grade Data



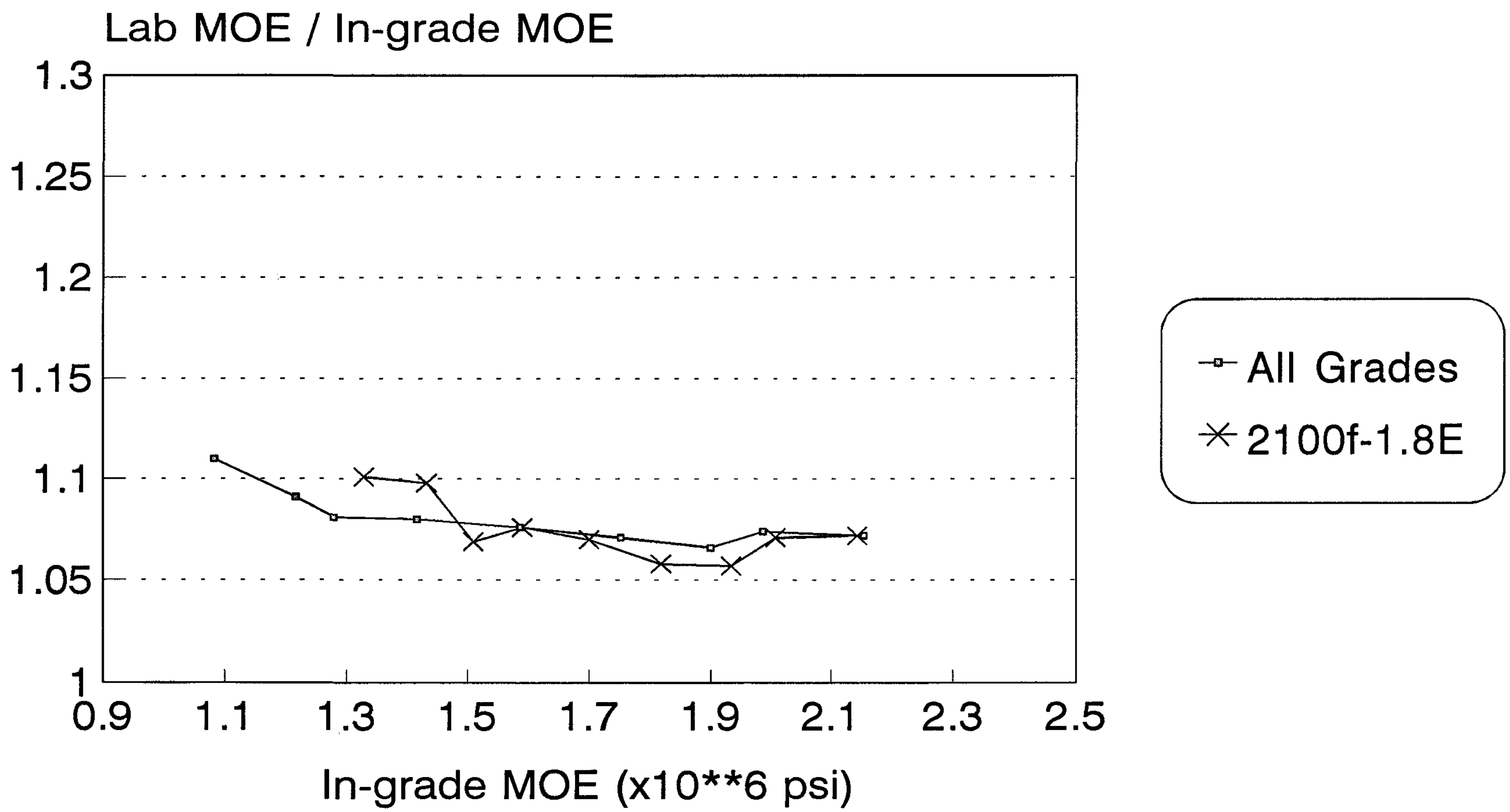
Both based on nominal dimensions and mach. defl. adjusted

Figure 12. Plot of 21:1 / 17:1 vs 17:1 MOE
MSR Lumber In-grade Data



Both based on nominal dimensions and mach. defl. adjusted

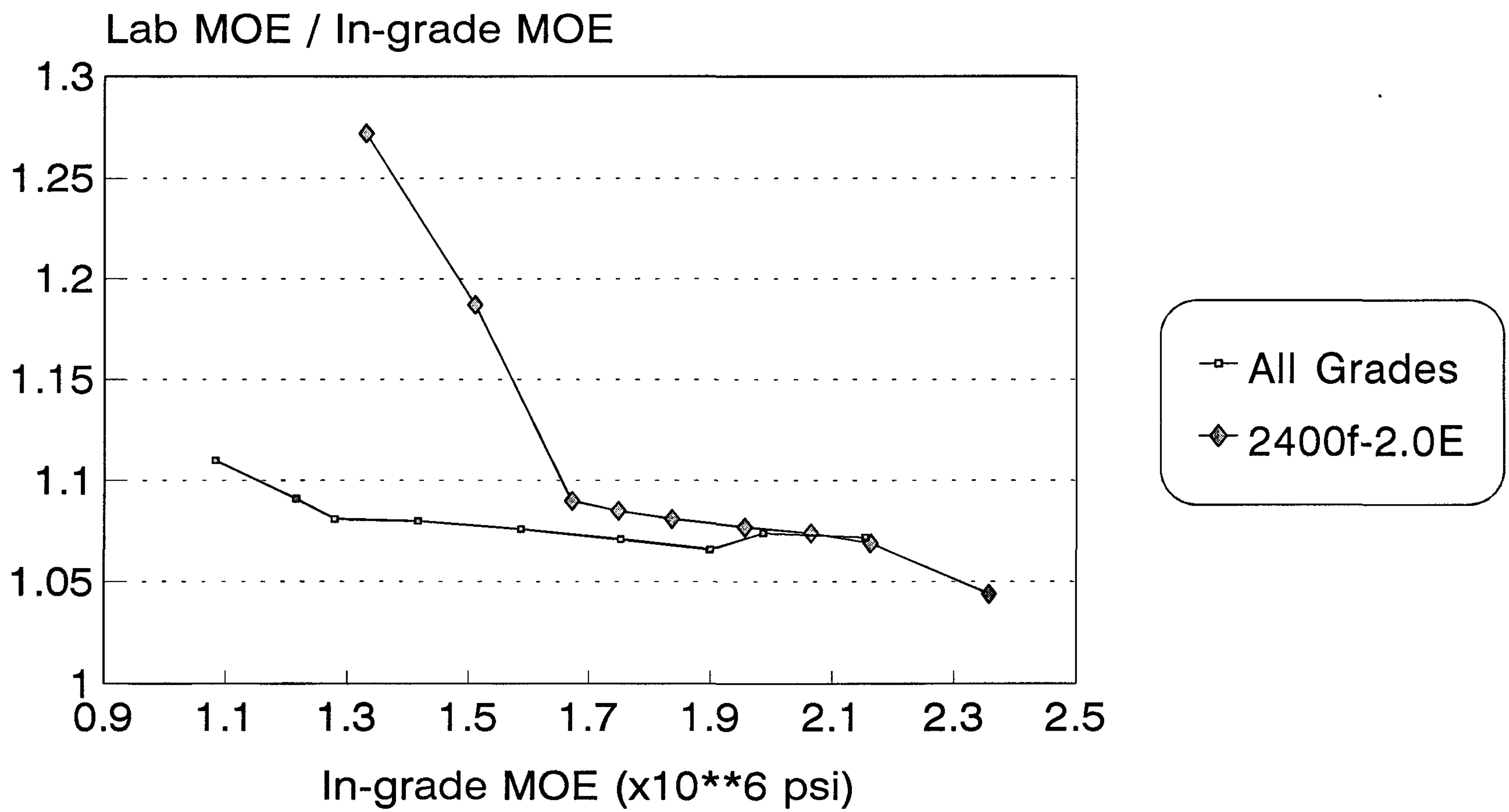
Figure 13. Plot of 21:1 / 17:1 vs 17:1 MOE
MSR Lumber In-grade Data



Both based on nominal dimensions and mach. defl. adjusted

Figure 14. Plot of 21:1 / 17:1 vs 17:1 MOE

MSR Lumber In-grade Data



Both based on nominal dimensions and mach. defl. adjusted

Figure 15. Cumulative Relative Frequencies
MSR L.P. Data - 2x4 S-P-F

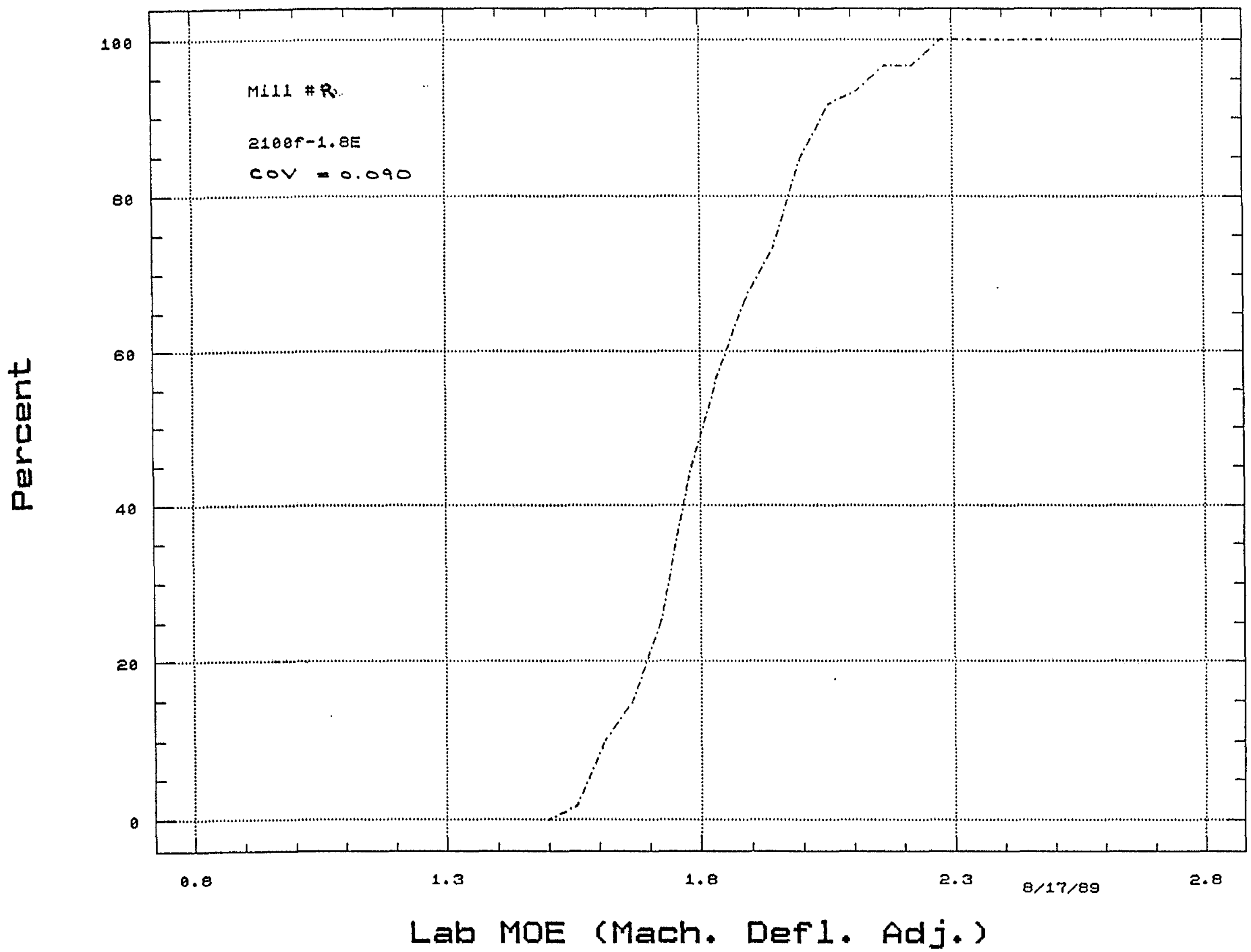


Figure 16. Cumulative Relative Frequencies
MSR L.P. Data - 2x4 S-P-F

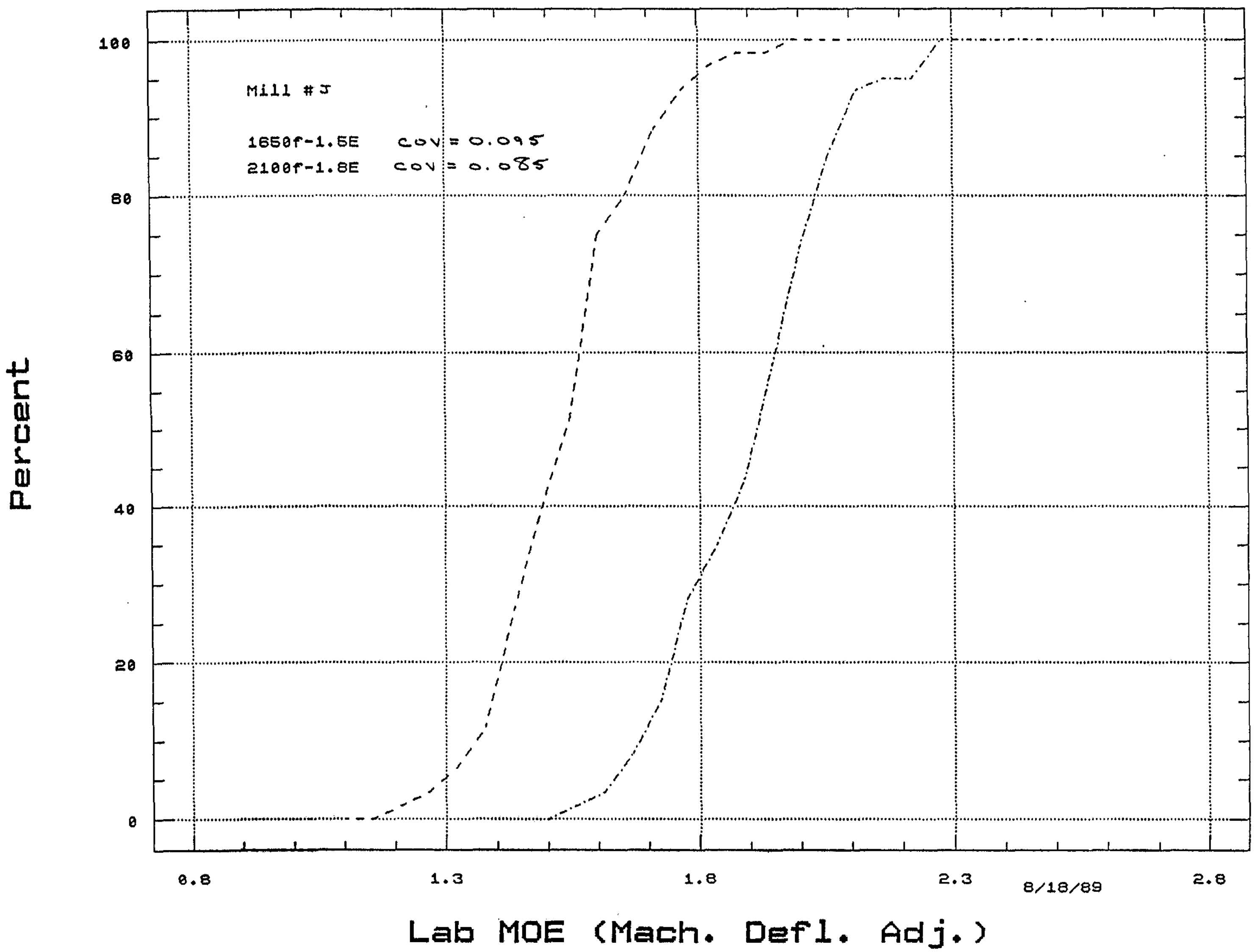


Figure 17. Cumulative Relative Frequencies
MSR L.P. Data - 2X4 S-P-F

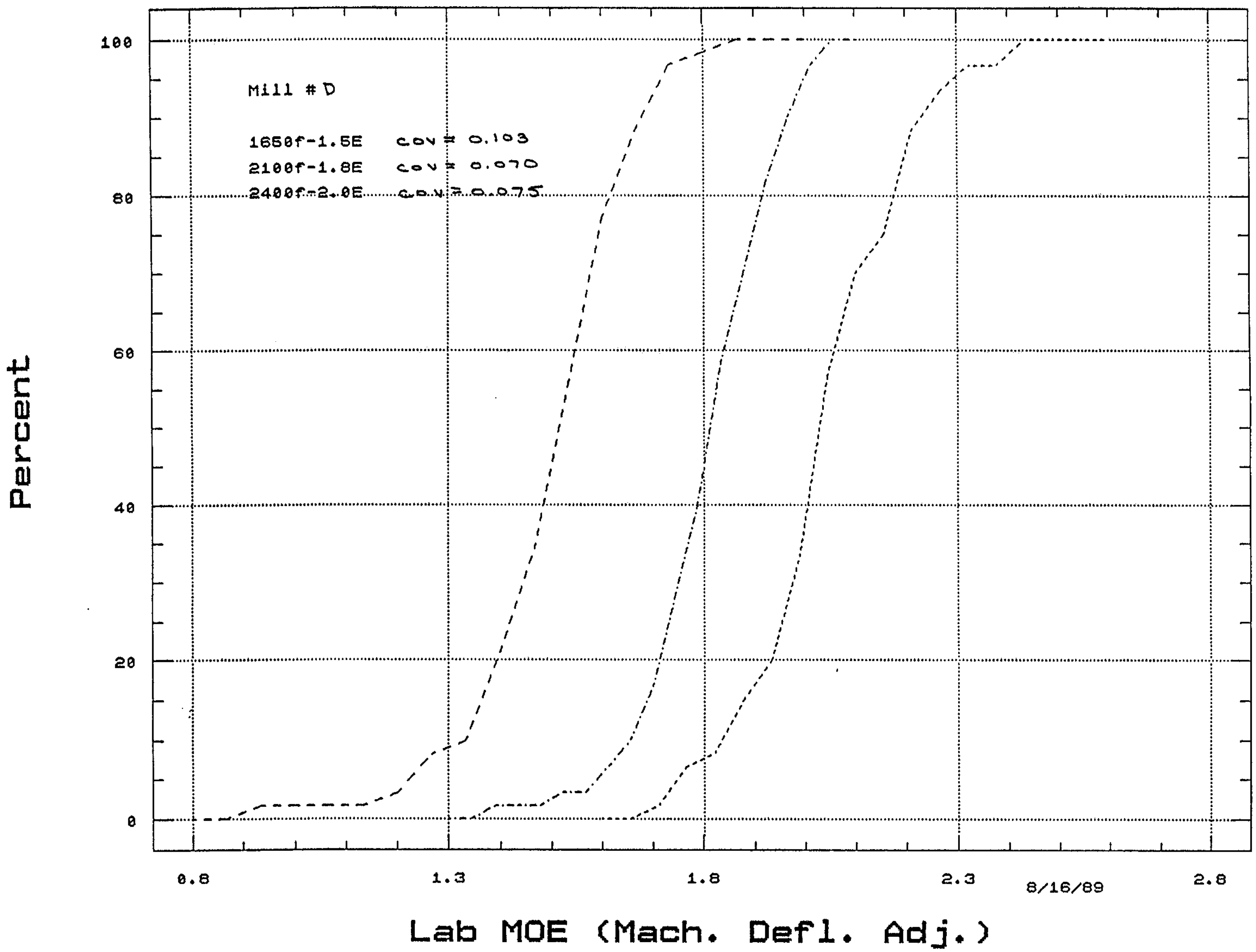


Figure 18. Cumulative Relative Frequencies
MSR L.P. Data - 2X4 S-P-F

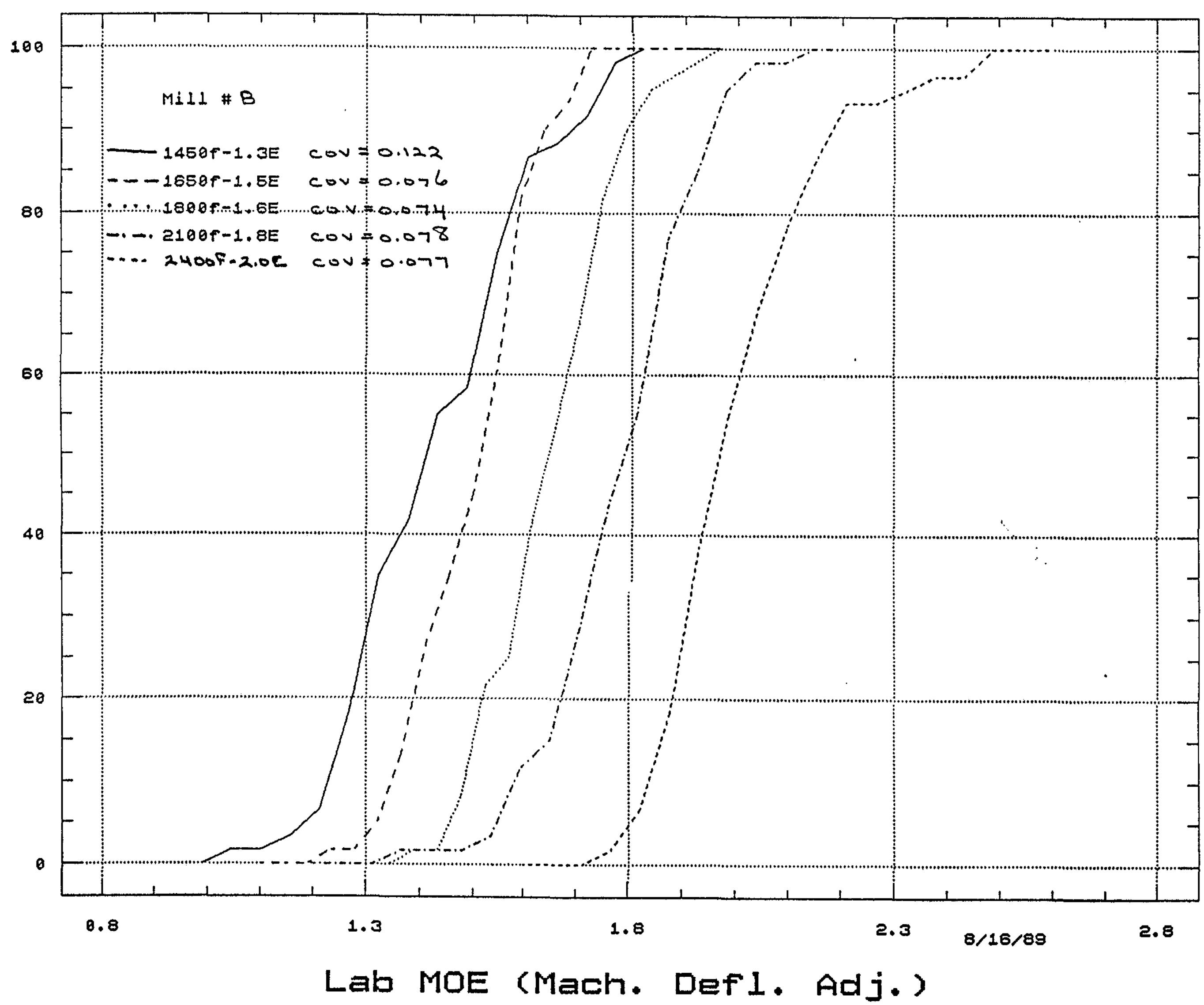


Figure 19. Cumulative Relative Frequencies
MSR L.P. Data - 2X4 S-P-F

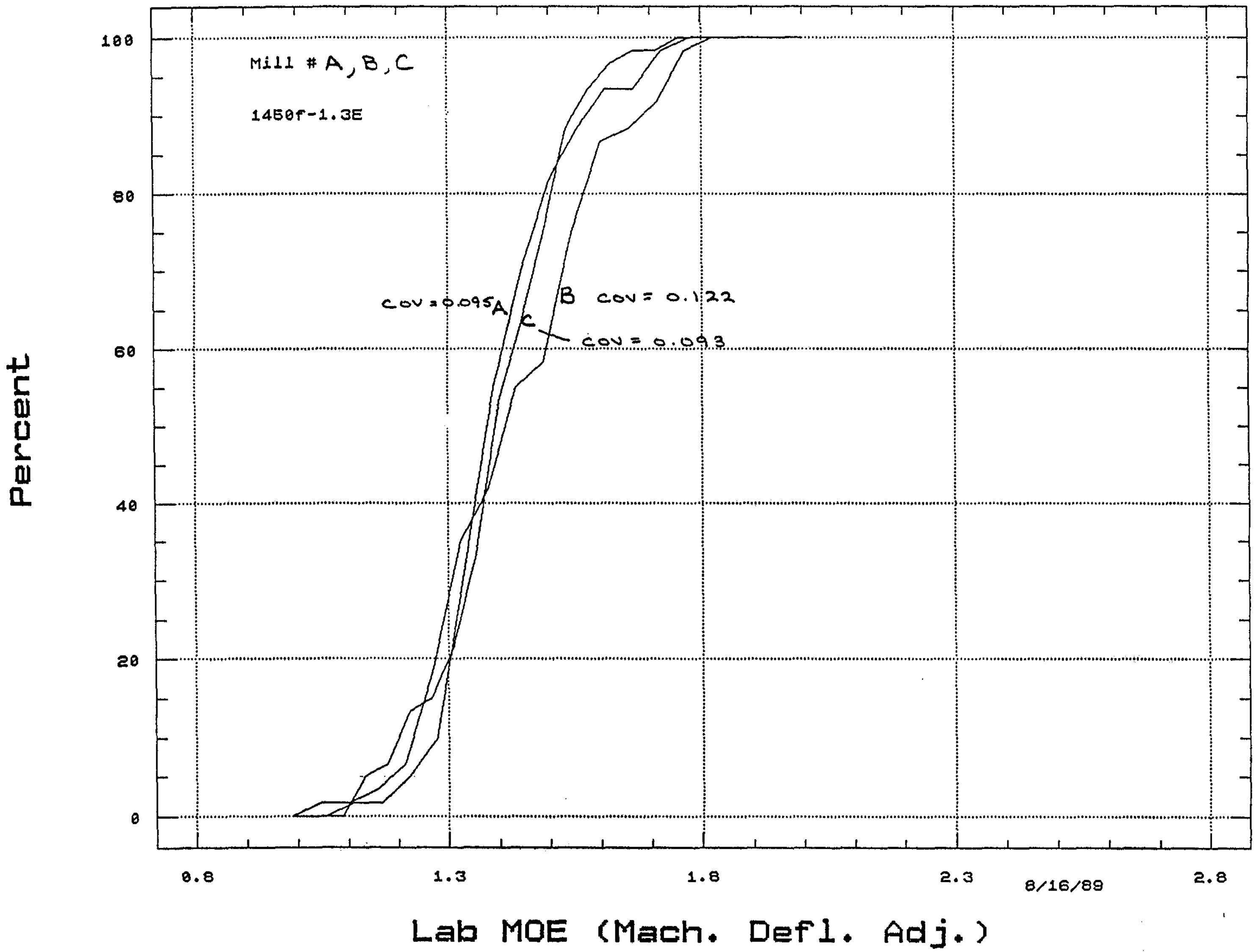


Figure 20. Cumulative Relative Frequencies
MSR L.P. Data - 2x4 S-P-F

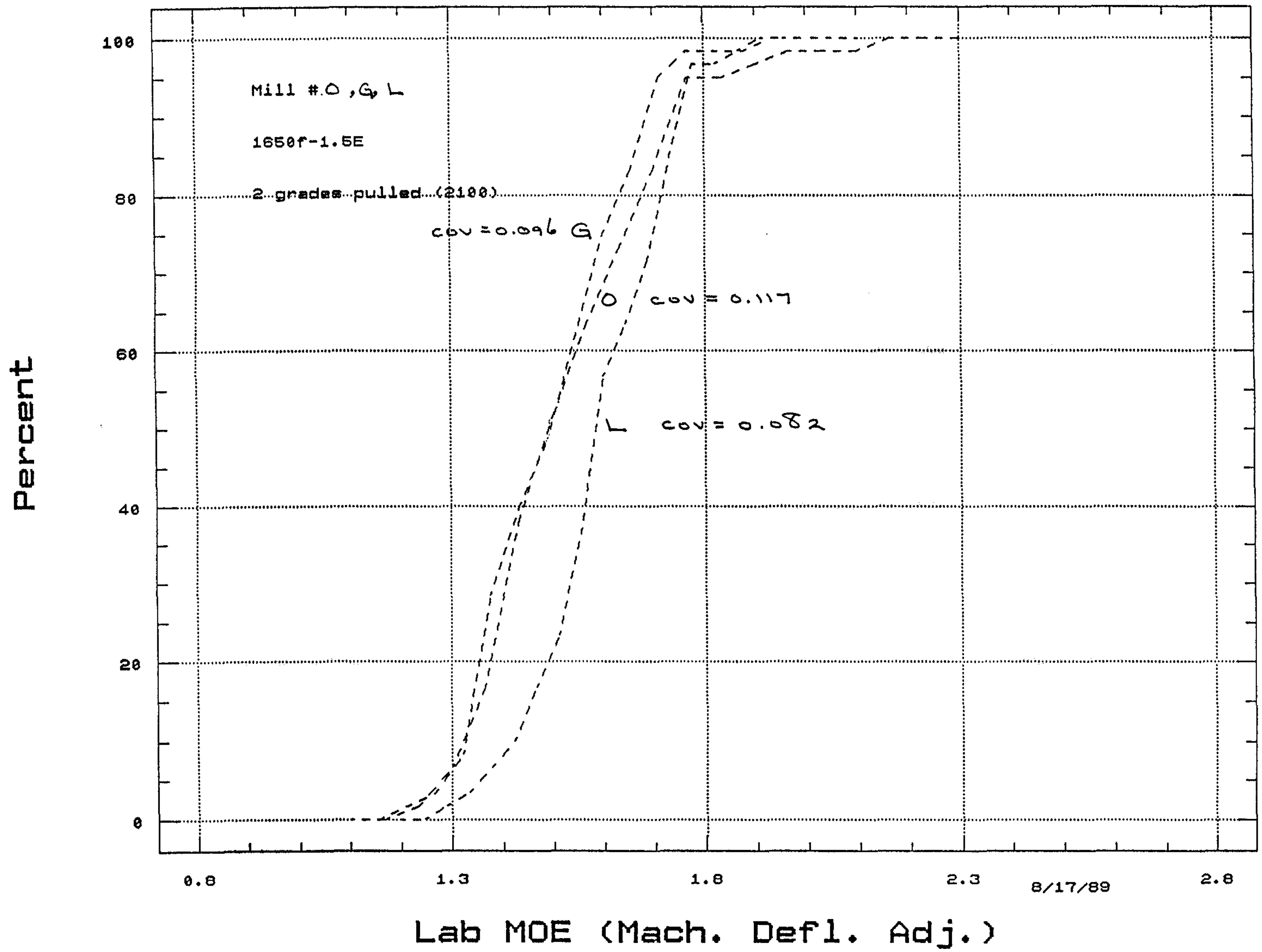


Figure 21. Cumulative Relative Frequencies
MSR L.P. Data - 2X4 S-P-F

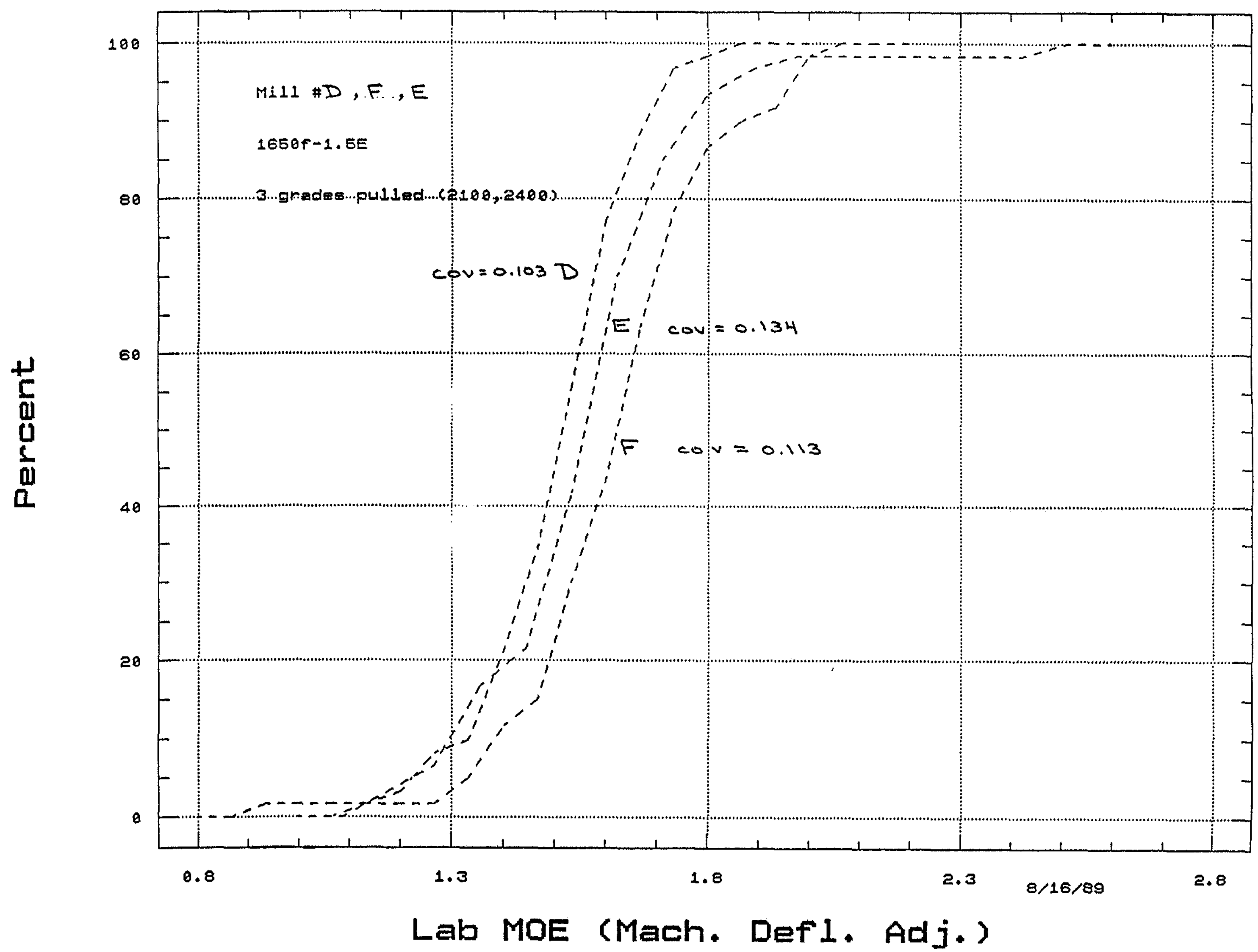


Figure 22. Cumulative Relative Frequencies
MSR L.P. Data - 2x4 S-P-F

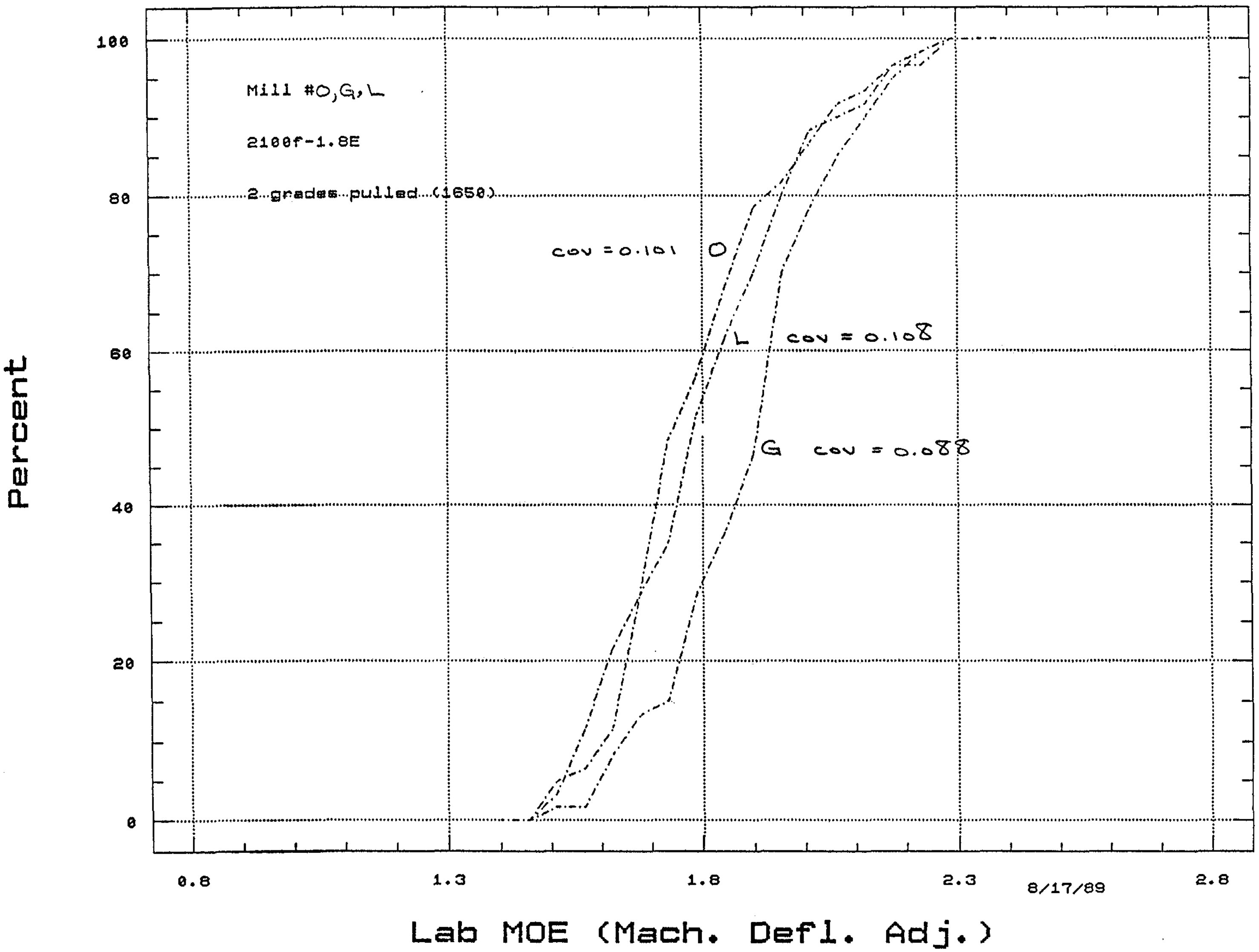


Figure 23. Cumulative Relative Frequencies
MSR L.P. Data - 2X4 S-P-F

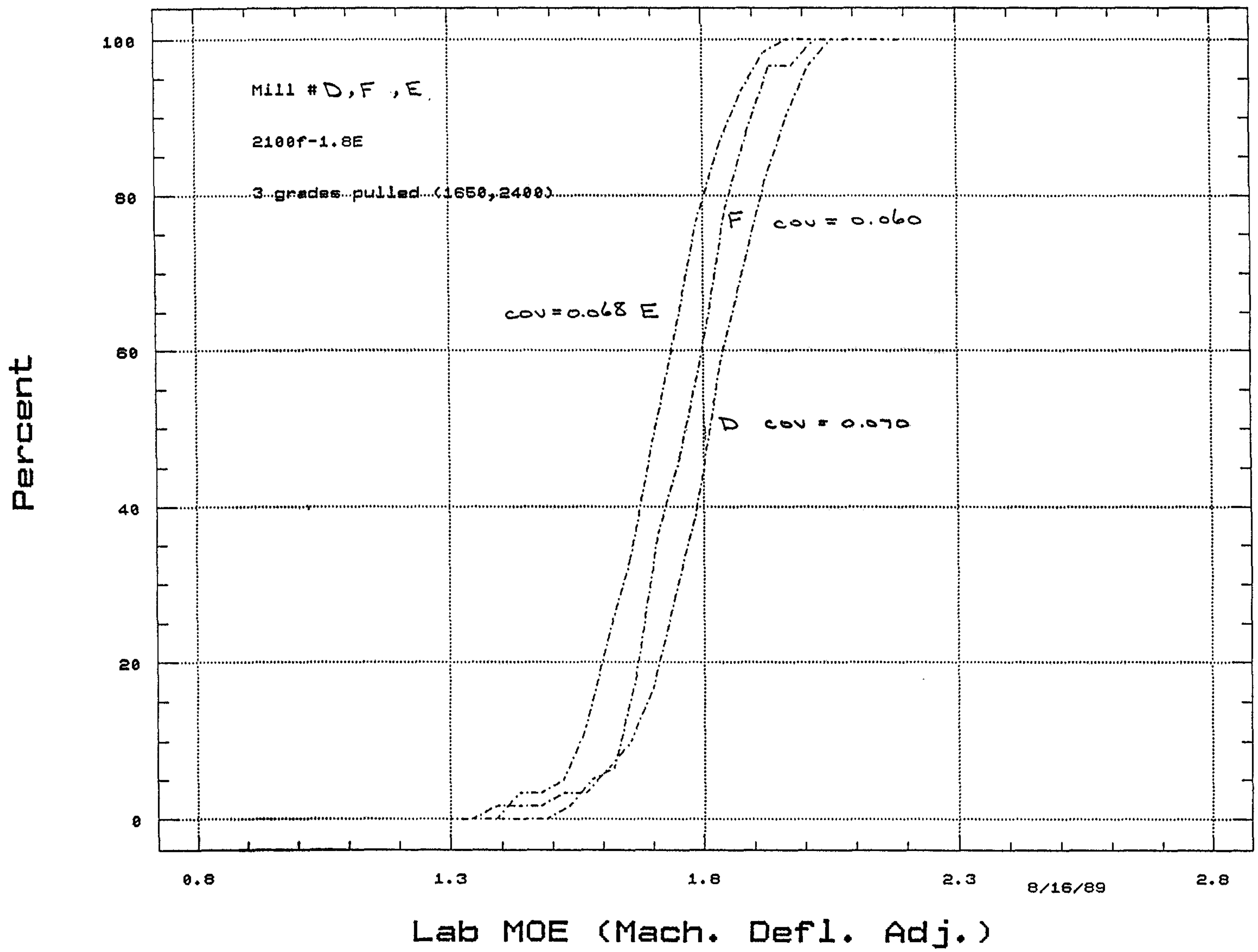
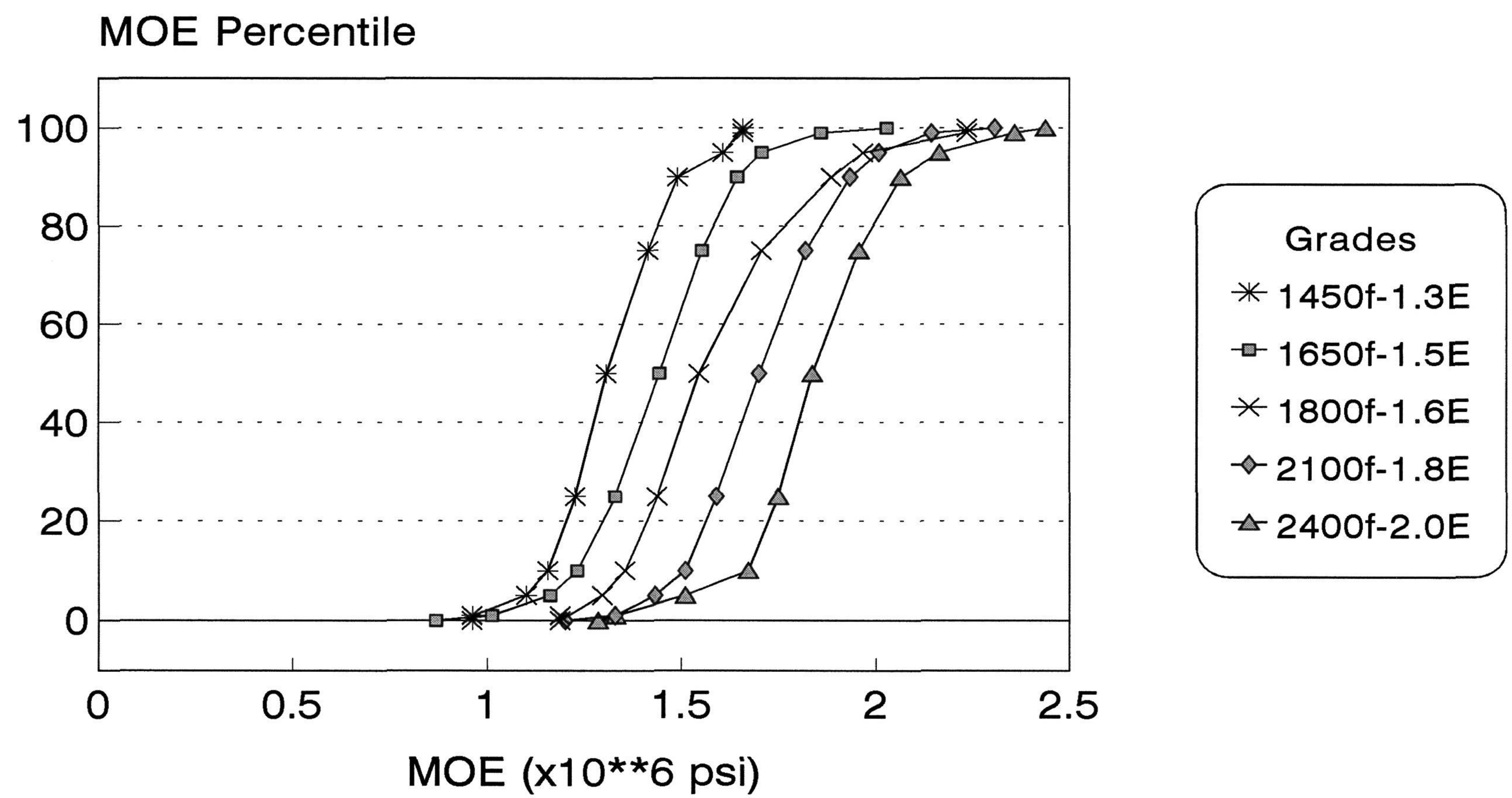
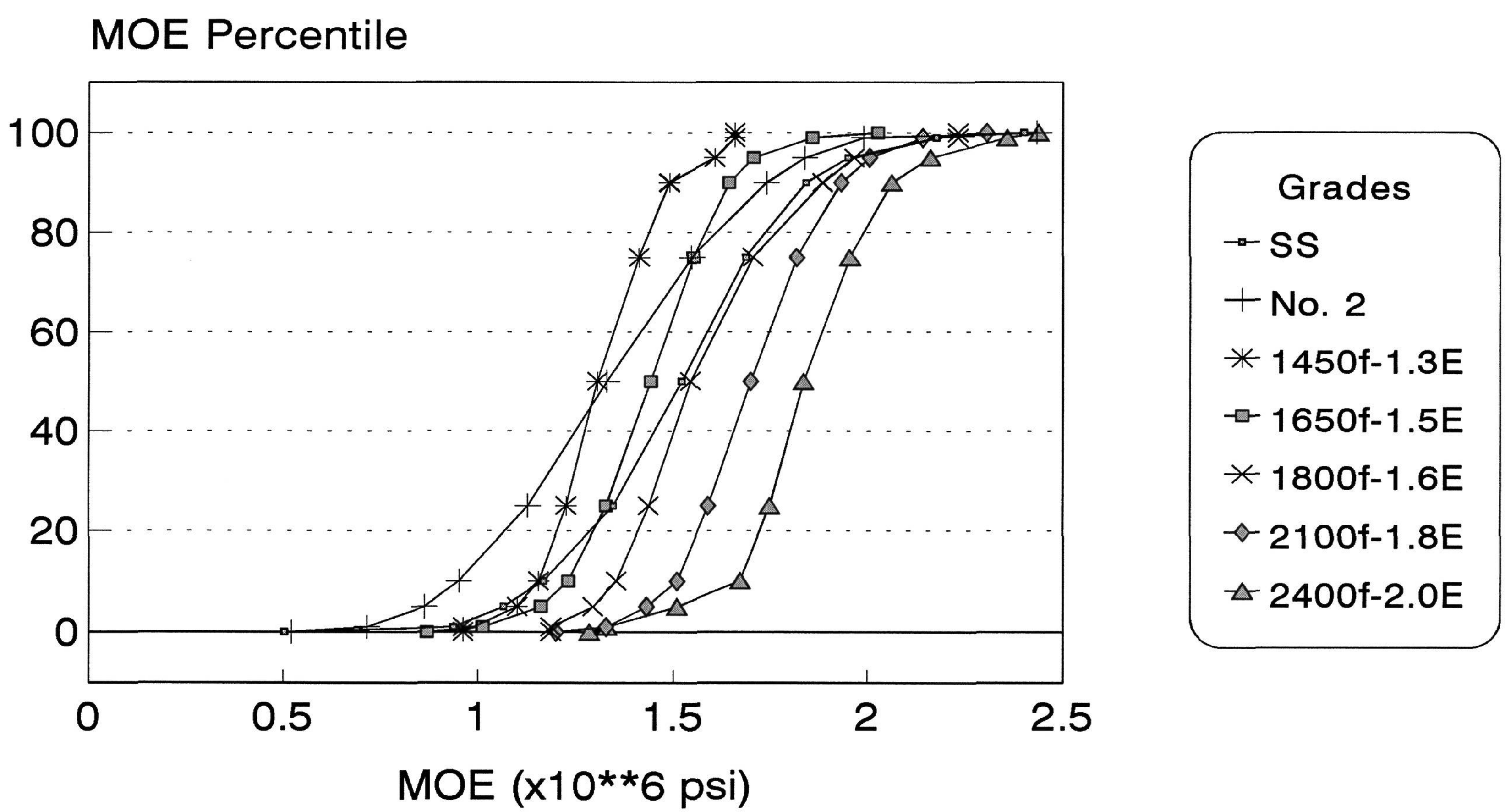


Figure 24. MOE Comparisons
S-P-F 2x4 MSR Grades



Based on 17:1 testing, machine deflection adjusted

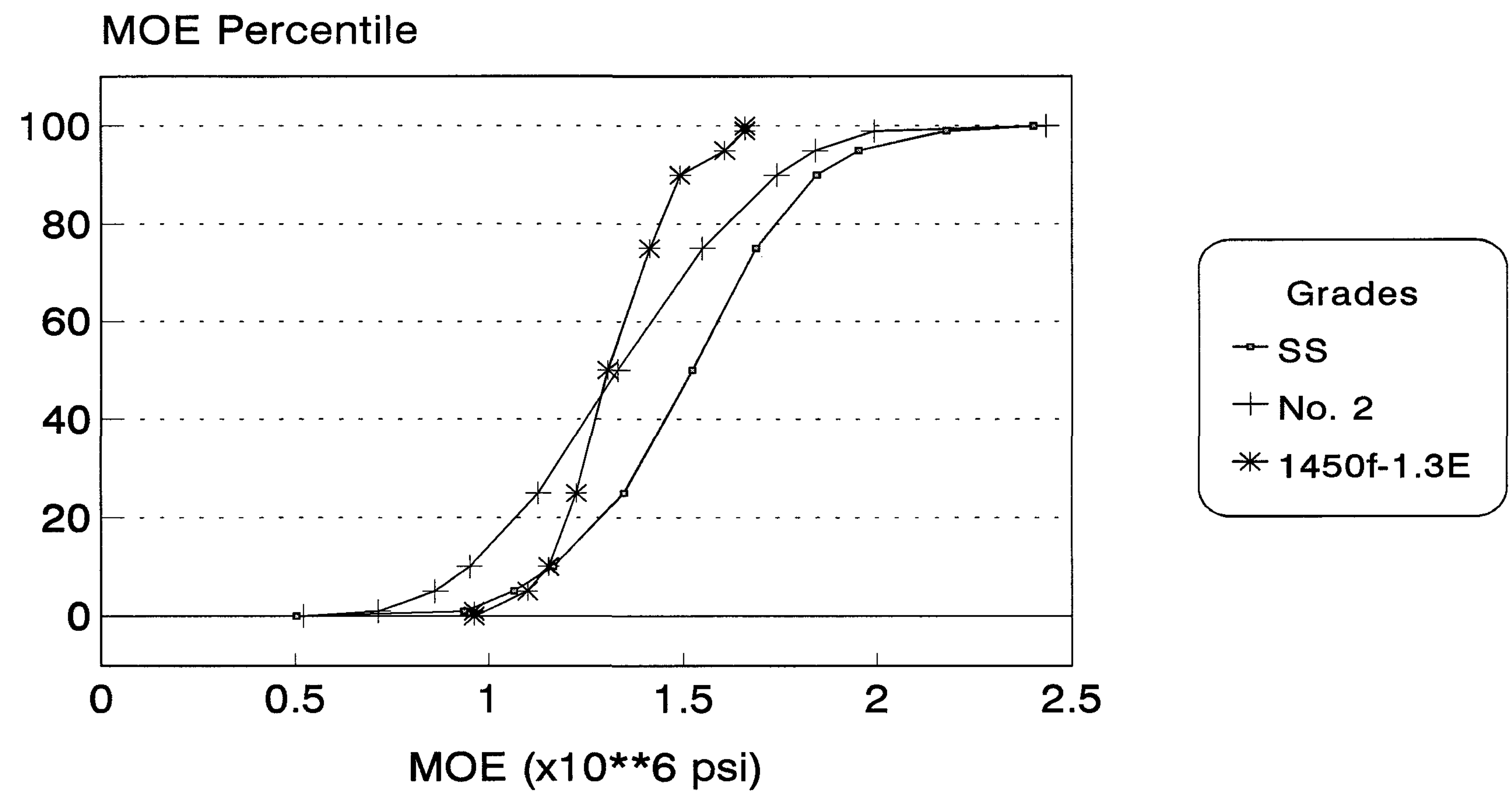
Figure 25. MOE Comparisons
S-P-F 2x4 Visual and MSR Grades



Based on 17:1 testing, machine deflection adjusted

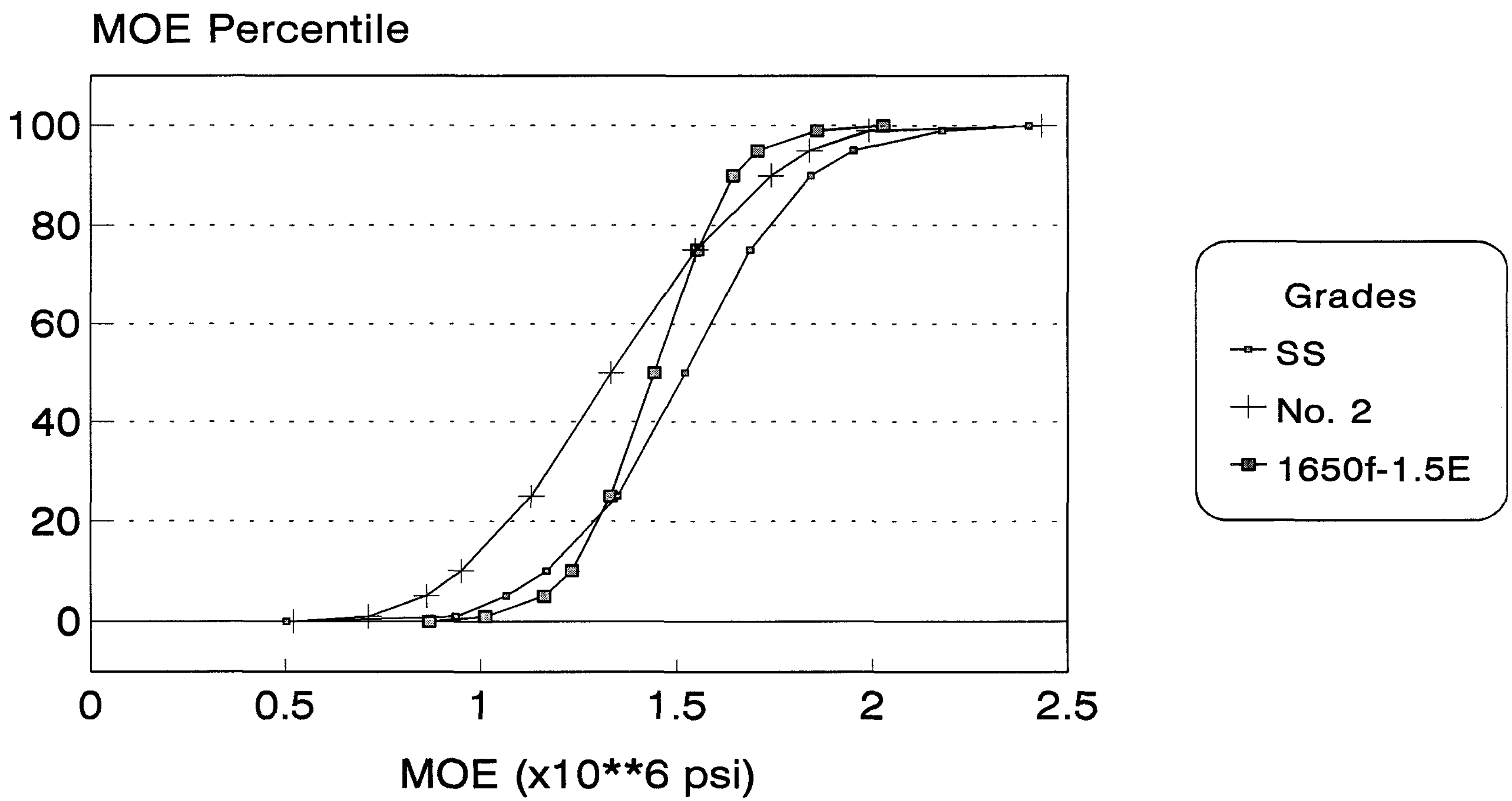
Figure 26. MOE Comparisons

S-P-F 2x4 Visual and MSR Grades



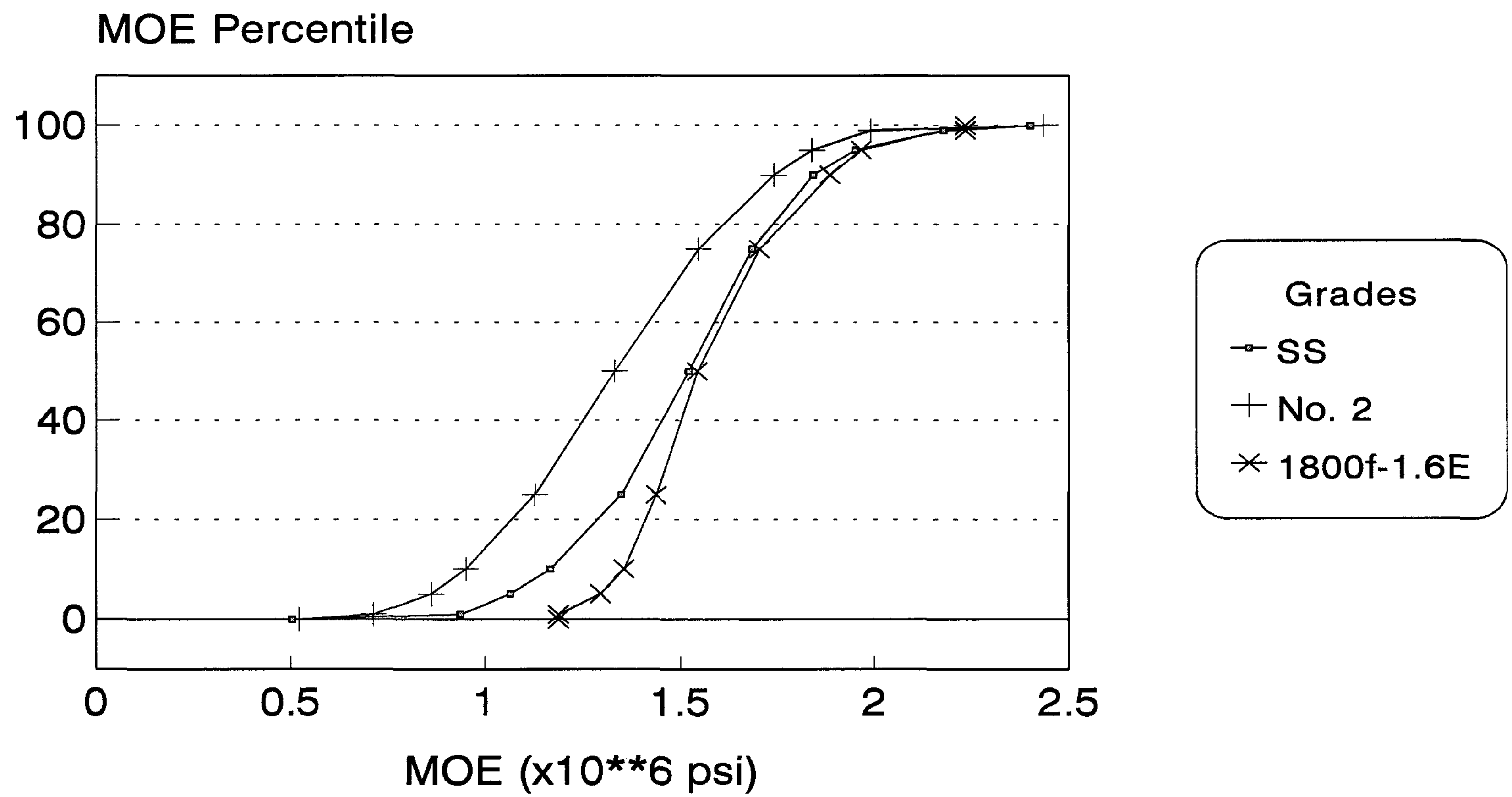
Based on 17:1 testing, machine deflection adjusted

Figure 27. MOE Comparisons
S-P-F 2x4 Visual and MSR Grades



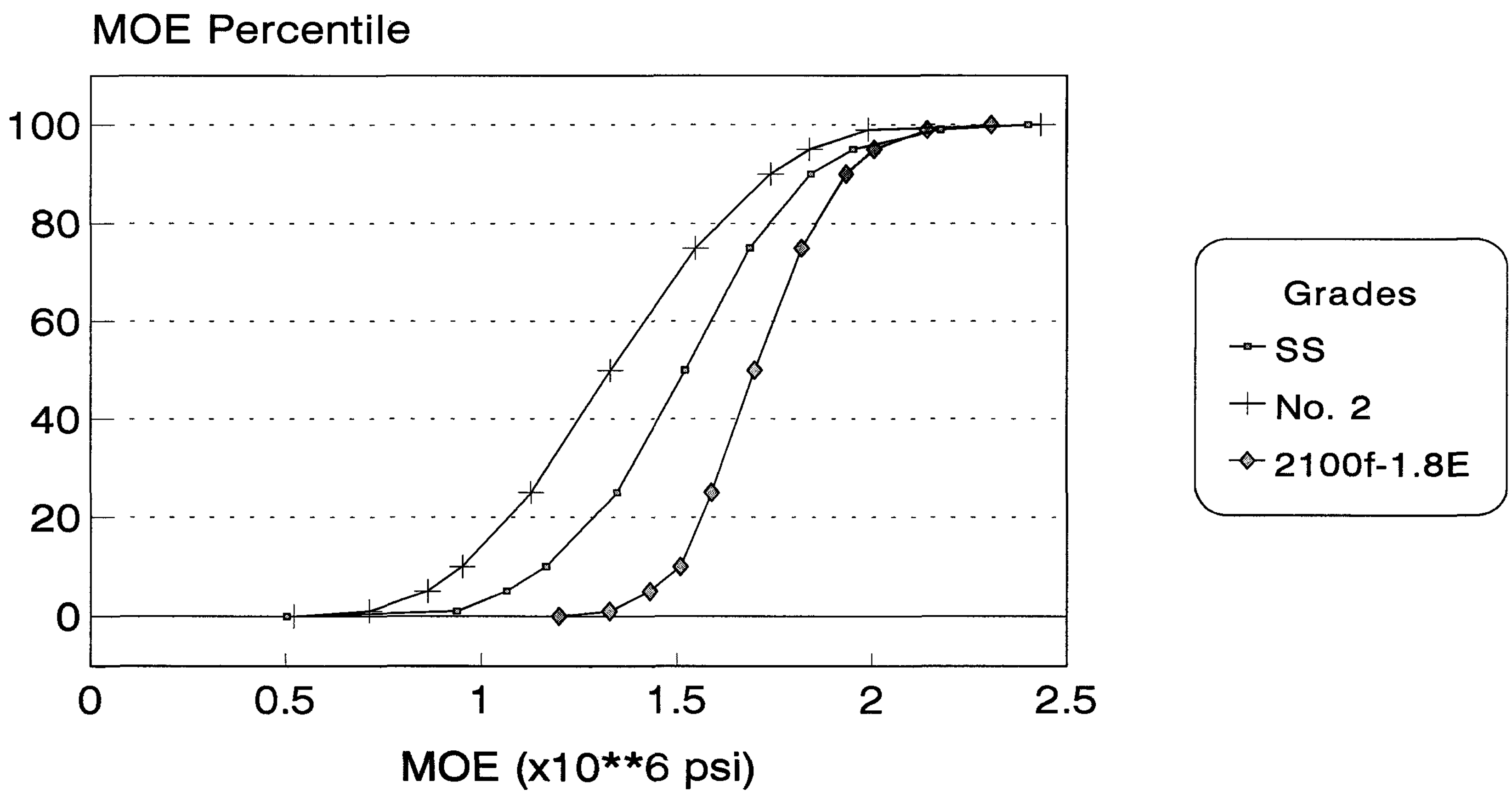
Based on 17:1 testing, machine deflection adjusted

Figure 28. MOE Comparisons
S-P-F 2x4 Visual and MSR Grades



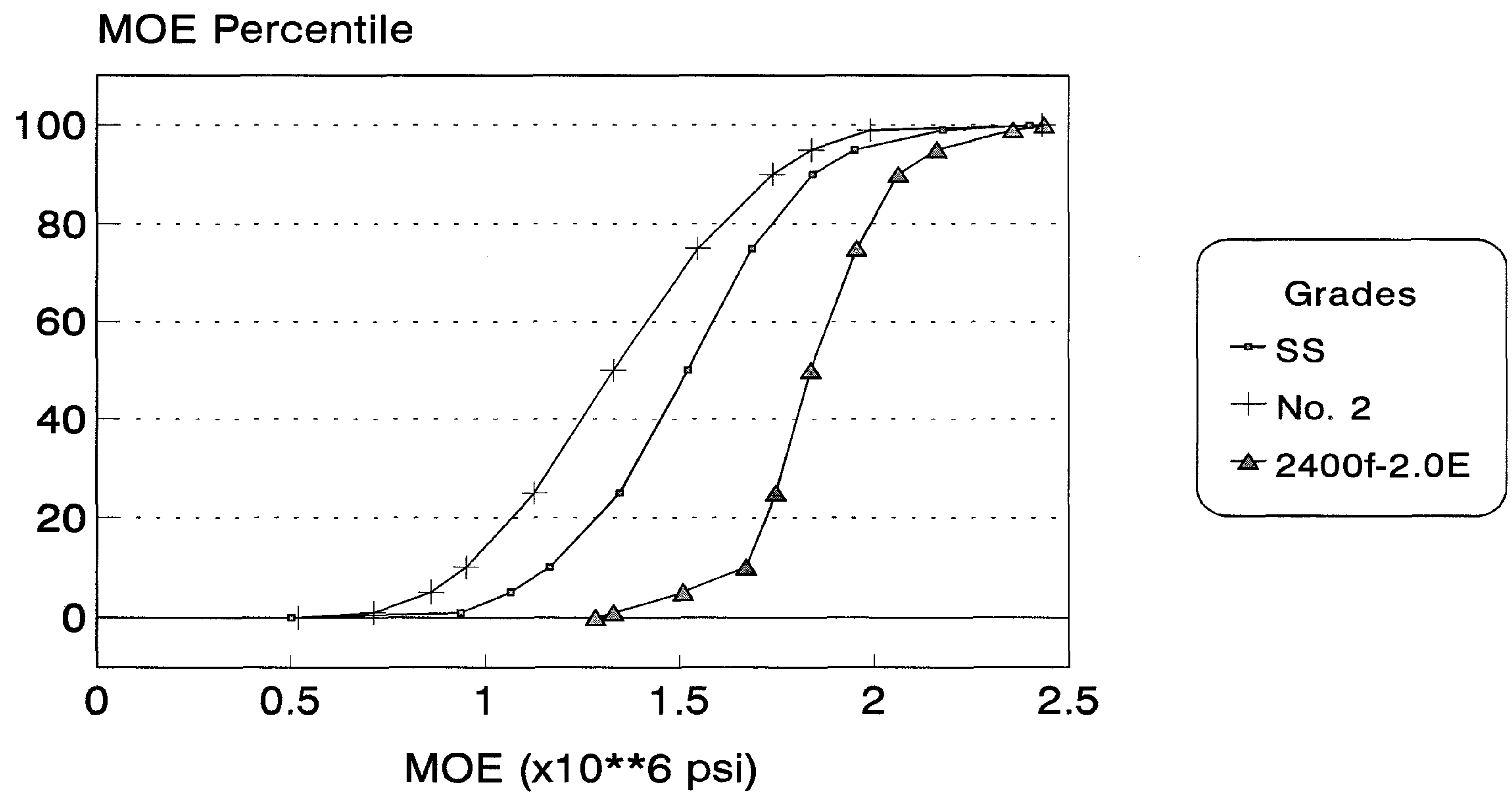
Based on 17:1 testing, machine deflection adjusted

Figure 29. MOE Comparisons
S-P-F 2x4 Visual and MSR Grades



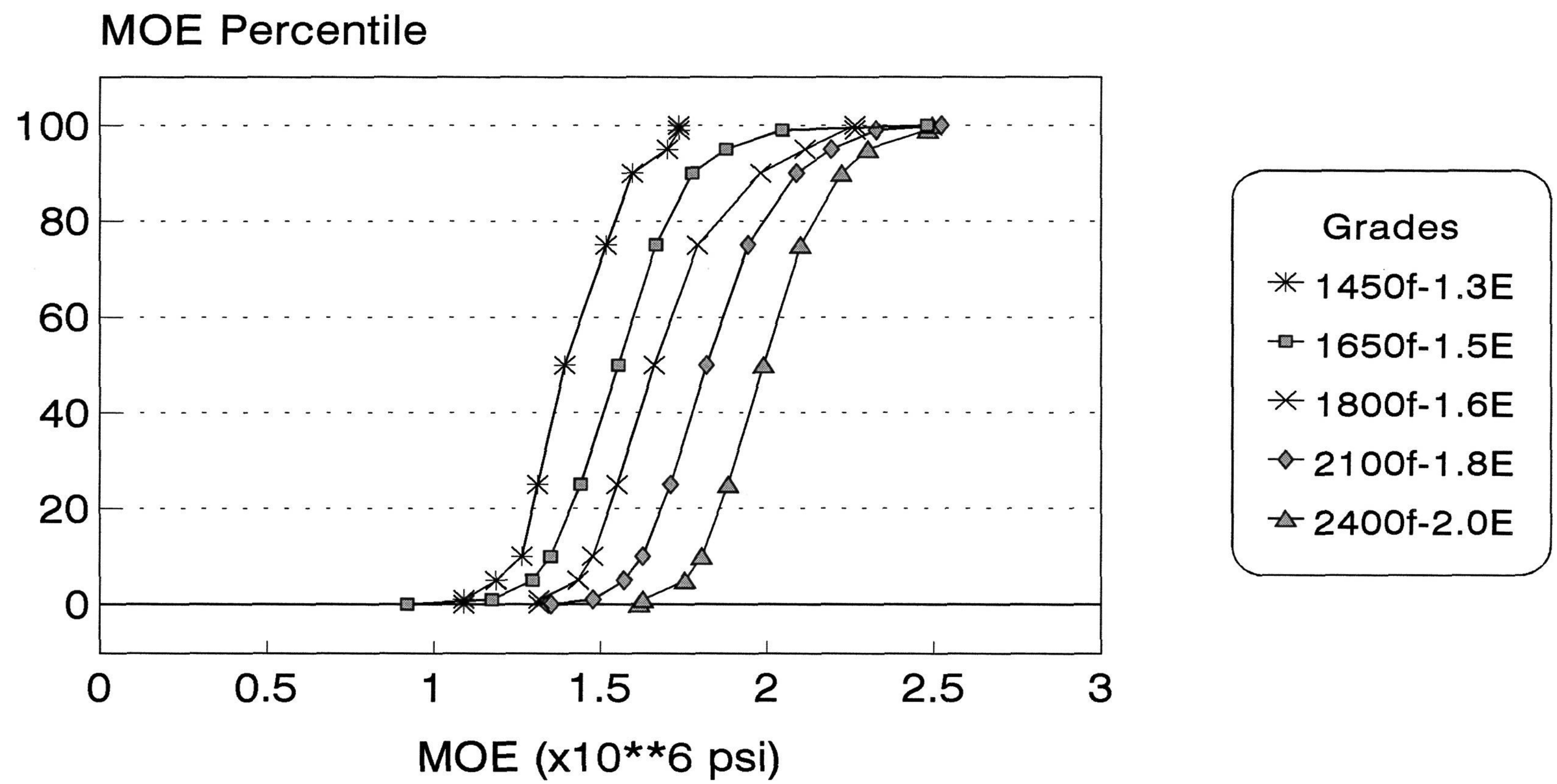
Based on 17:1 testing, machine deflection adjusted

Figure 30. MOE Comparisons
S-P-F 2x4 Visual and MSR Grades



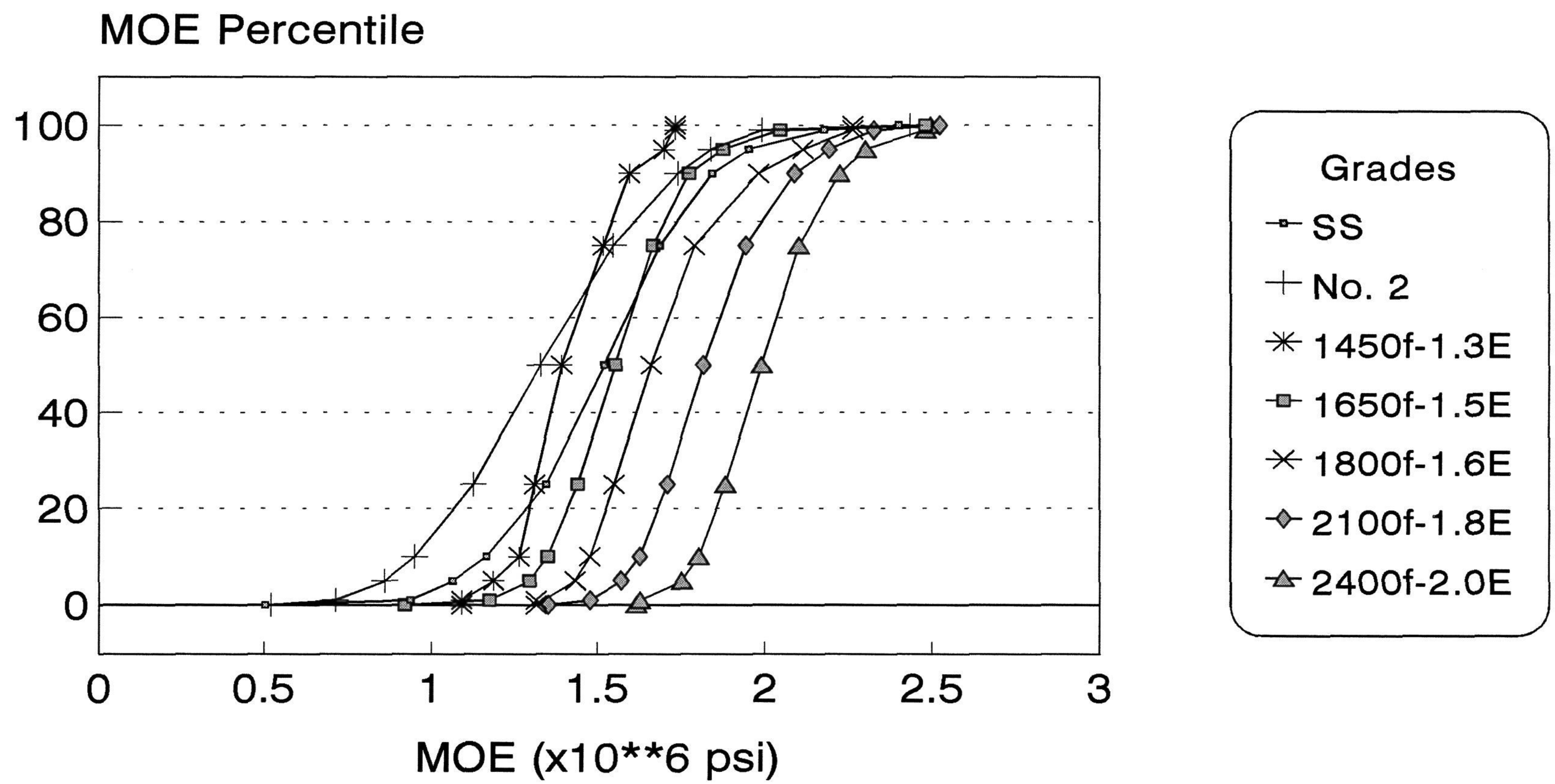
Based on 17:1 testing, machine deflection adjusted

Figure 31. MOE Comparisons
S-P-F 2x4 MSR Grades



Visual based on 17:1 testing, MSR based on 21:1 Lab MOE's from Tension sample
All data machine deflection adjusted

Figure 32. MOE Comparisons
S-P-F 2x4 MSR Grades



Visual based on 17:1 testing, MSR based on 21:1 Lab MOE's from Tension sample
All data machine deflection adjusted

122

Figure 33. MOR Comparisons
S-P-F 2x4 MSR Grades

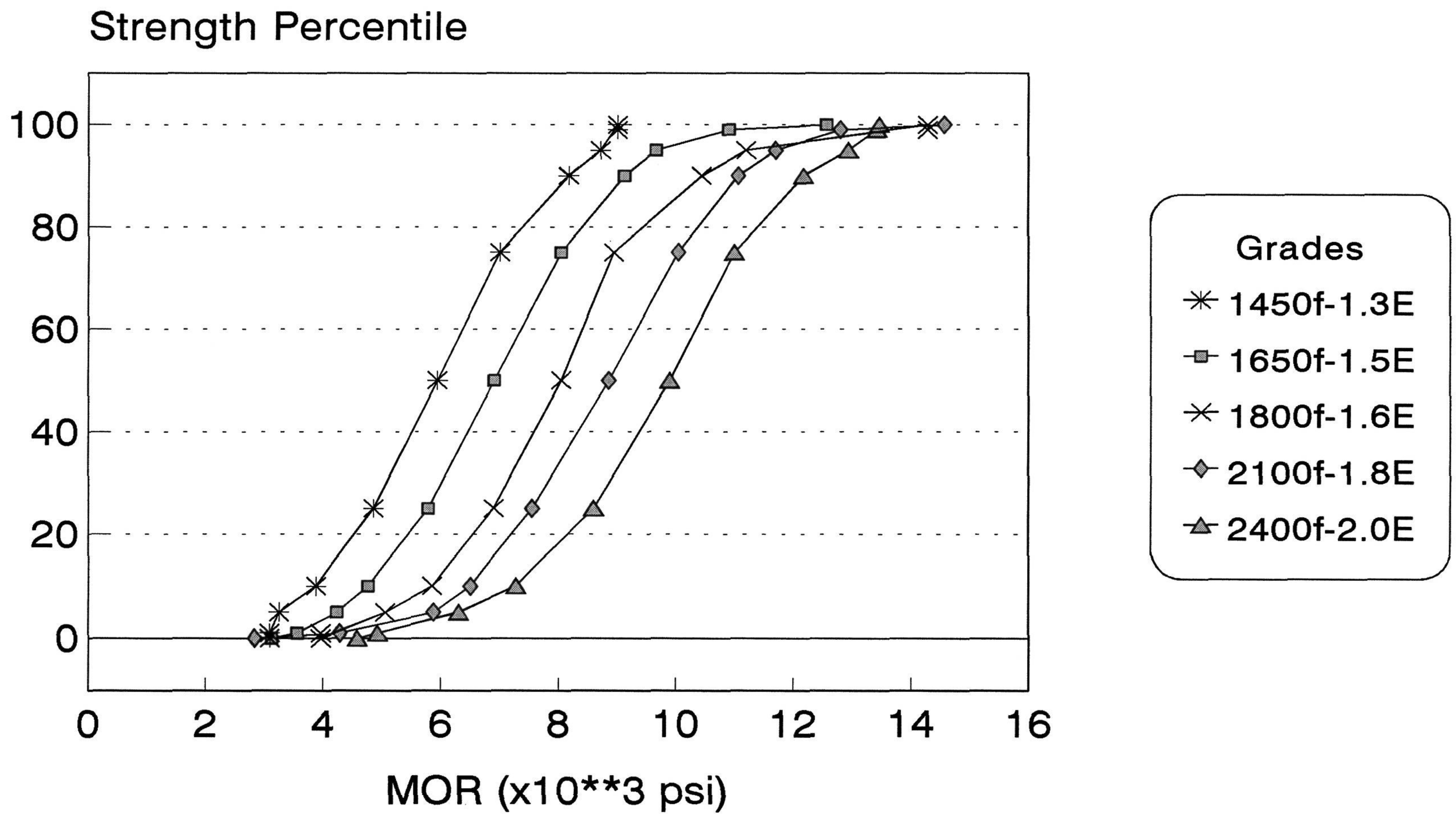
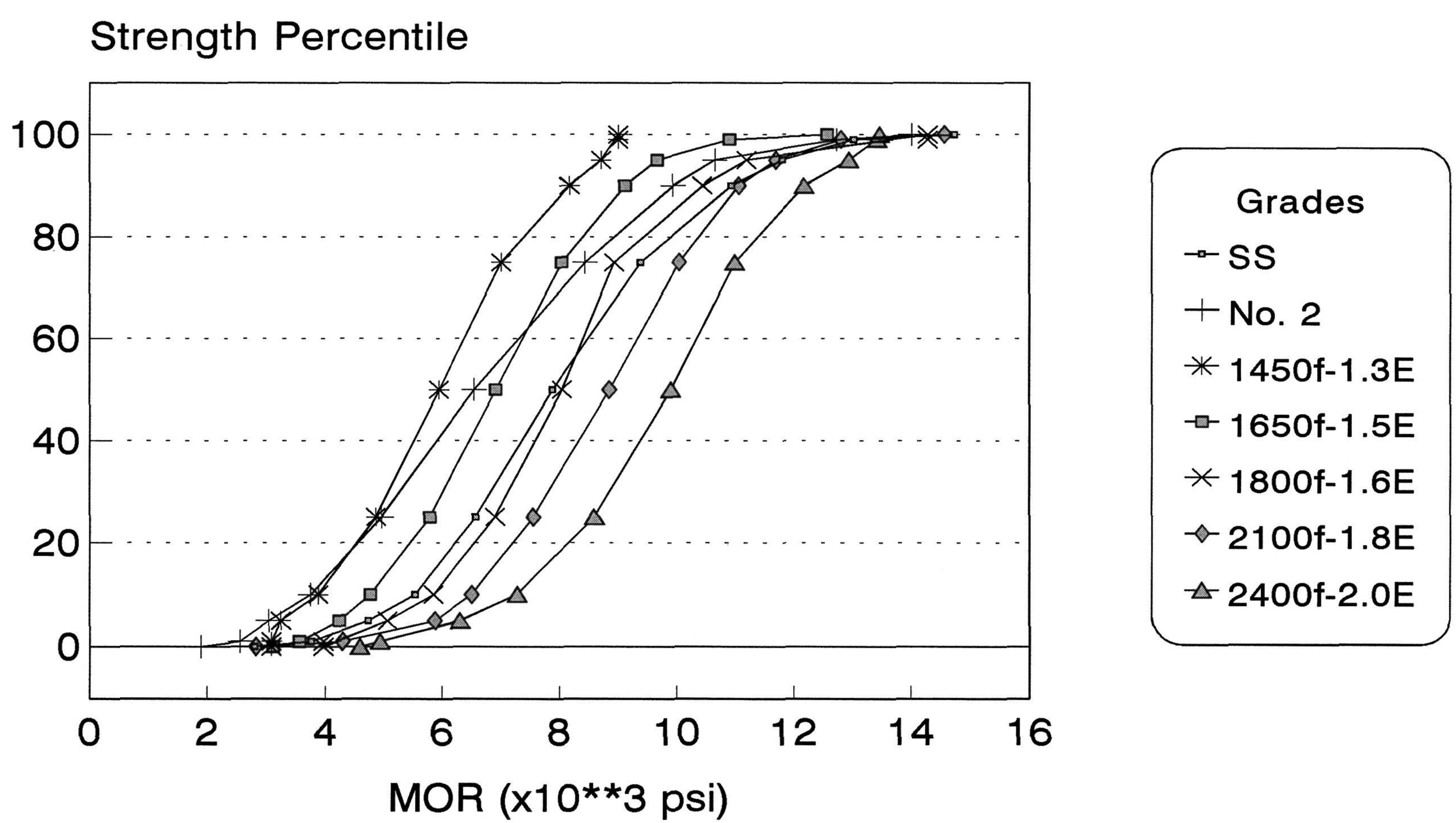


Figure 34. MOR Comparisons
S-P-F 2x4 Visual and MSR Grades



124

Figure 35. MOR Comparisons
S-P-F 2x4 Visual and MSR Grades

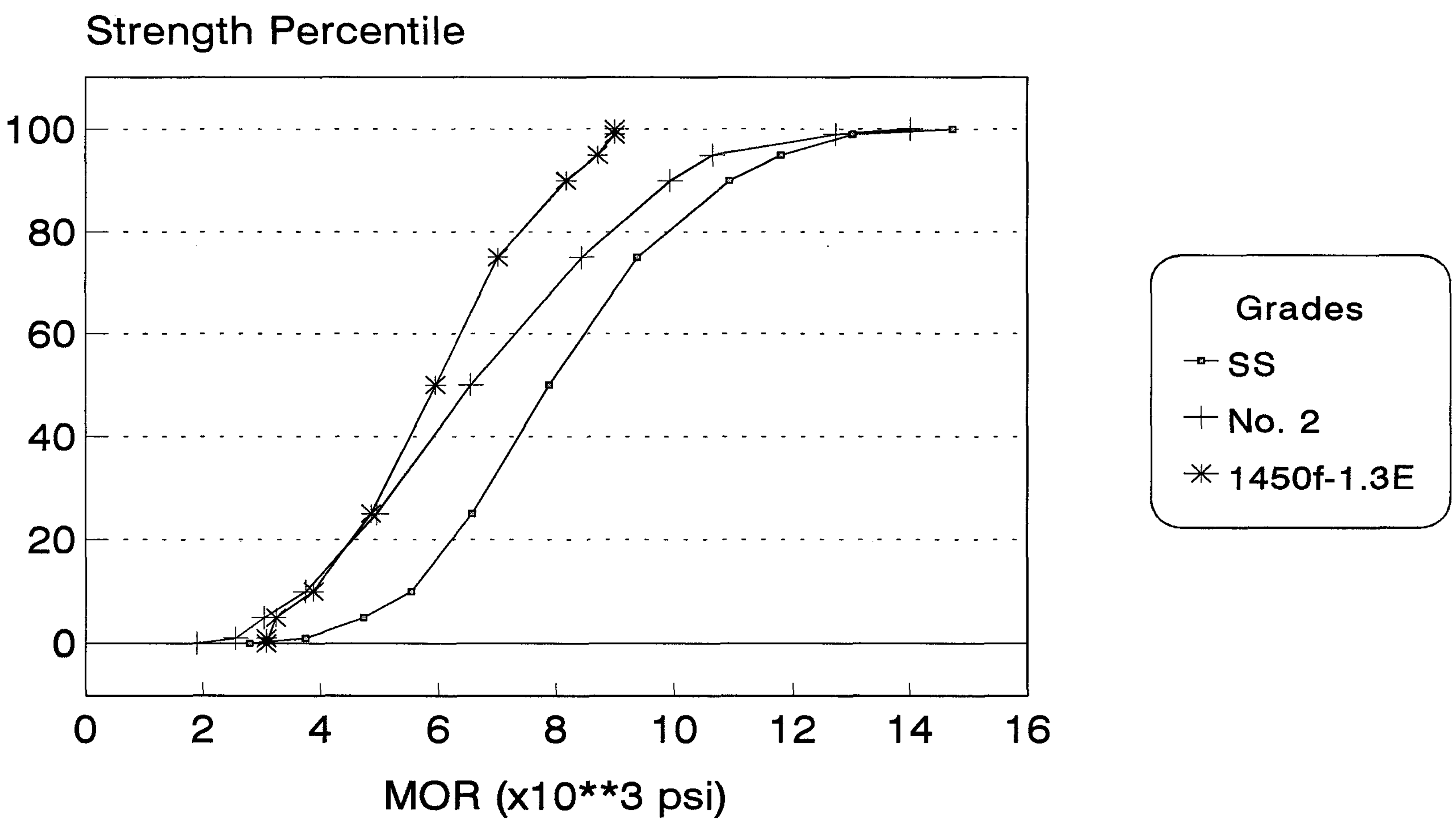


Figure 36. MOR Comparisons
S-P-F 2x4 Visual and MSR Grades

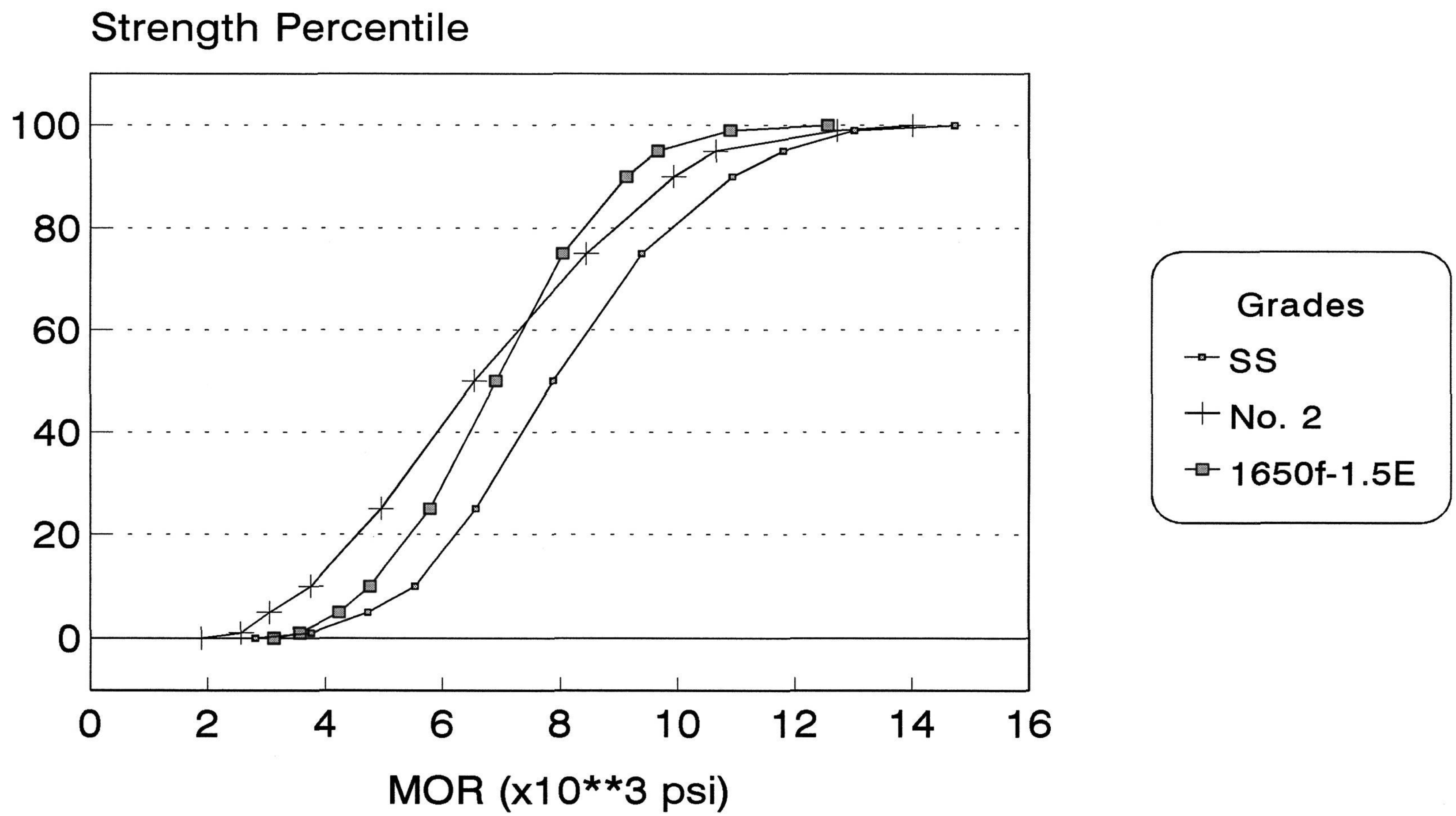


Figure 37. MOR Comparisons
S-P-F 2x4 Visual and MSR Grades

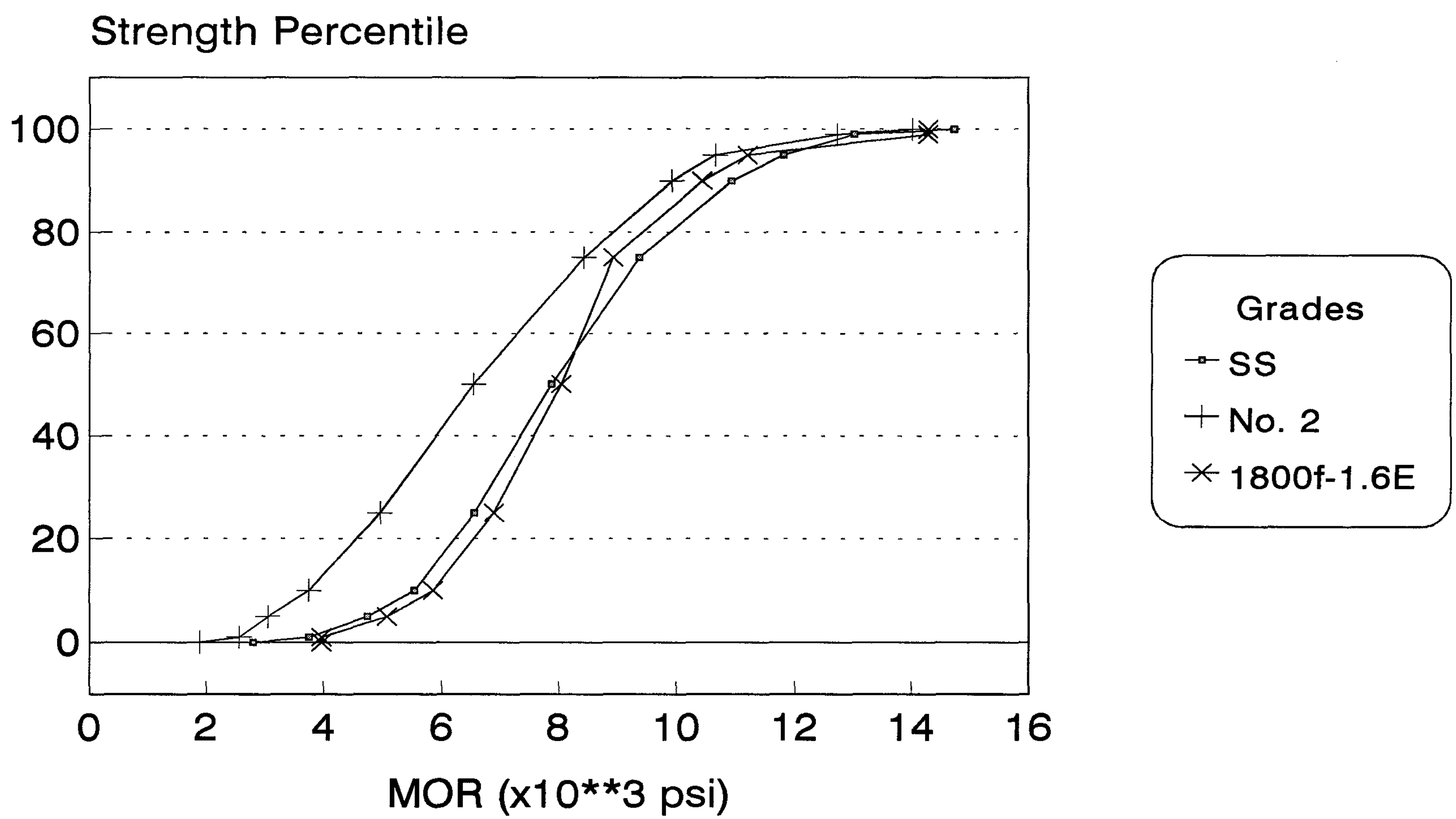


Figure 38. MOR Comparisons
S-P-F 2x4 Visual and MSR Grades

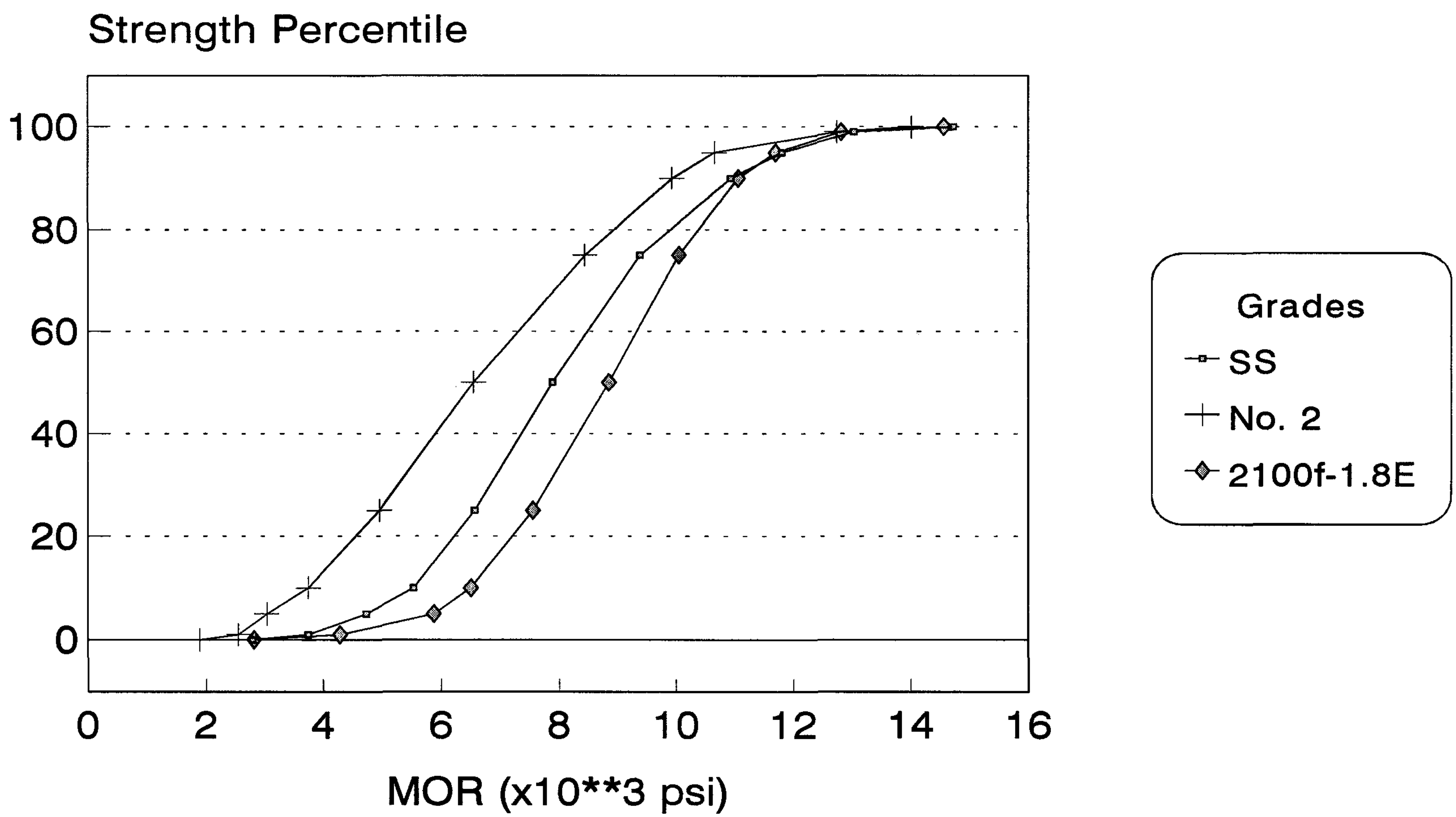


Figure 39. MOR Comparisons
S-P-F 2x4 Visual and MSR Grades

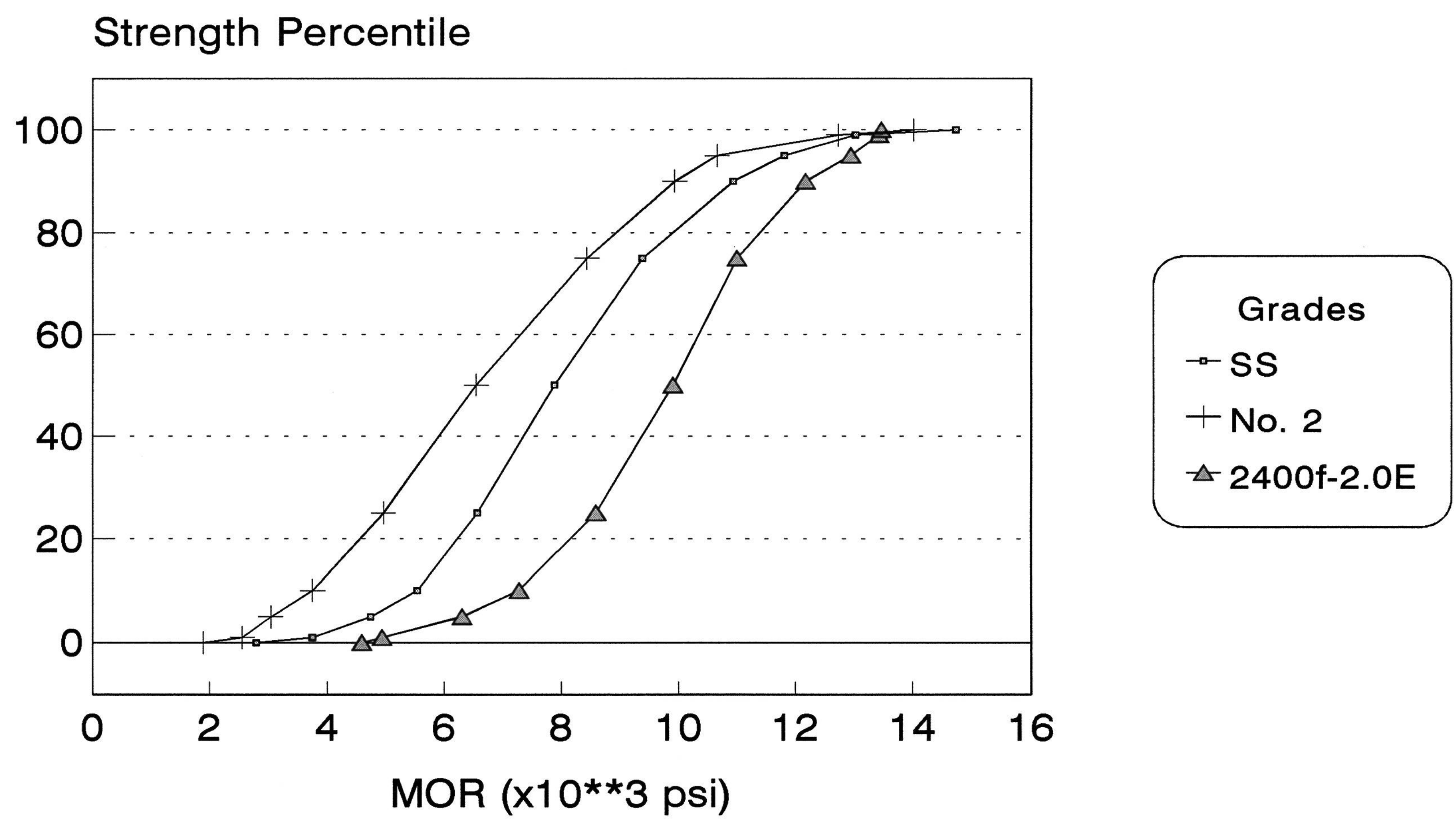


Figure 40. UTS Comparisons
S-P-F 2x4 MSR Grades

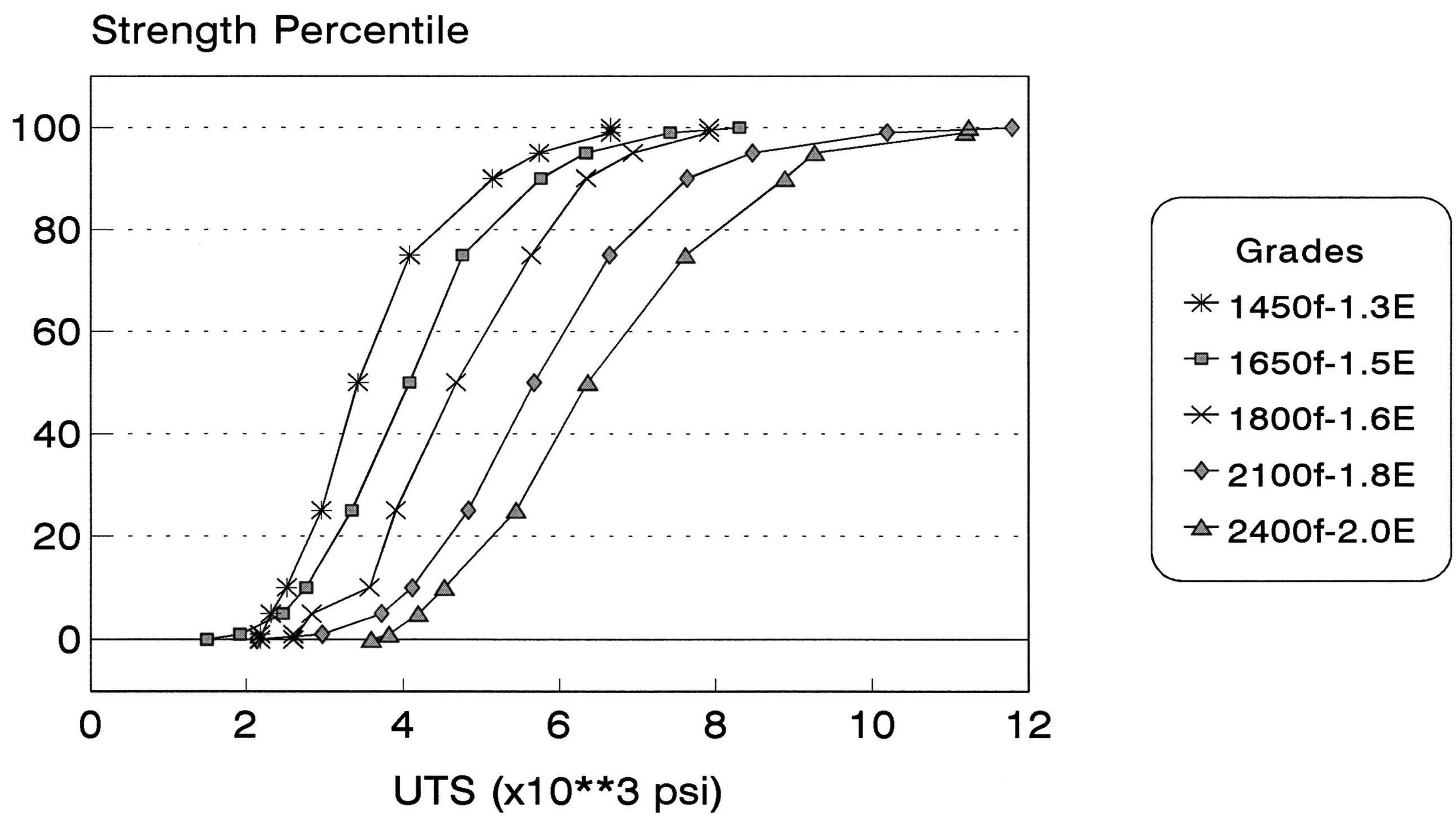


Figure 41. UTS Comparisons
S-P-F 2x4 Visual Grades

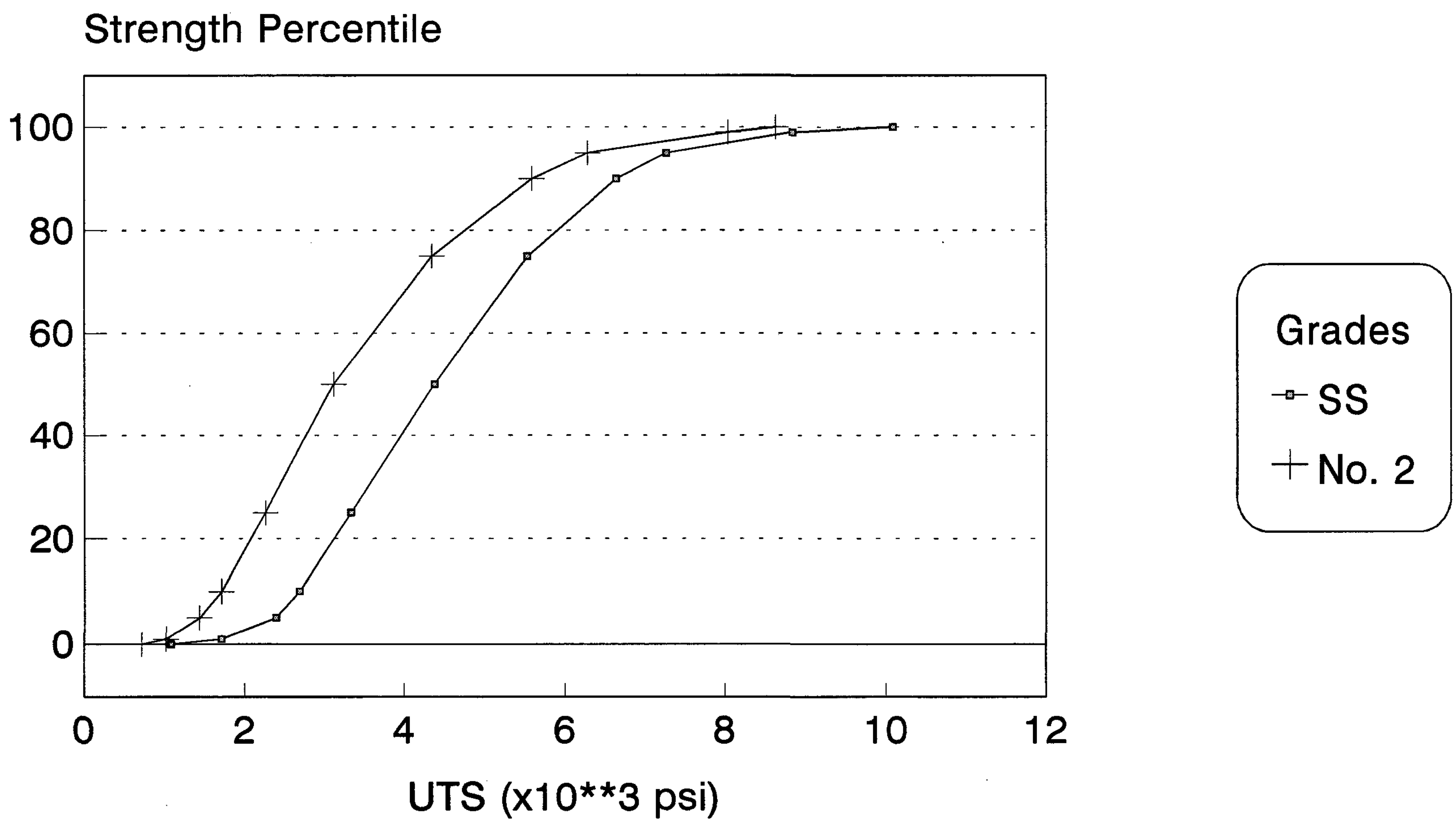


Figure 42. UTS Comparisons
S-P-F 2x4 Visual and MSR Grades

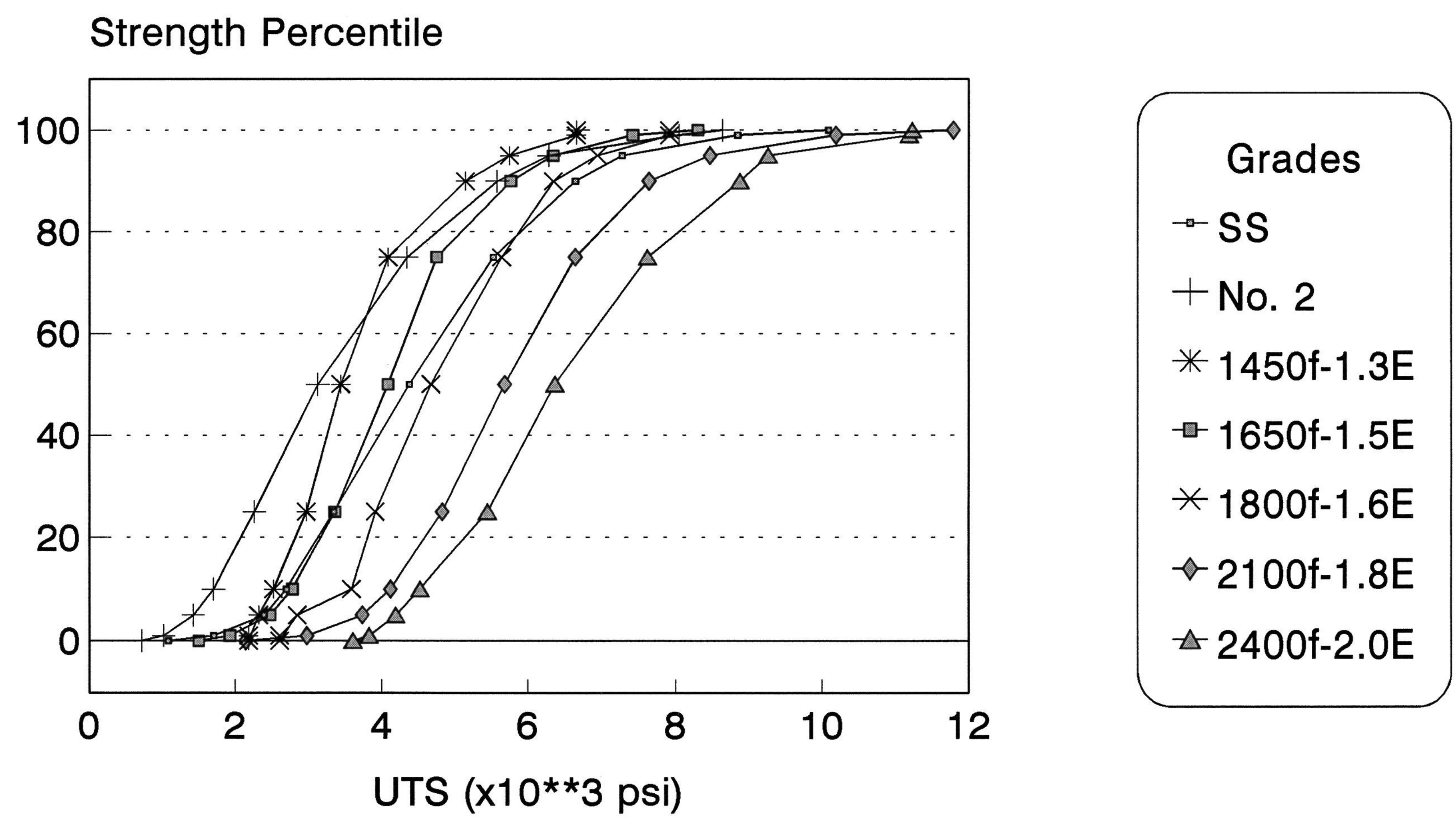
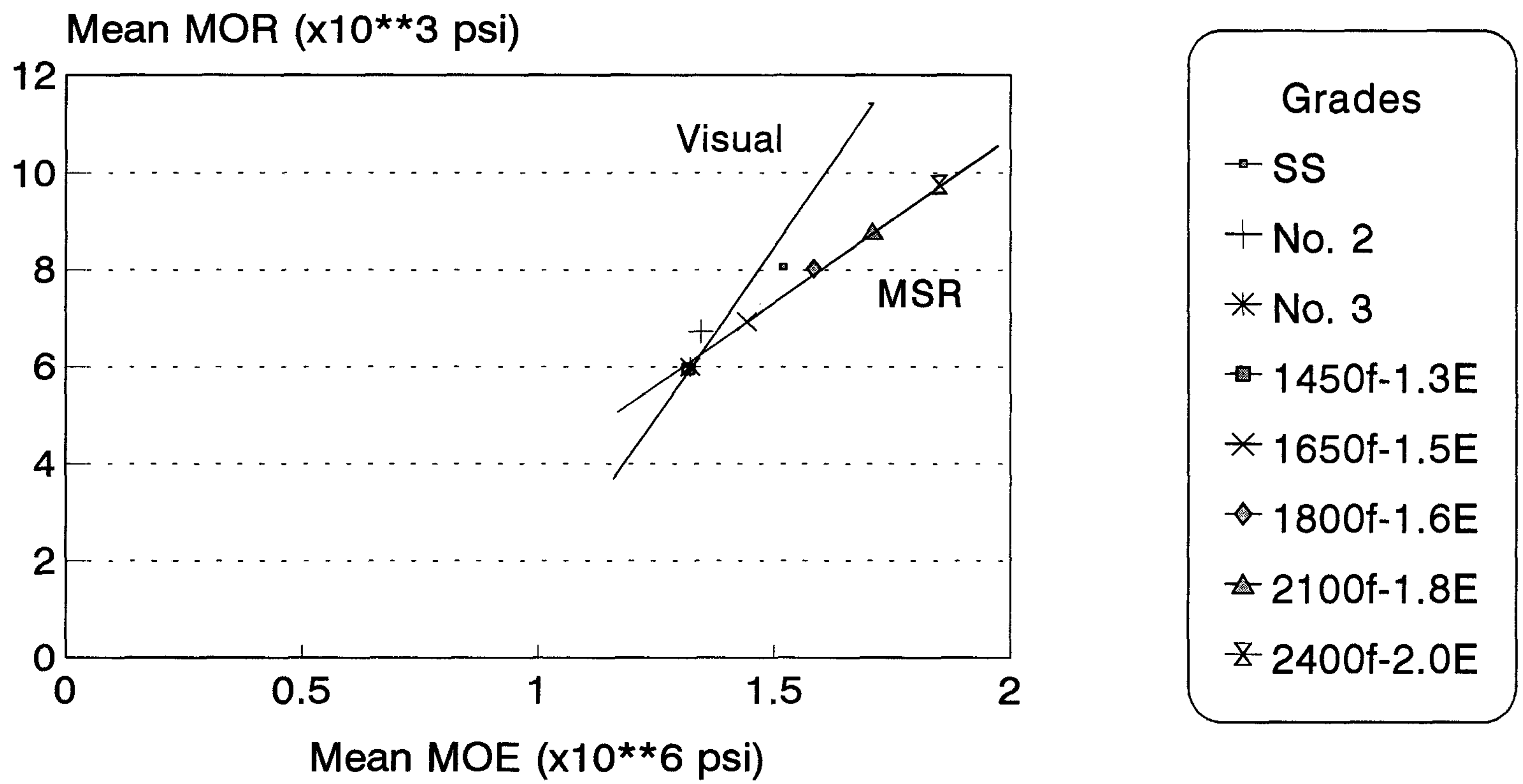
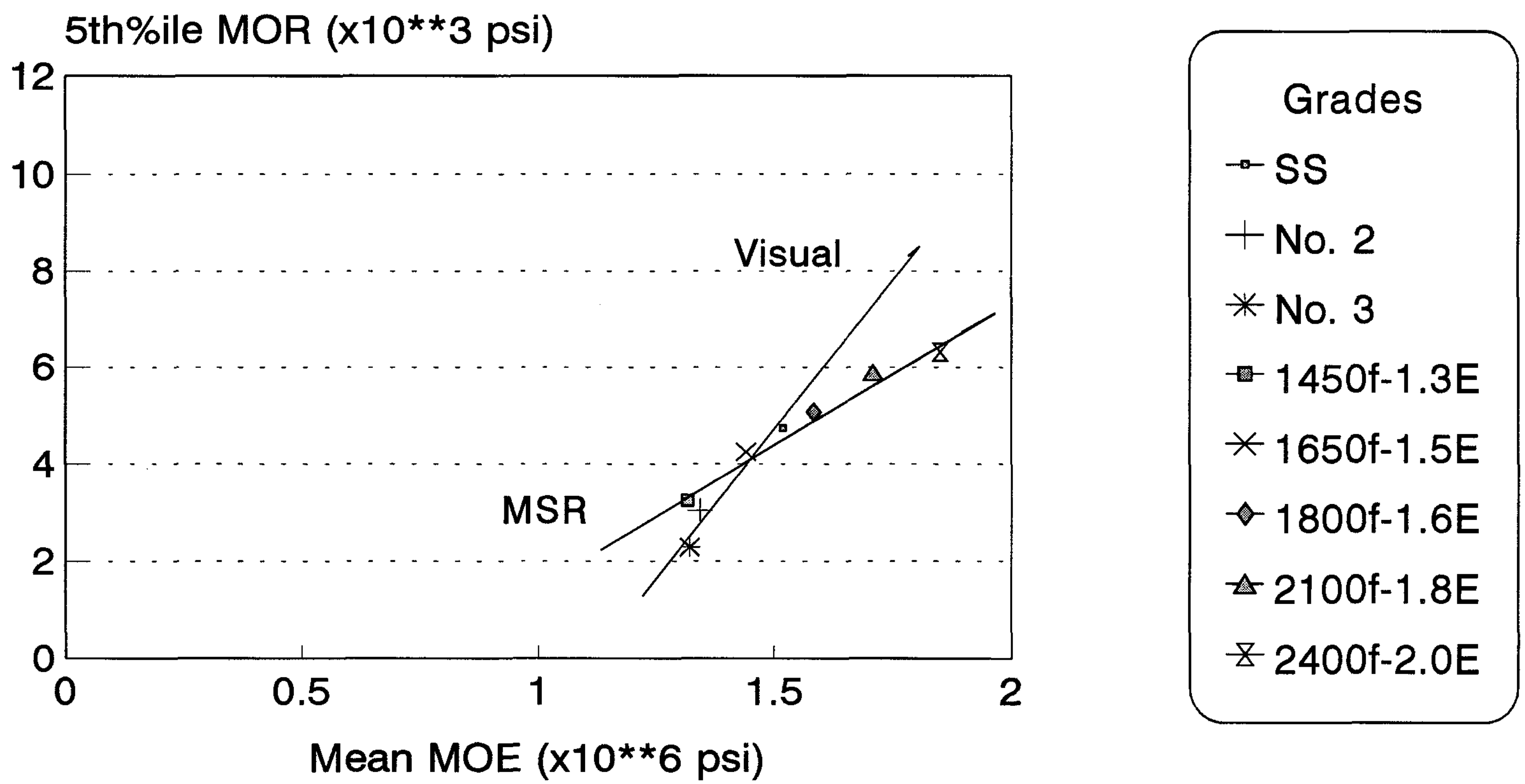


Figure 43. Mean MOR vs Mean MOE
S-P-F 2x4 Visual and MSR Grades



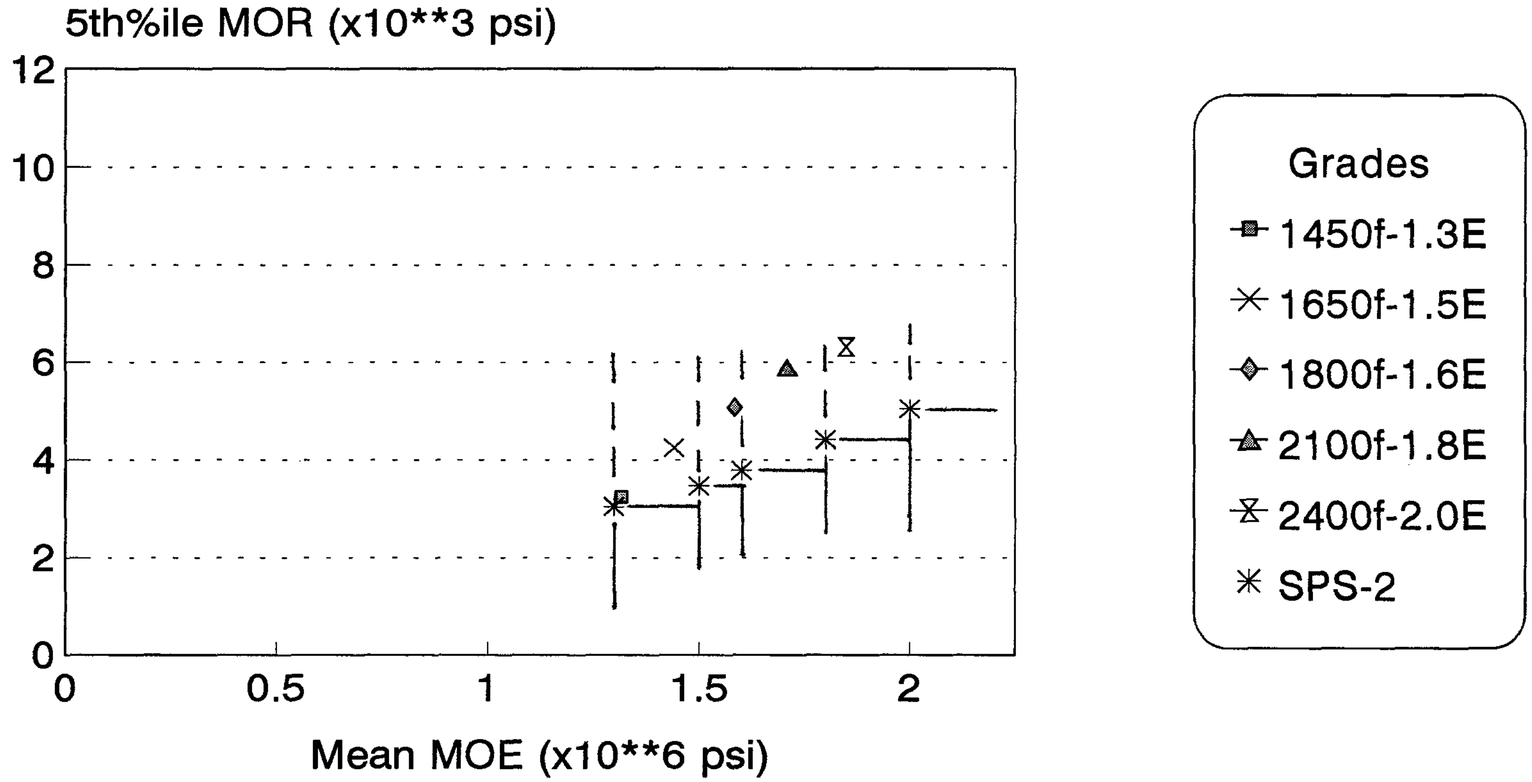
Based on 17:1 testing, machine deflection adjusted

Figure 44. 5th%ile MOR vs Mean MOE
S-P-F 2x4 Visual and MSR Grades



Based on 17:1 testing, machine deflection adjusted

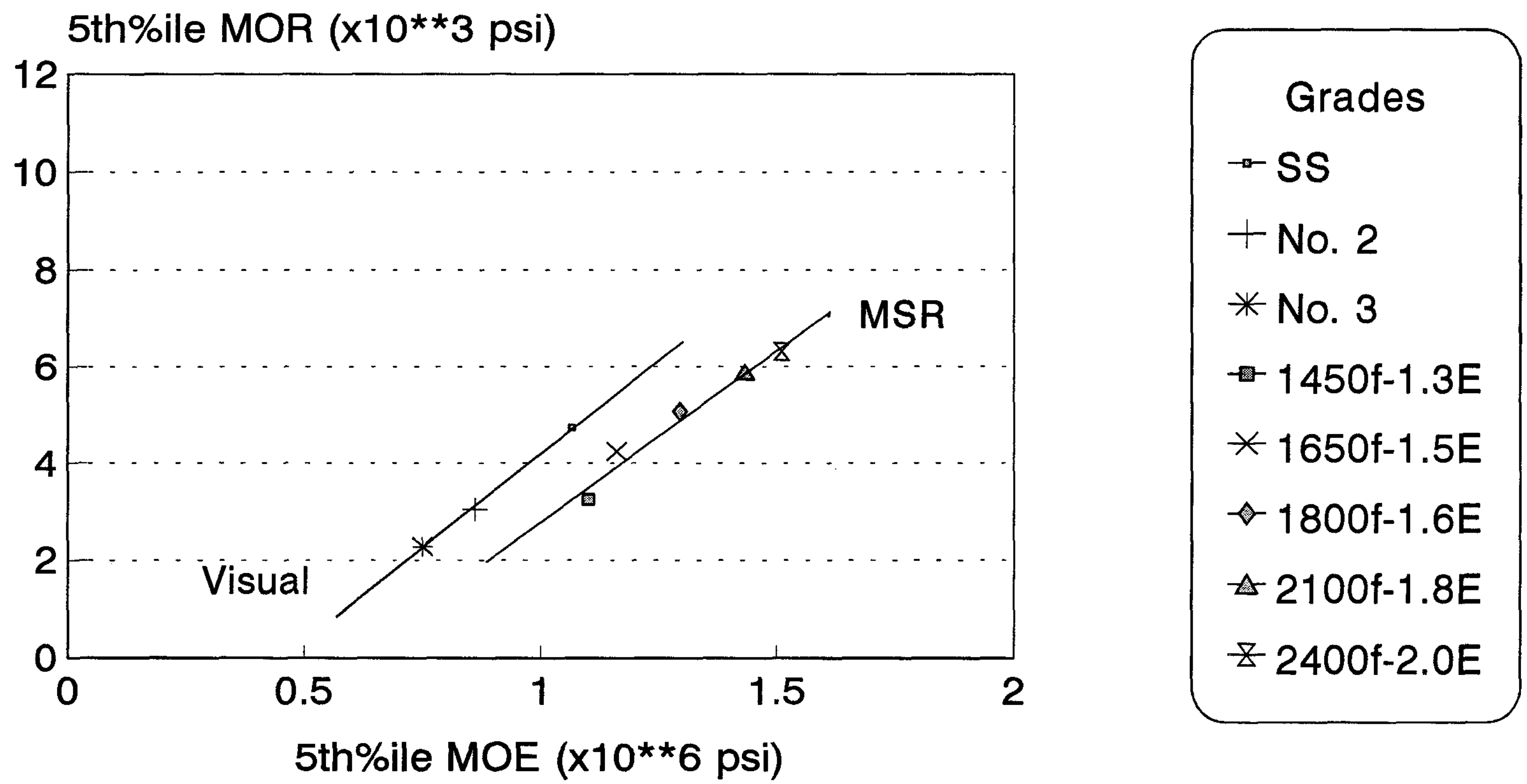
Figure 45. 5th%ile MOR vs Mean MOE
S-P-F 2x4 MSR Grades and SPS-2 Values



135

Based on 17:1 testing, machine deflection adjusted

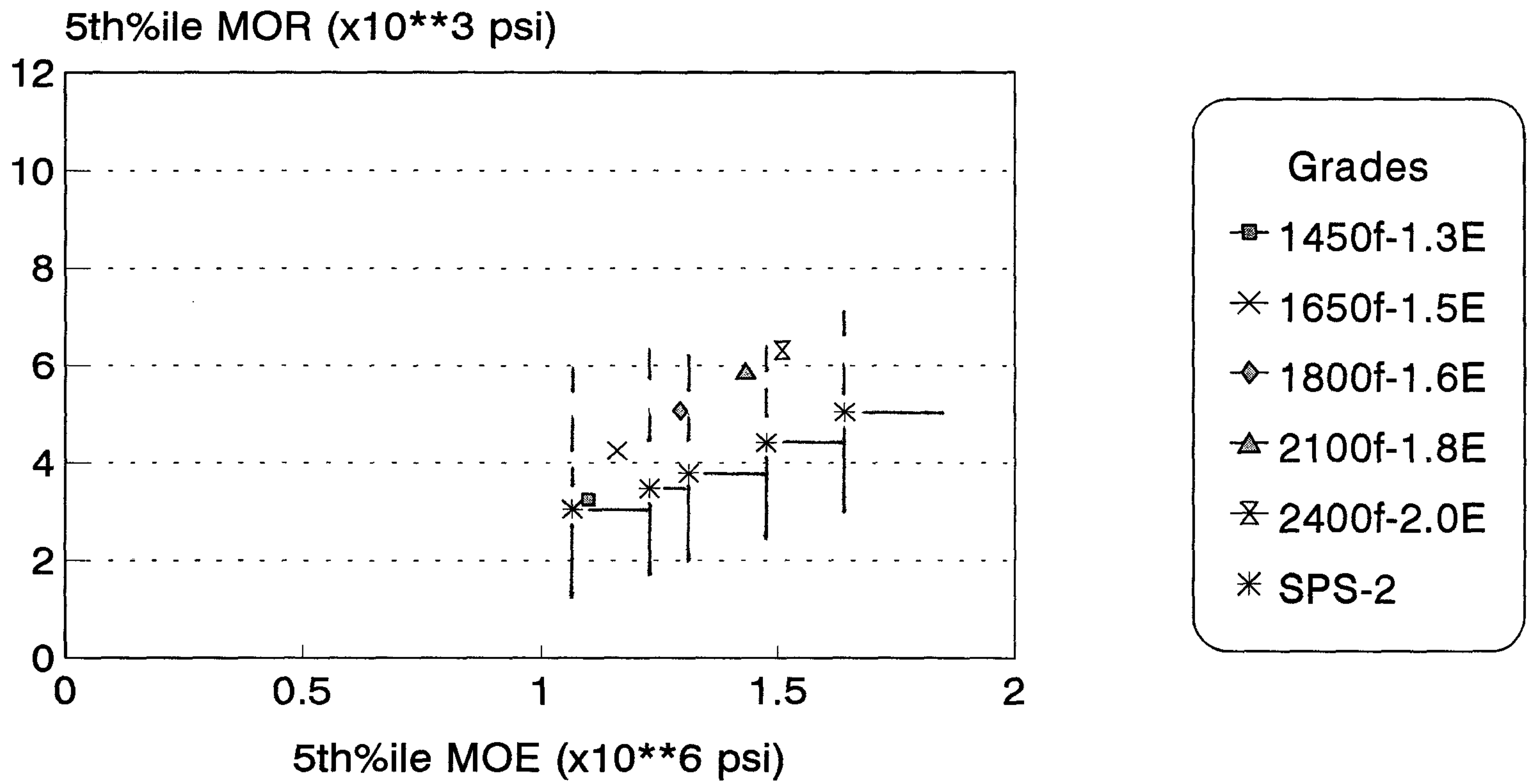
Figure 46. 5th%ile MOR vs 5th%ile MOE
S-P-F 2x4 Visual and MSR Grades



136

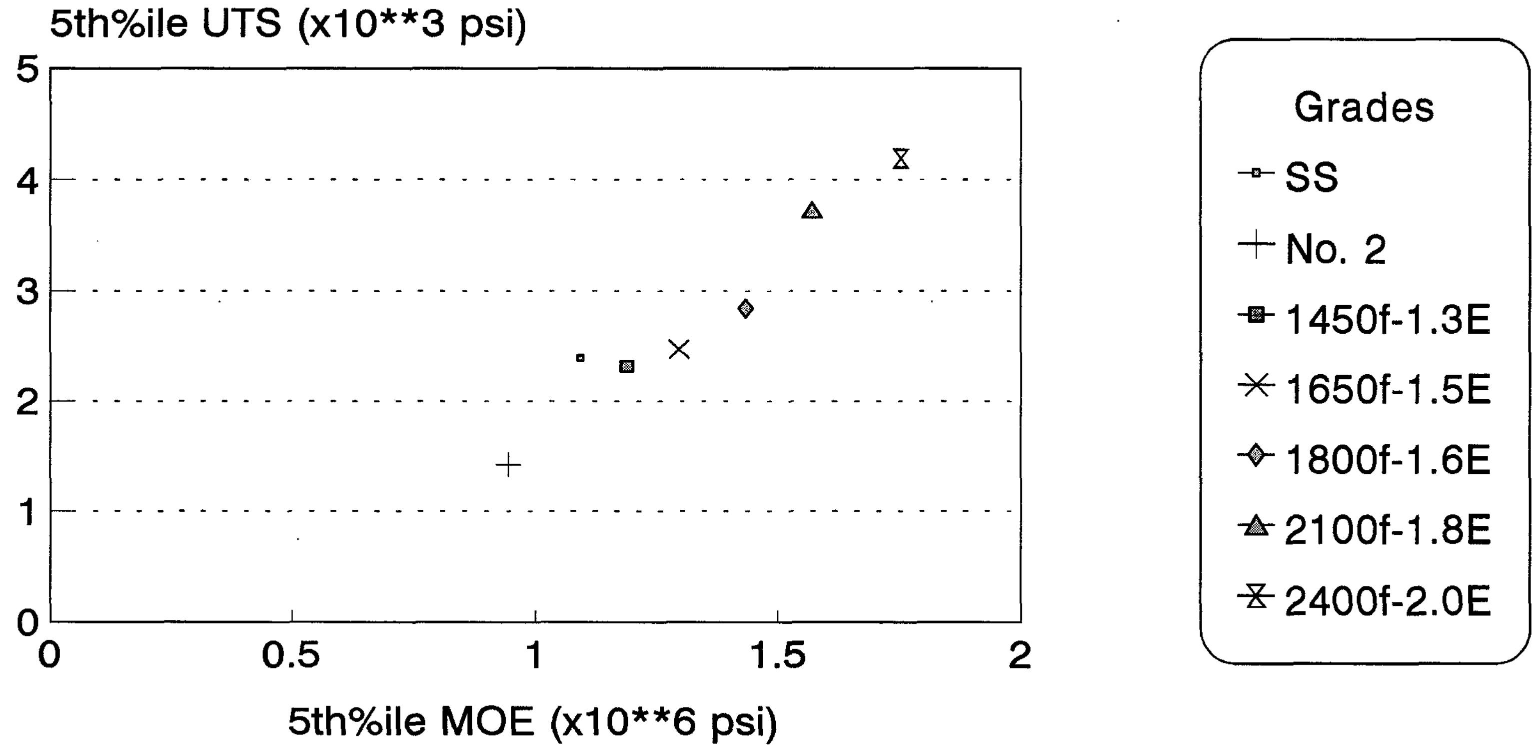
Based on 17:1 testing, machine deflection adjusted

Figure 47. 5th%ile MOR vs 5th%ile MOE
S-P-F 2x4 MSR Grades and SPS-2 Values



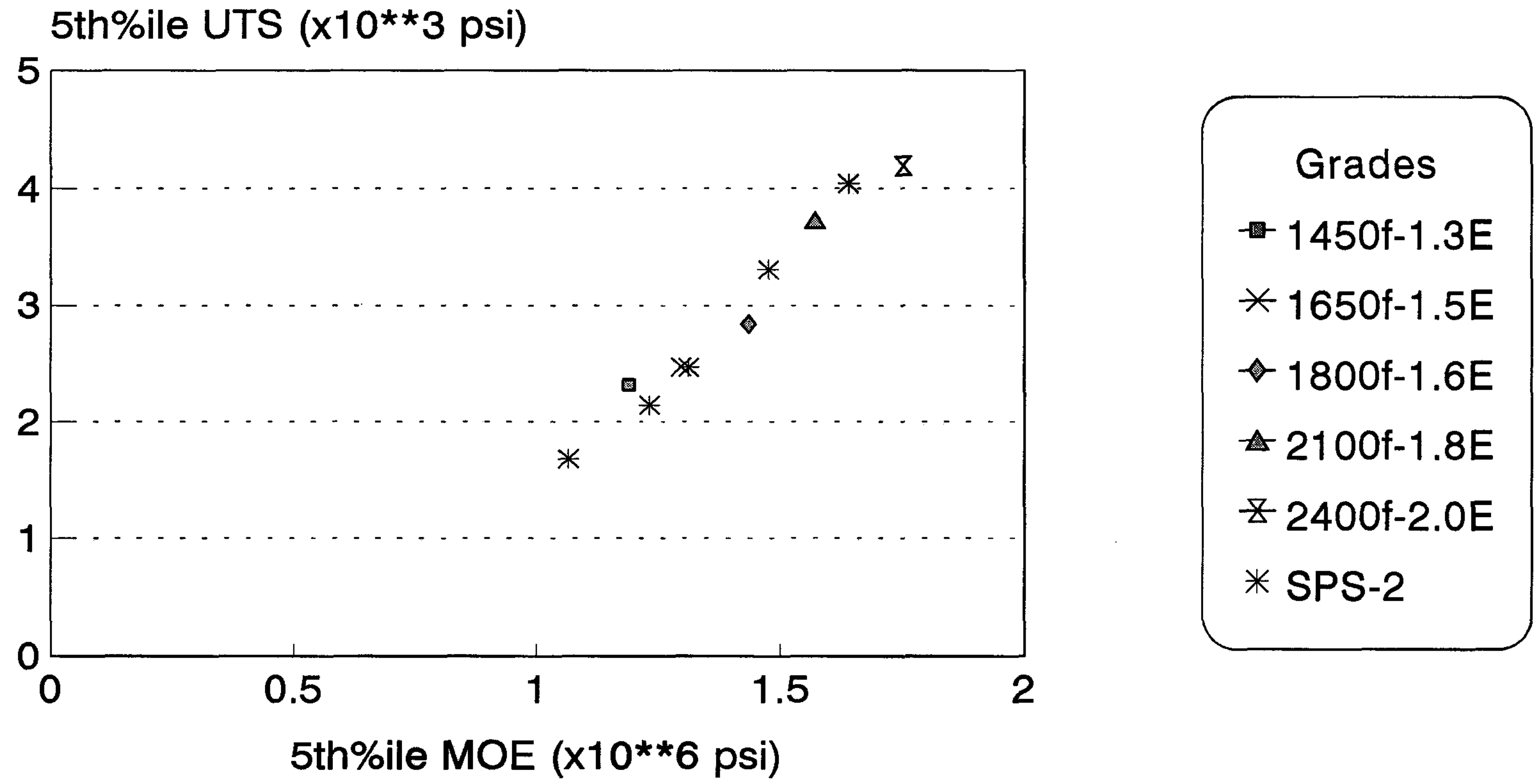
Based on 17:1 testing, machine deflection adjusted

Figure 48. 5th%ile UTS vs 5th%ile MOE
S-P-F 2x4 Visual and MSR Grades



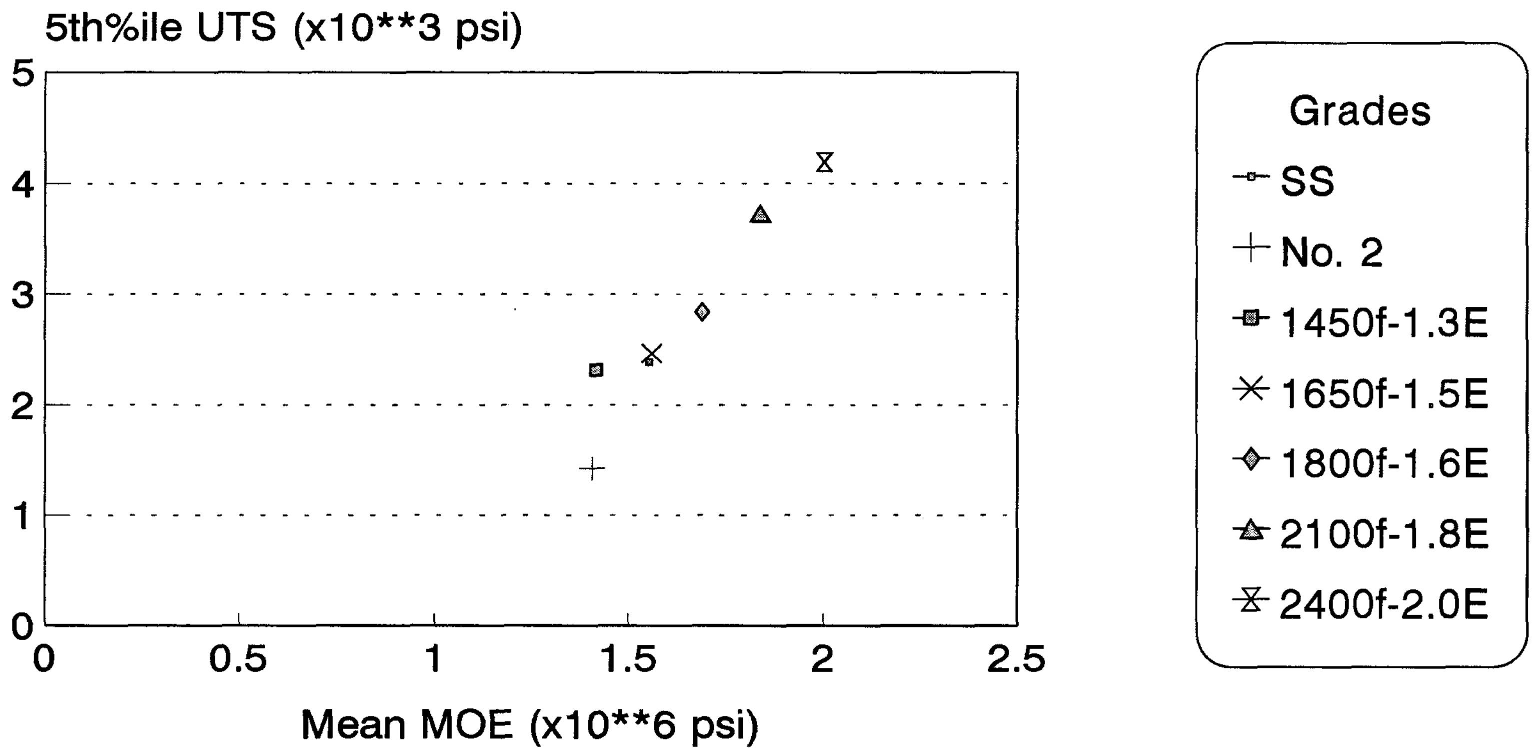
Visual based on 17:1 testing, MSR based on 21:1 Lab MOE's from Tension sample
All data machine deflection adjusted

Figure 49. 5th%ile UTS vs 5th%ile MOE
S-P-F 2x4 MSR Grades and SPS-2 Values



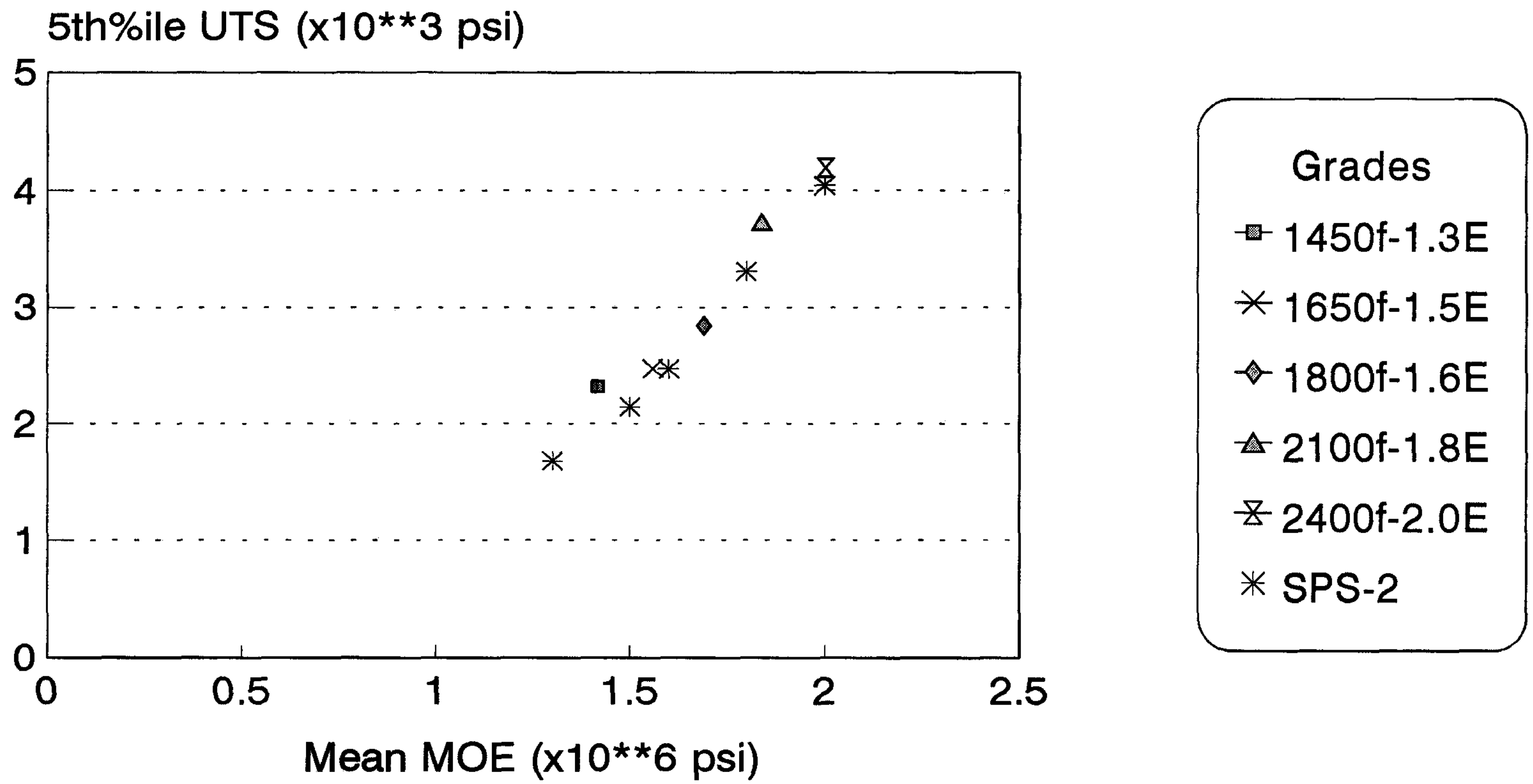
MSR based on 21:1 Lab MOE's from Tension sample - machine deflection adjusted

Figure 50. 5th%ile UTS vs Mean MOE
S-P-F 2x4 Visual and MSR Grades



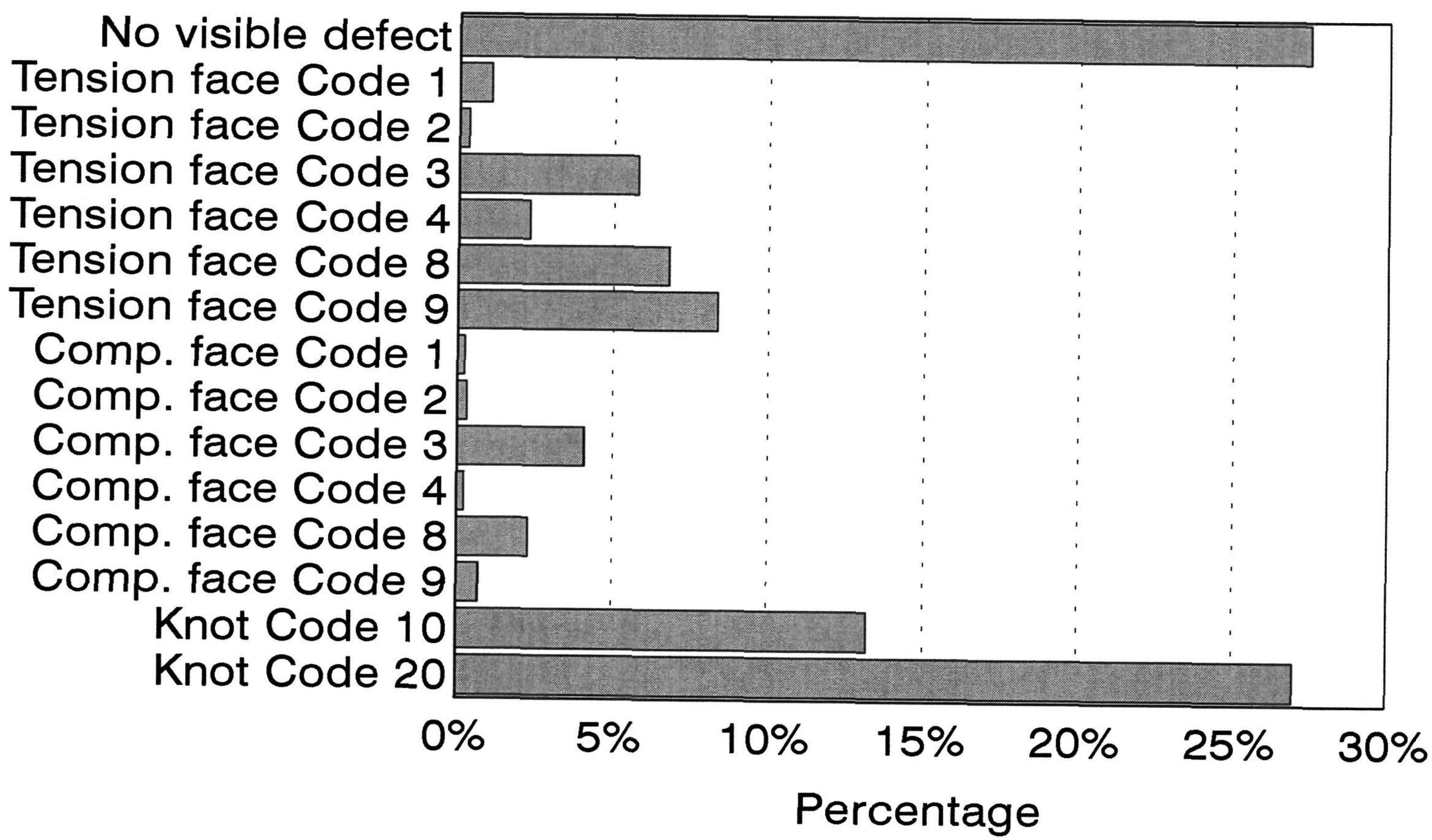
Visual based on 17:1 testing, MSR based on 21:1 Lab MOE's from Tension sample
All data machine deflection adjusted

Figure 51. 5th%ile UTS vs Mean MOE
S-P-F 2x4 MSR Grades and SPS-2 Values



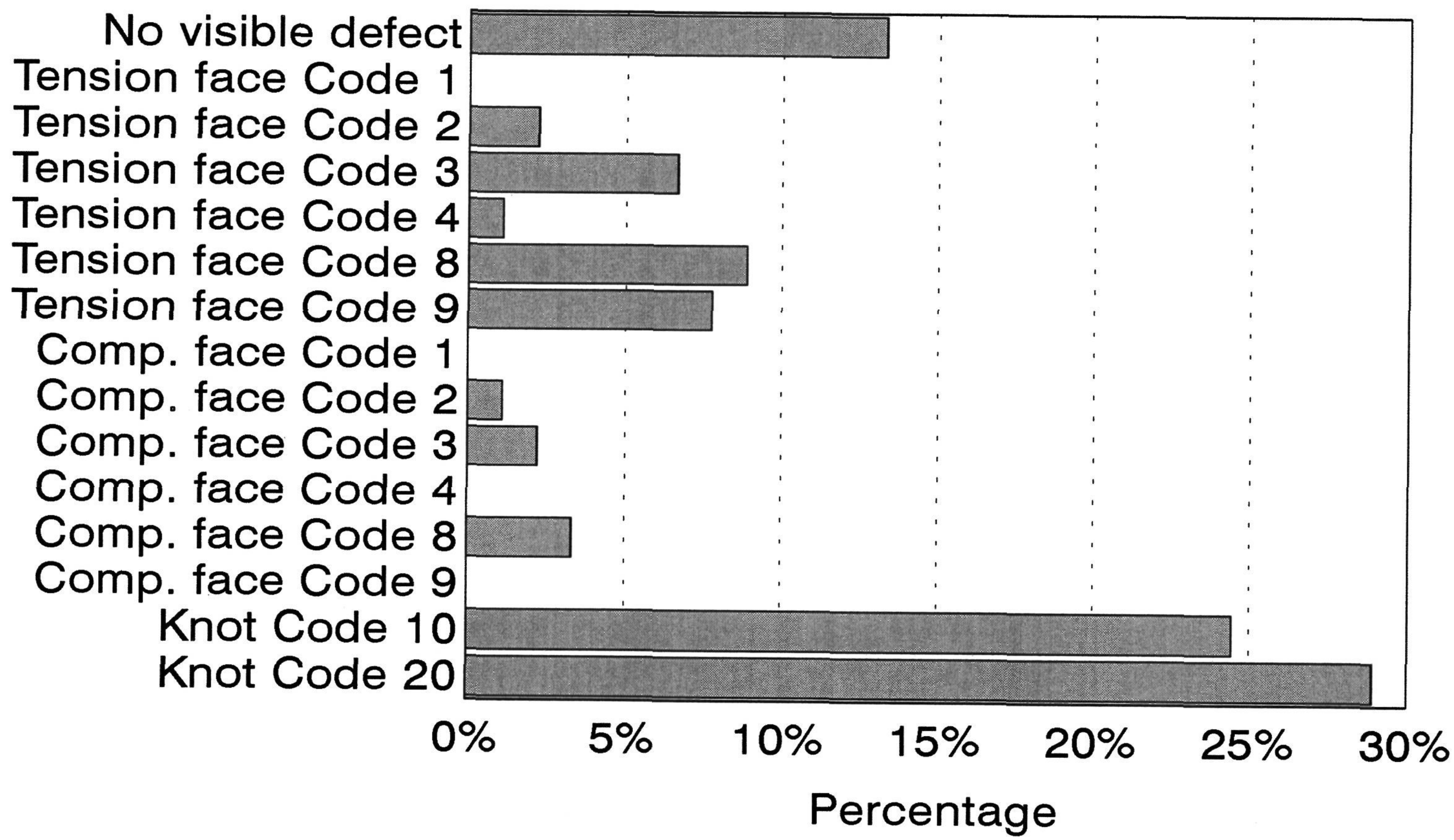
MSR based on 21:1 Lab MOE's from Tension sample - machine deflection adjusted

Figure 52. MSR Lumber In-grade Program
Bending Failure By Forintek Failure Code



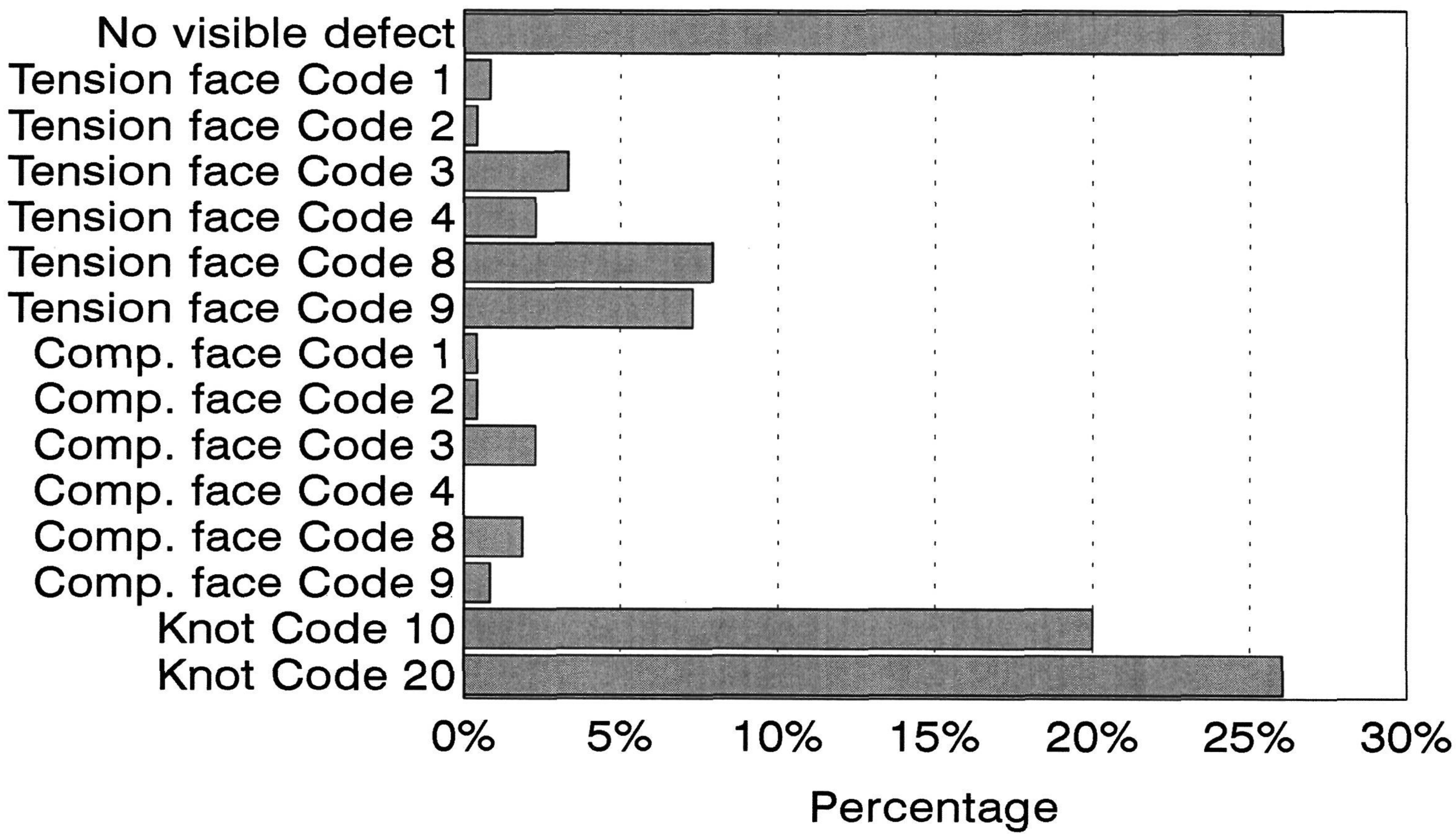
S-P-F All MSR grades together - 1279 pieces

Figure 53. MSR Lumber In-grade Program
Bending Failure By Forintek Failure Code



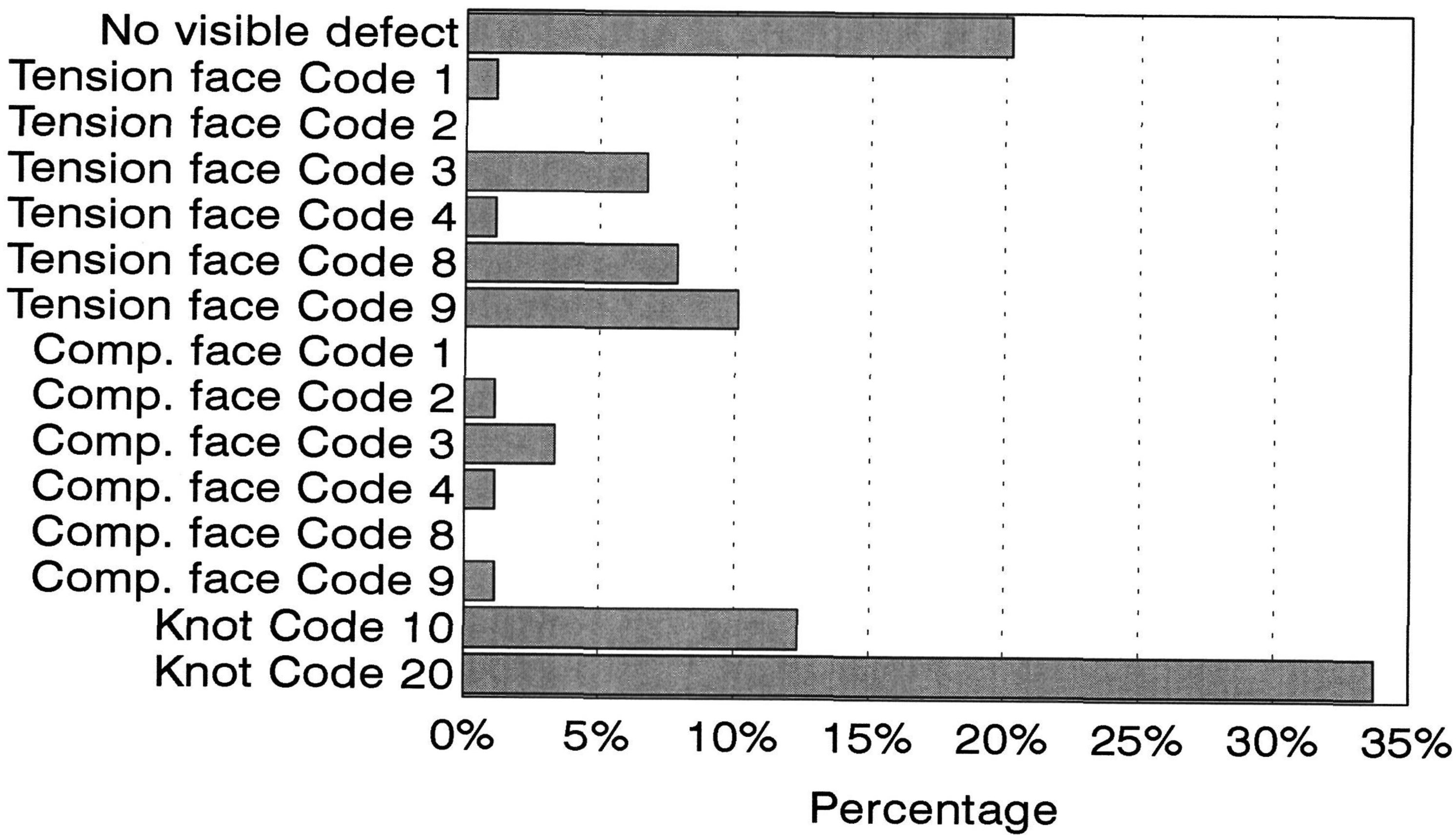
S-P-F 1450f-1.3E grade - 90 pieces

Figure 54. MSR Lumber In-grade Program
Bending Failure By Forintek Failure Code



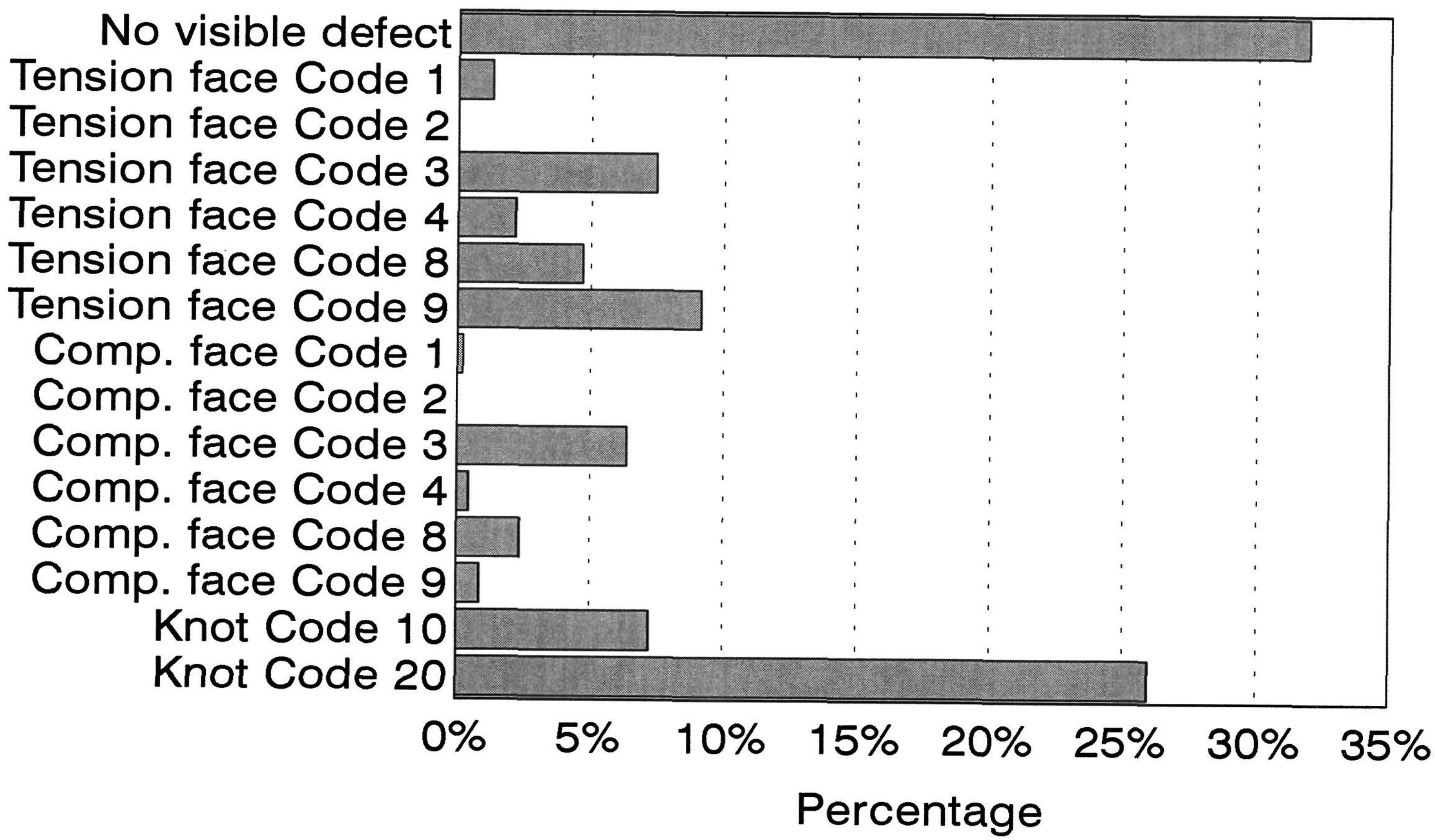
S-P-F 1650f-1.5E grade - 480 pieces

Figure 55. MSR Lumber In-grade Program
Bending Failure By Forintek Failure Code



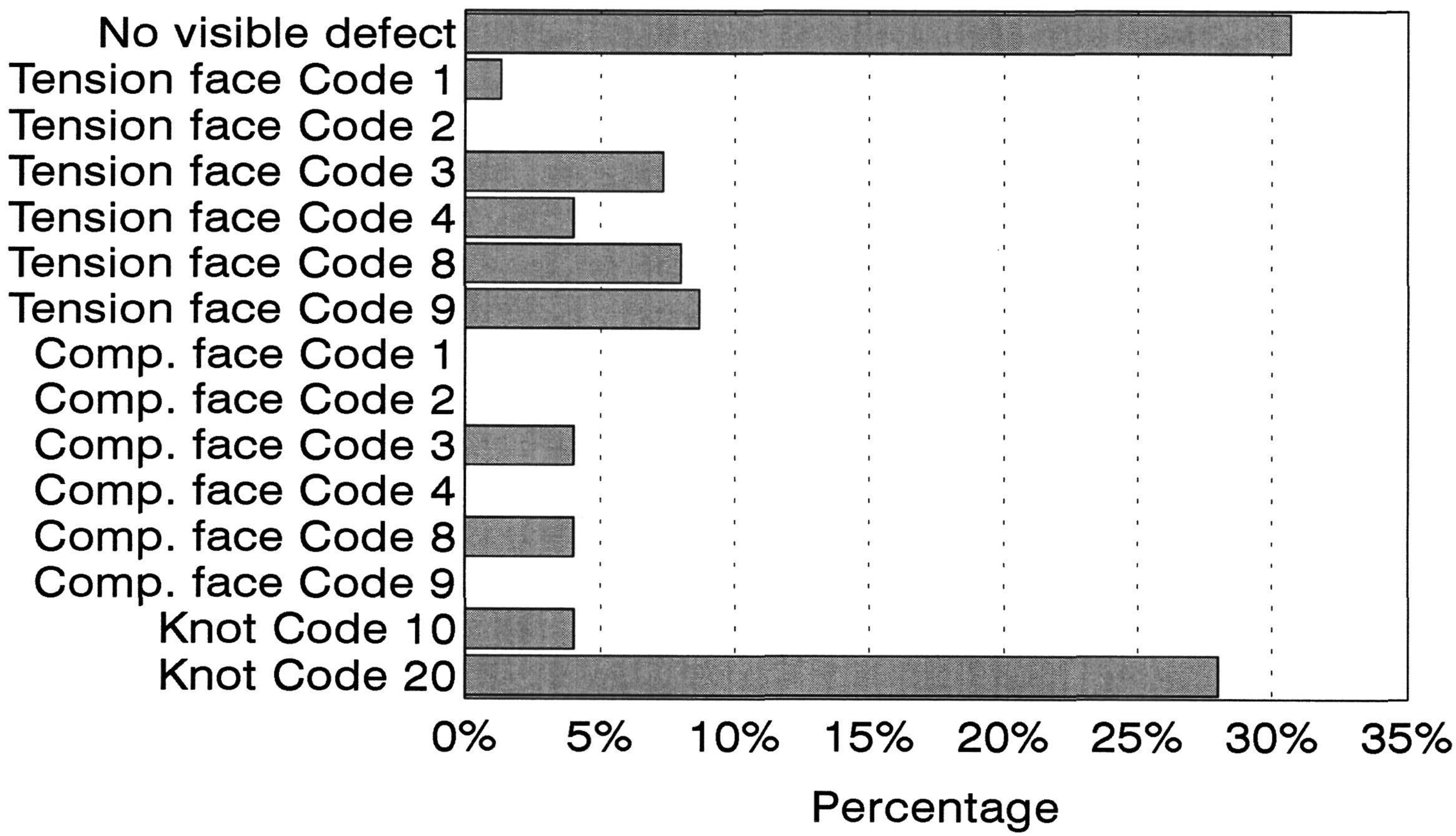
S-P-F 1800f-1.6E grade - 89 pieces

Figure 56. MSR Lumber In-grade Program
Bending Failure By Forintek Failure Code



S-P-F 2100f-1.8E grade - 470 pieces

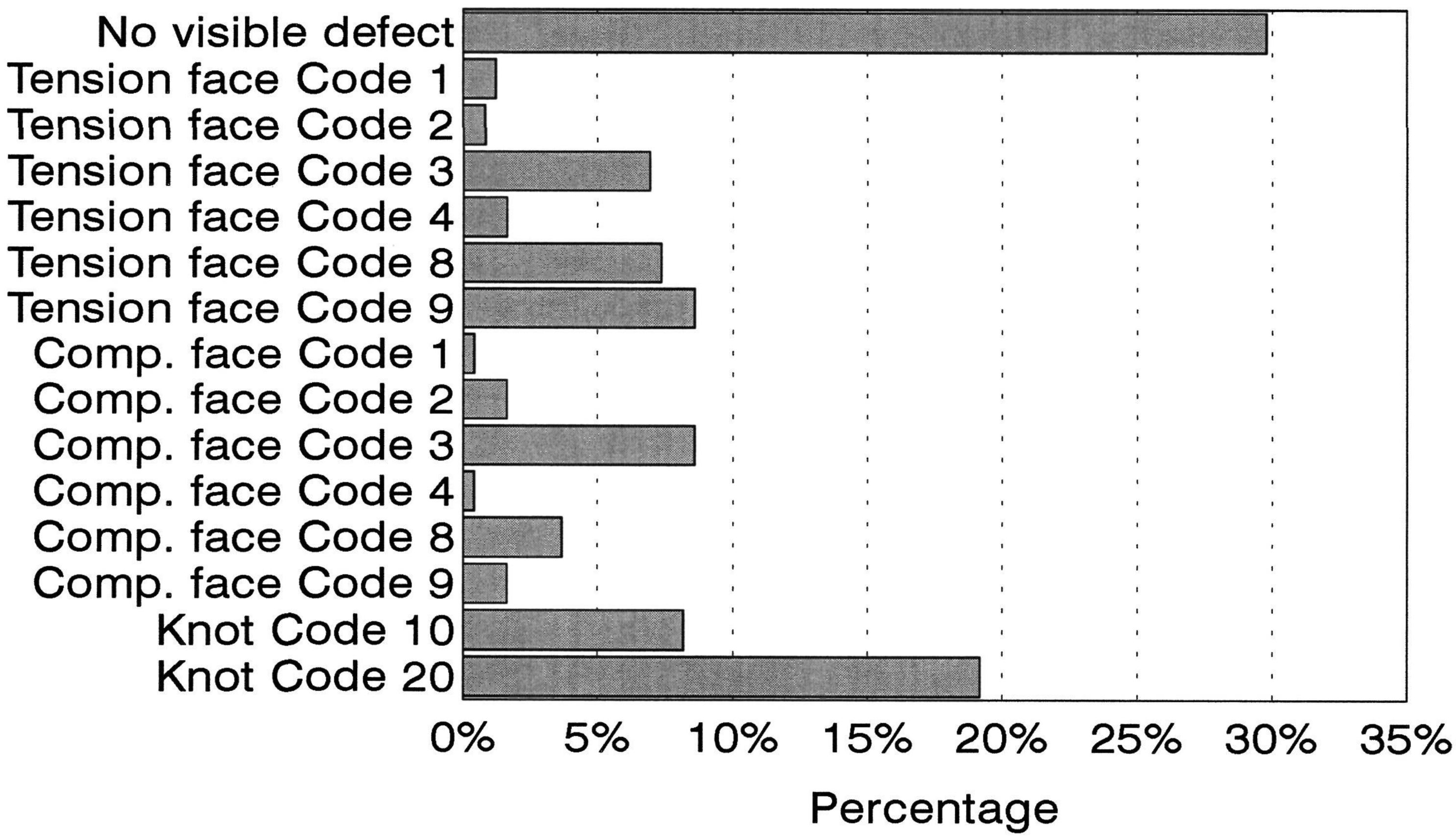
Figure 57. MSR Lumber In-grade Program
Bending Failure By Forintek Failure Code



S-P-F 2400f-2.0E grade - 150 pieces

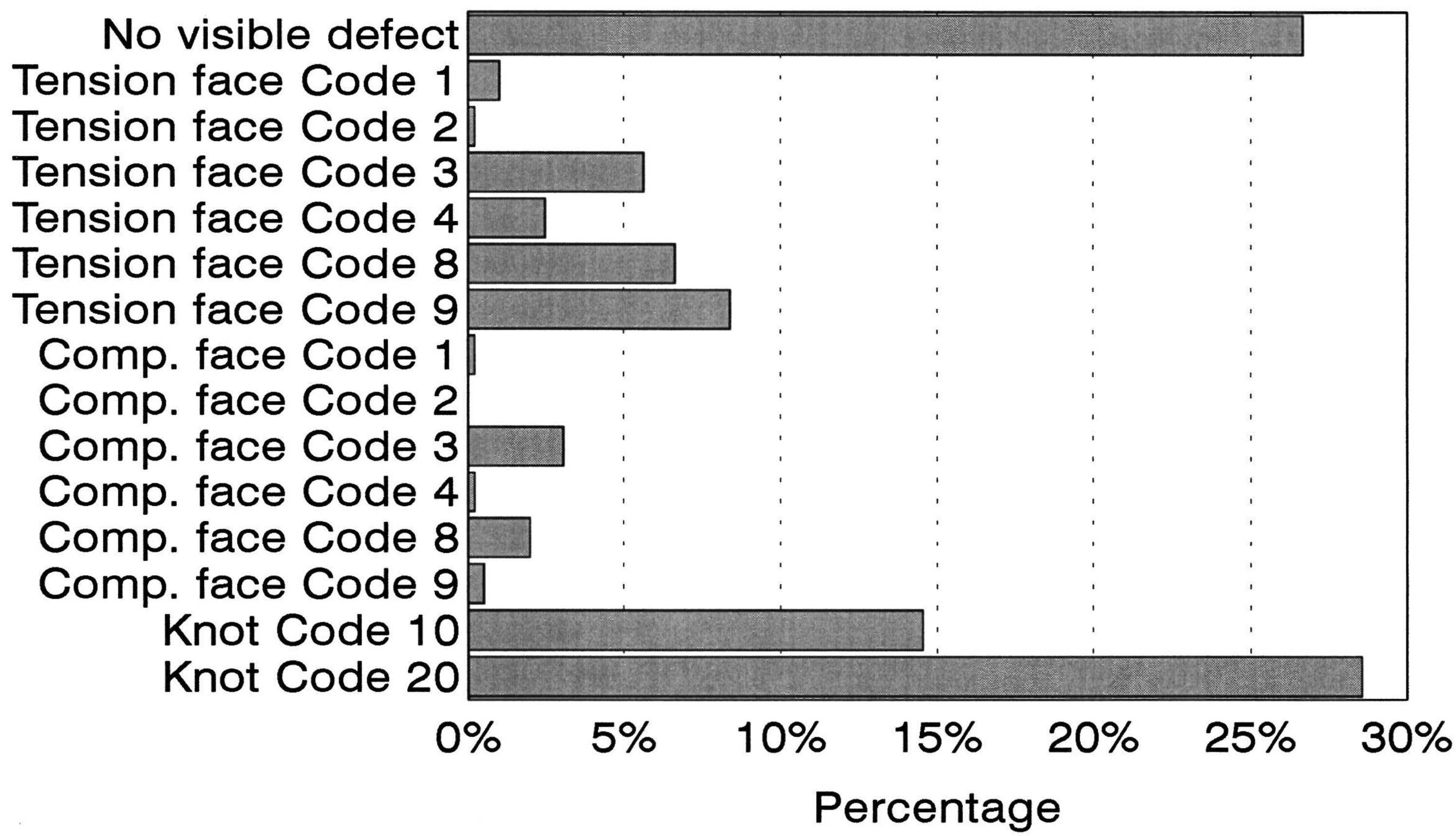
Figure 58. MSR Lumber In-grade Program

Bending Failure By Forintek Failure Code



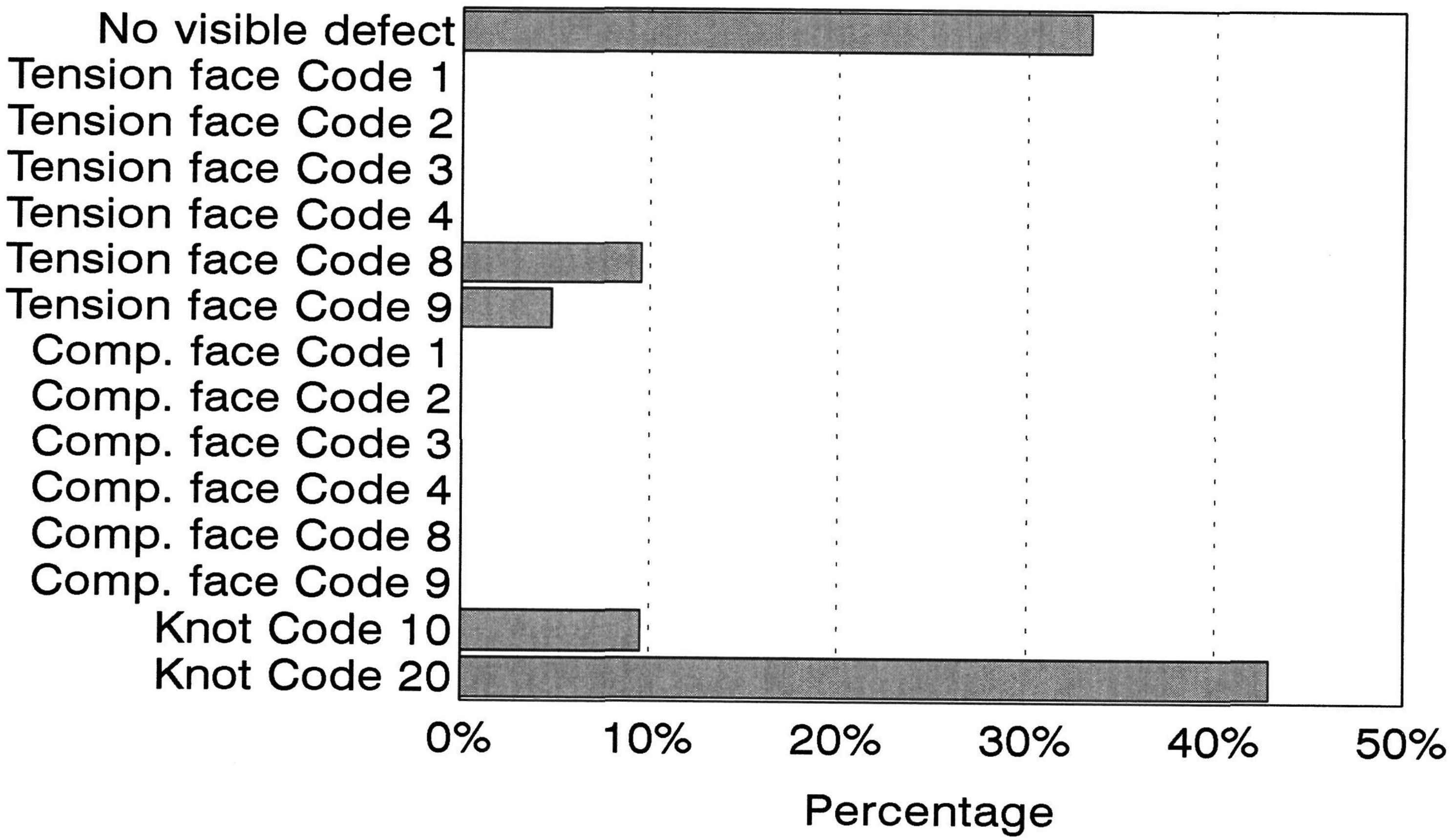
Spruce All MSR grades together - 245 pieces

Figure 59. MSR Lumber In-grade Program
Bending Failure By Forintek Failure Code



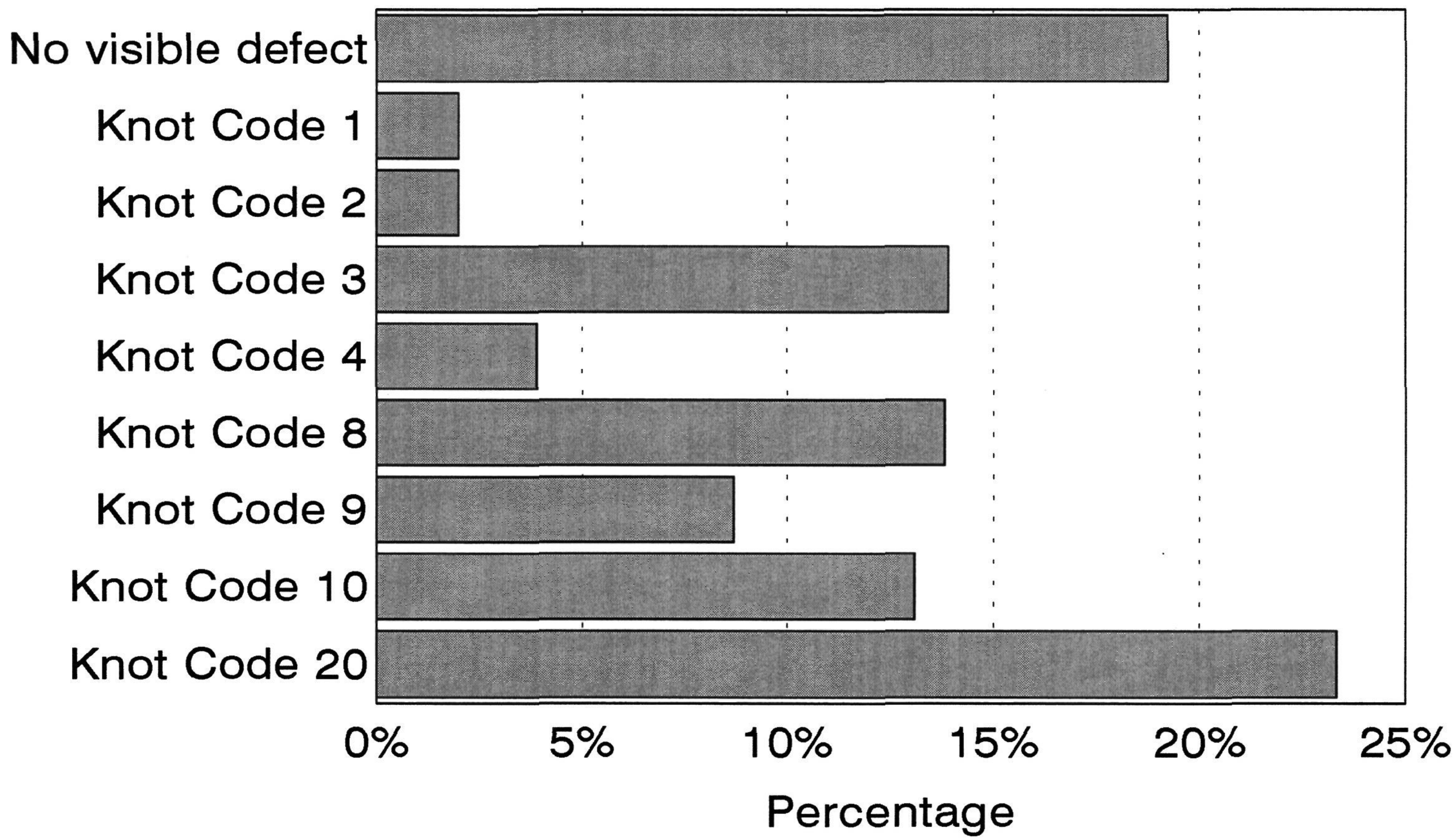
Pine All MSR grades together - 1012 pieces

Figure 60. MSR Lumber In-grade Program
Bending Failure By Forintek Failure Code



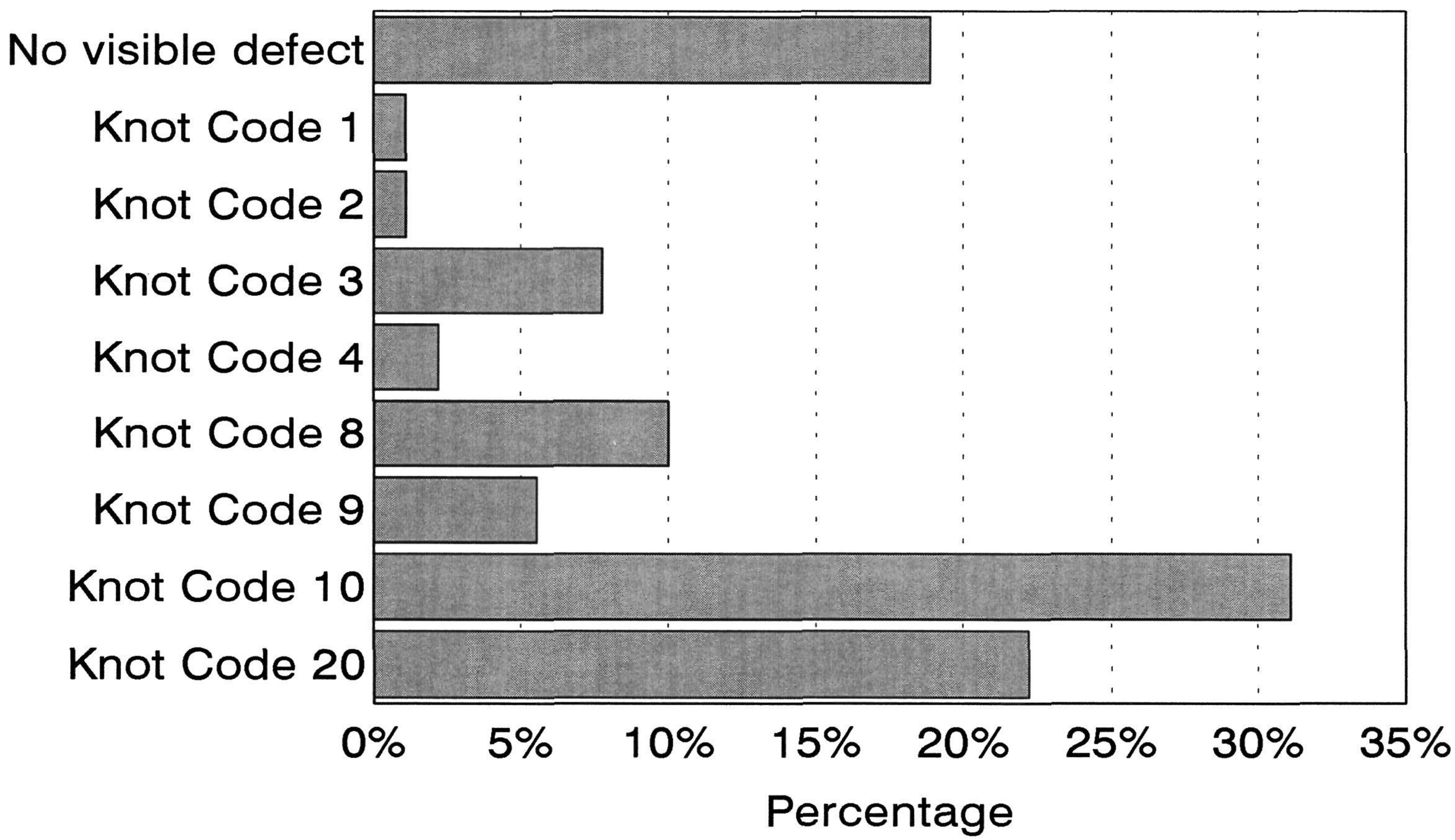
Fir All MSR grades together - 21 pieces

Figure 61. MSR Lumber In-grade Program
Tension Failure By Forintek Failure Code



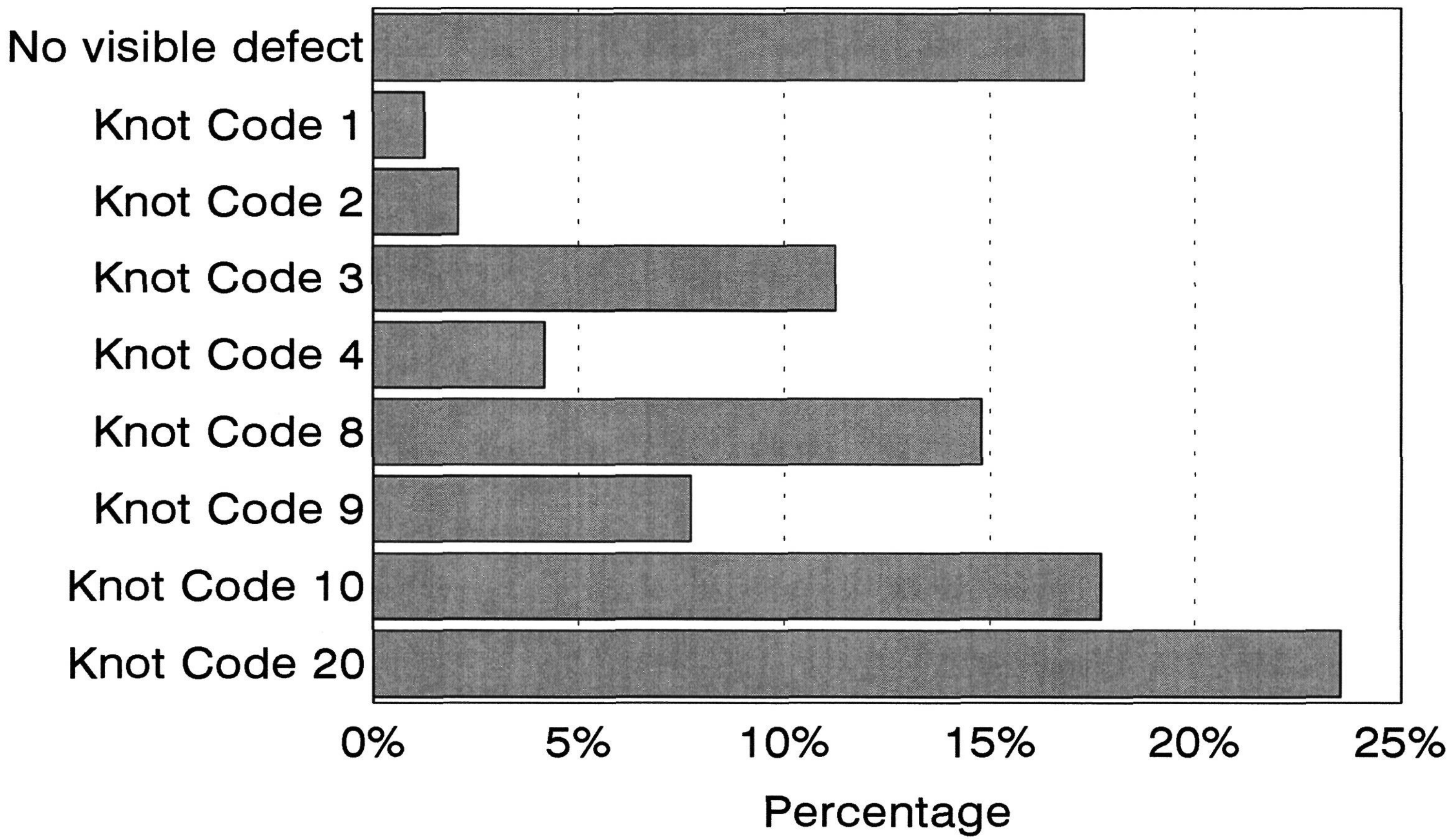
S-P-F All MSR grades together - 1300 pieces

Figure 62. MSR Lumber In-grade Program
Tension Failure By Forintek Failure Code



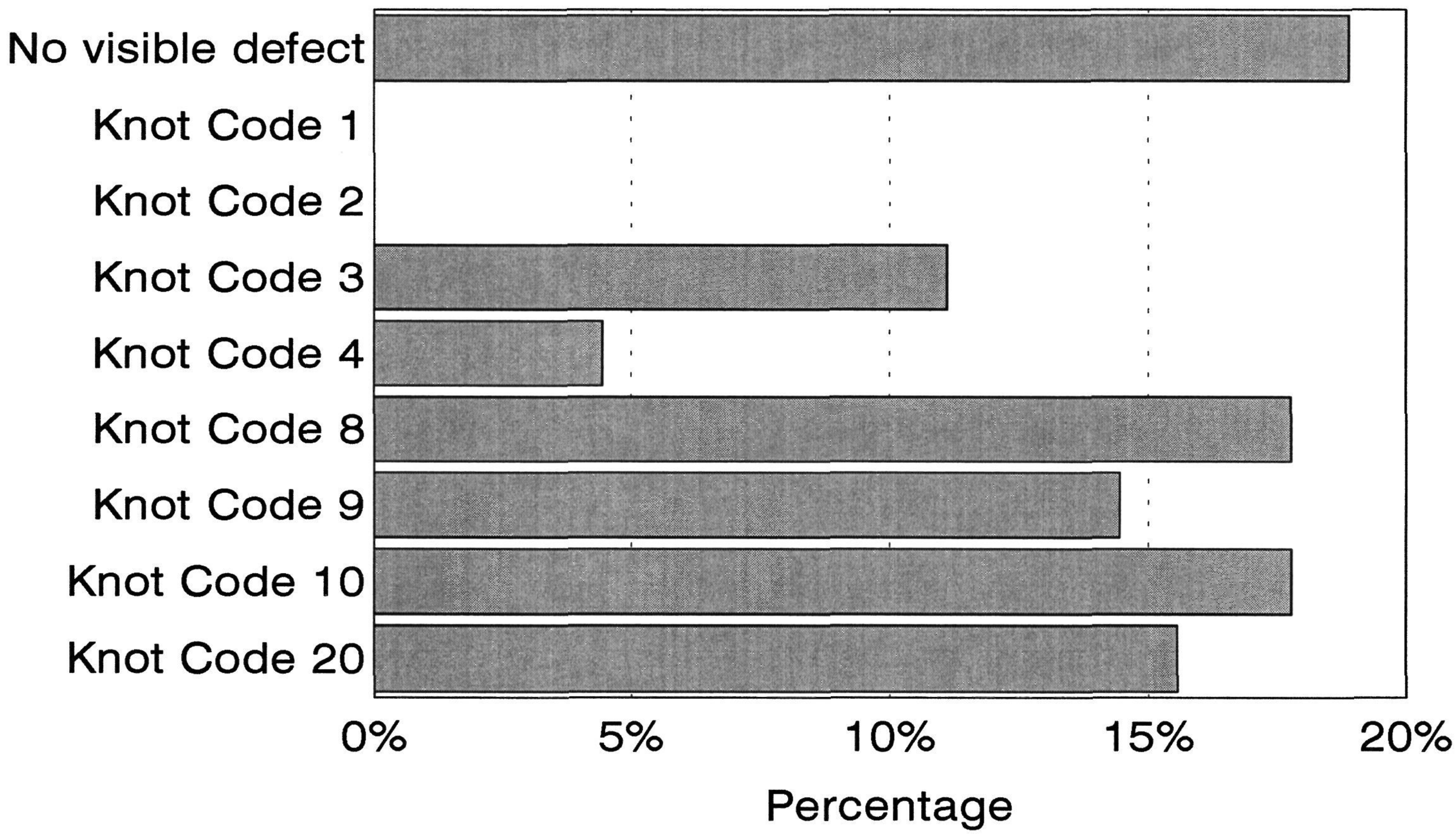
S-P-F 1450f-1.3E grade - 90 pieces

Figure 63. MSR Lumber In-grade Program
Tension Failure By Forintek Failure Code



S-P-F 1650f-1.5E grade - 480 pieces

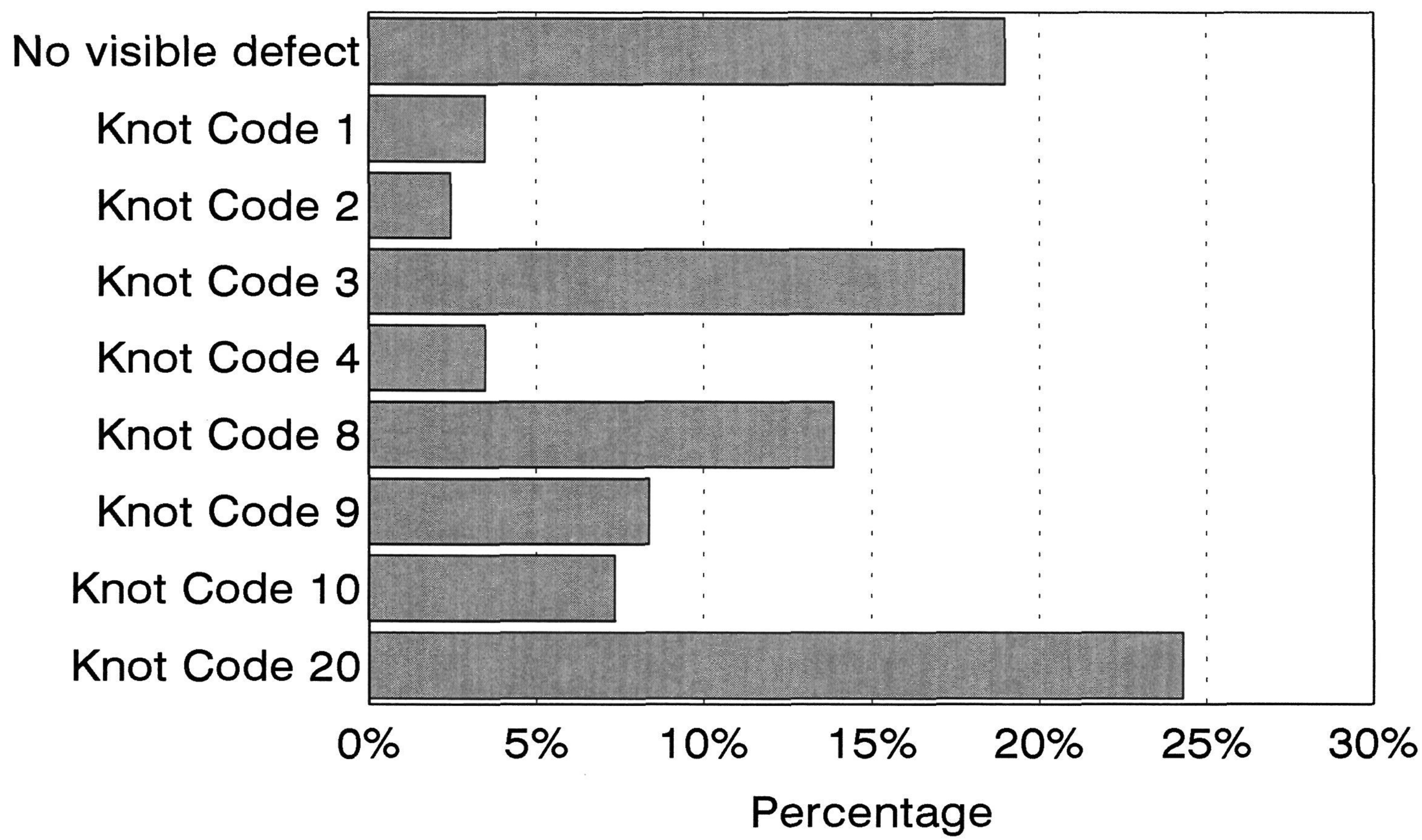
Figure 64. MSR Lumber In-grade Program
Tension Failure By Forintek Failure Code



S-P-F 1800f-1.6E grade - 90 pieces

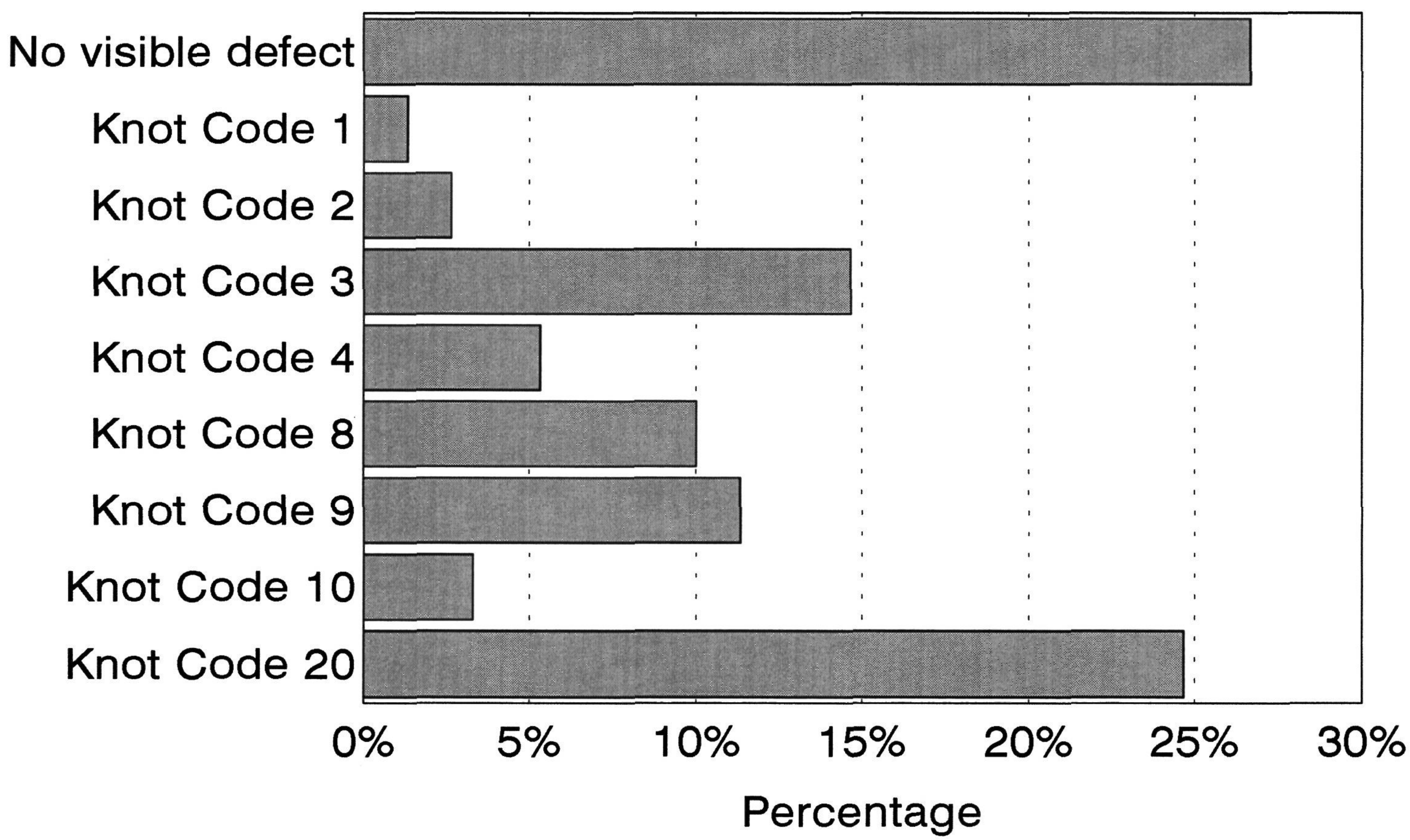
154

Figure 65. MSR Lumber In-grade Program
Tension Failure By Forintek Failure Code



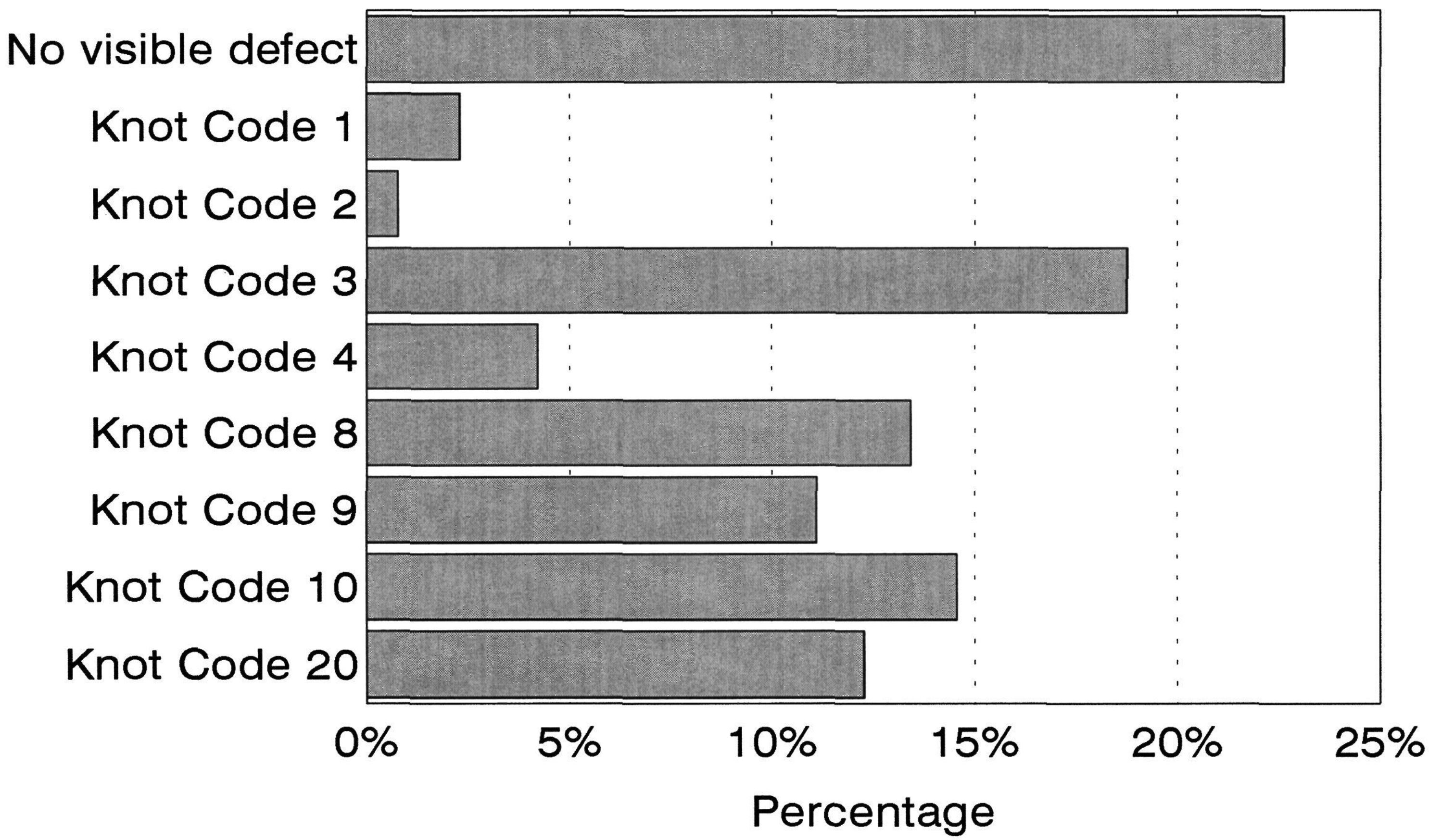
S-P-F 2100f-1.8E grade - 490 pieces

Figure 66. MSR Lumber In-grade Program
Tension Failure By Forintek Failure Code



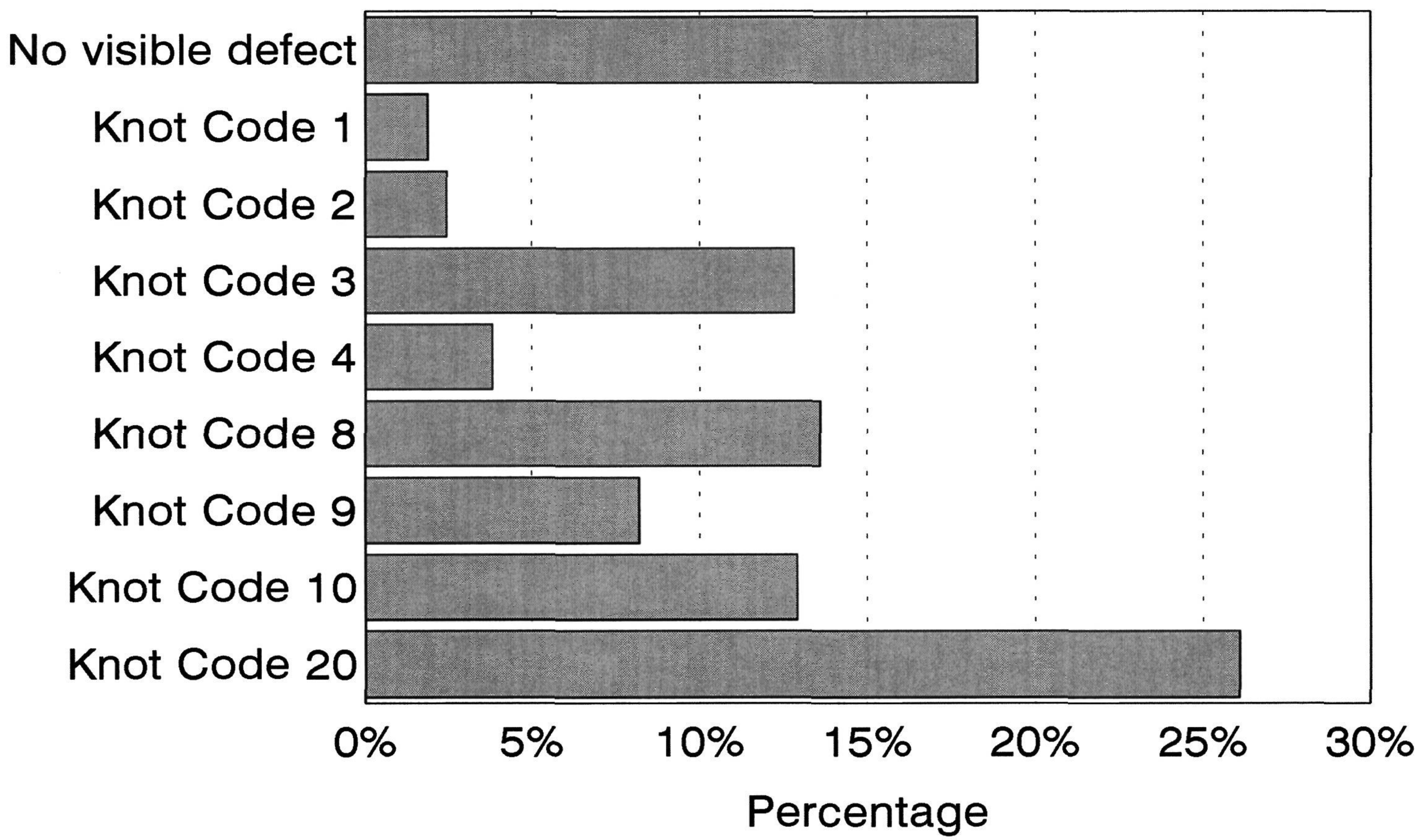
S-P-F 2400f-2.0E grade - 150 pieces

Figure 67. MSR Lumber In-grade Program
Tension Failure By Forintek Failure Code



Spruce All grades together - 261 pieces

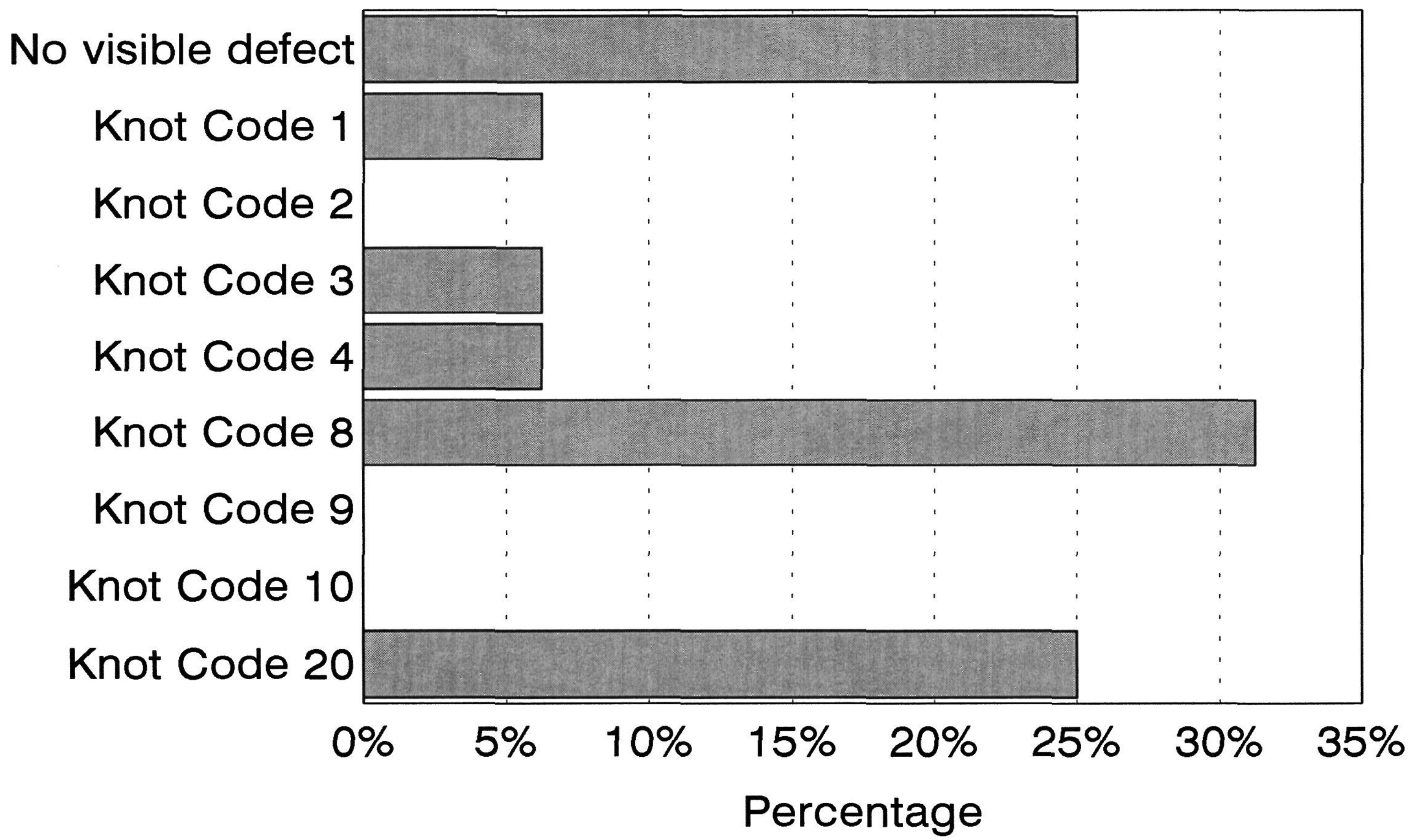
Figure 68. MSR Lumber In-grade Program
Tension Failure By Forintek Failure Code



Pine All grades together - 1023 pieces

Figure 69. MSR Lumber In-grade Program

Tension Failure By Forintek Failure Code



Fir All grades together - 16 pieces

Figure 70. Third Point Loading Moments

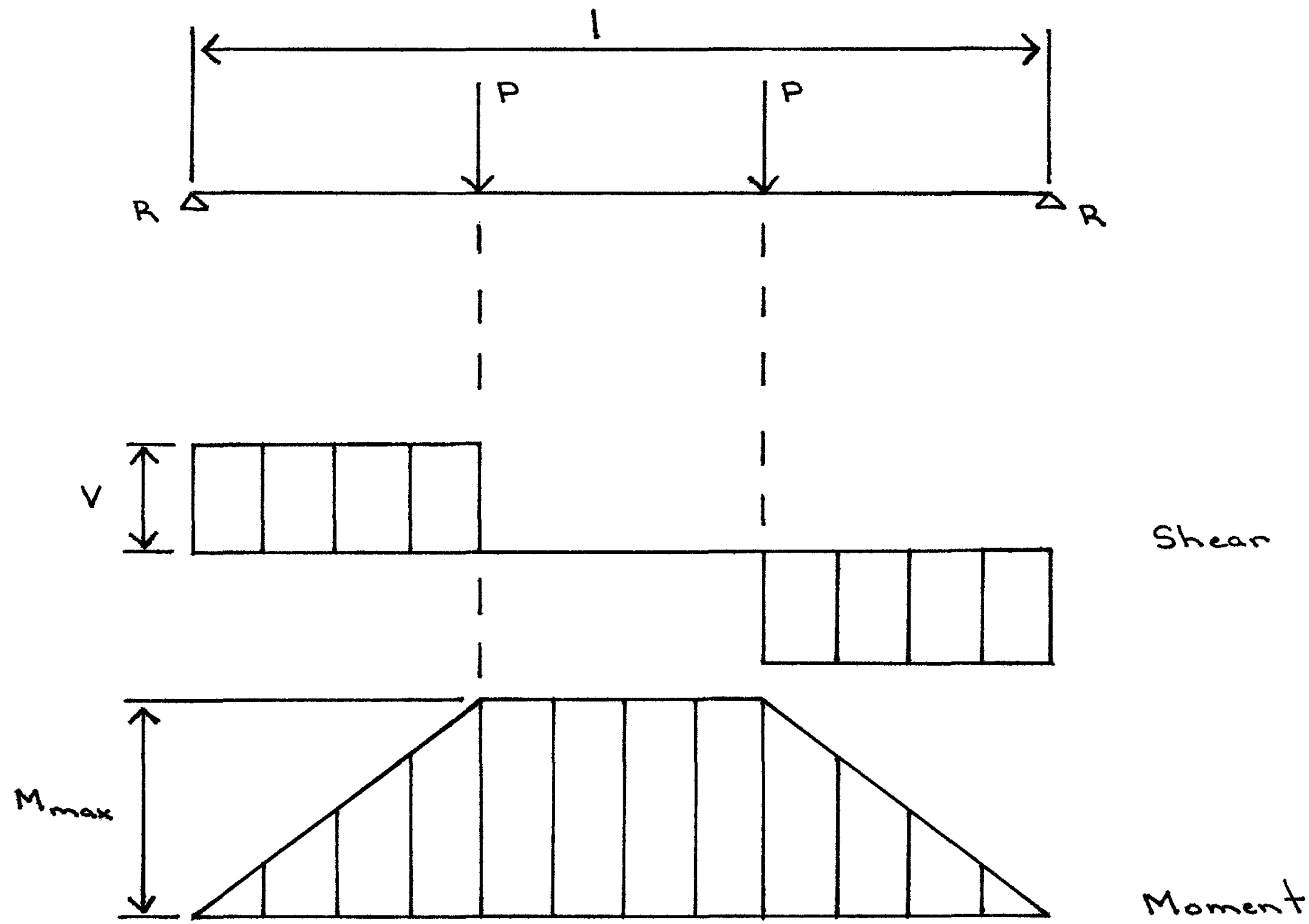


Figure 71. Bending Test Frame

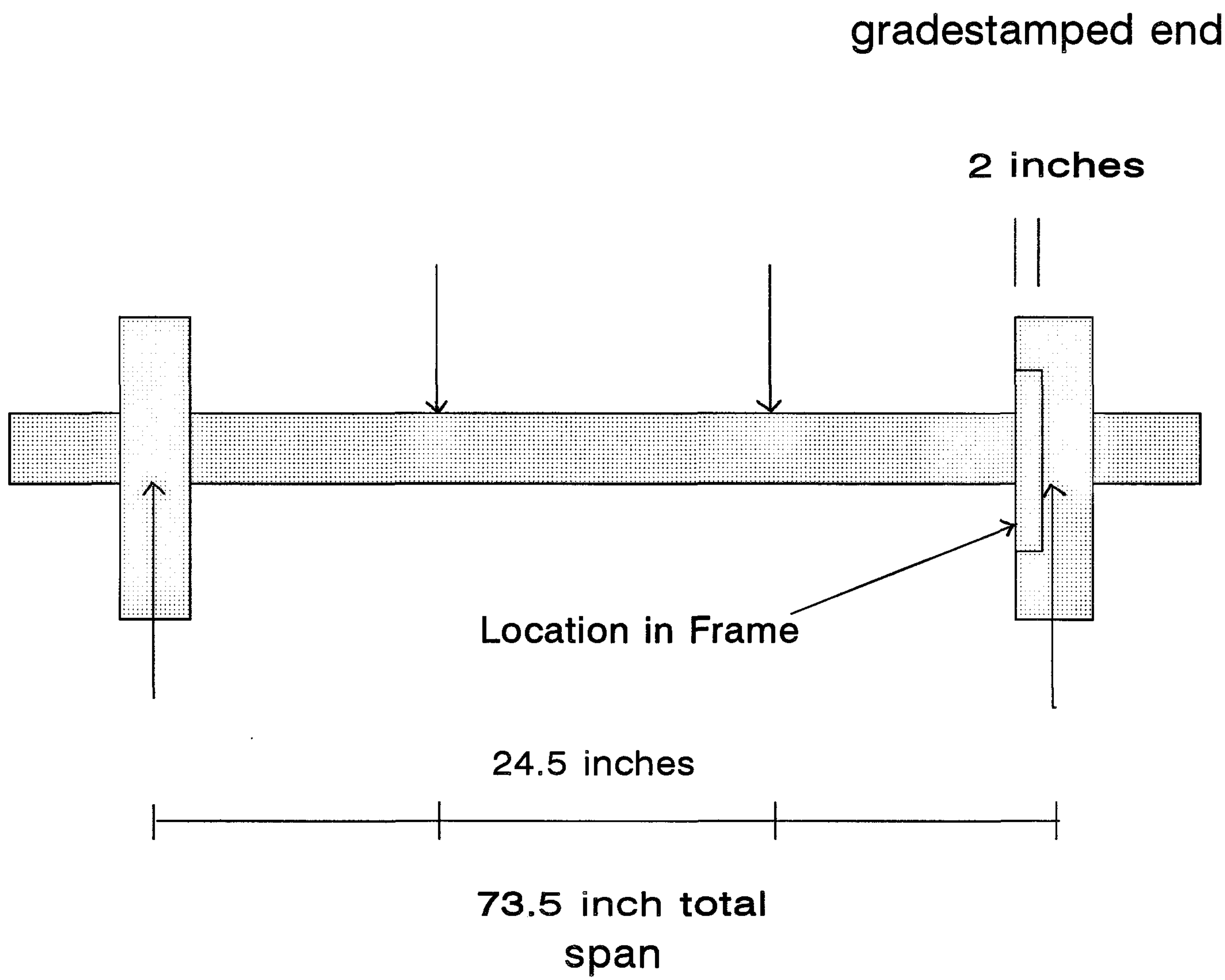
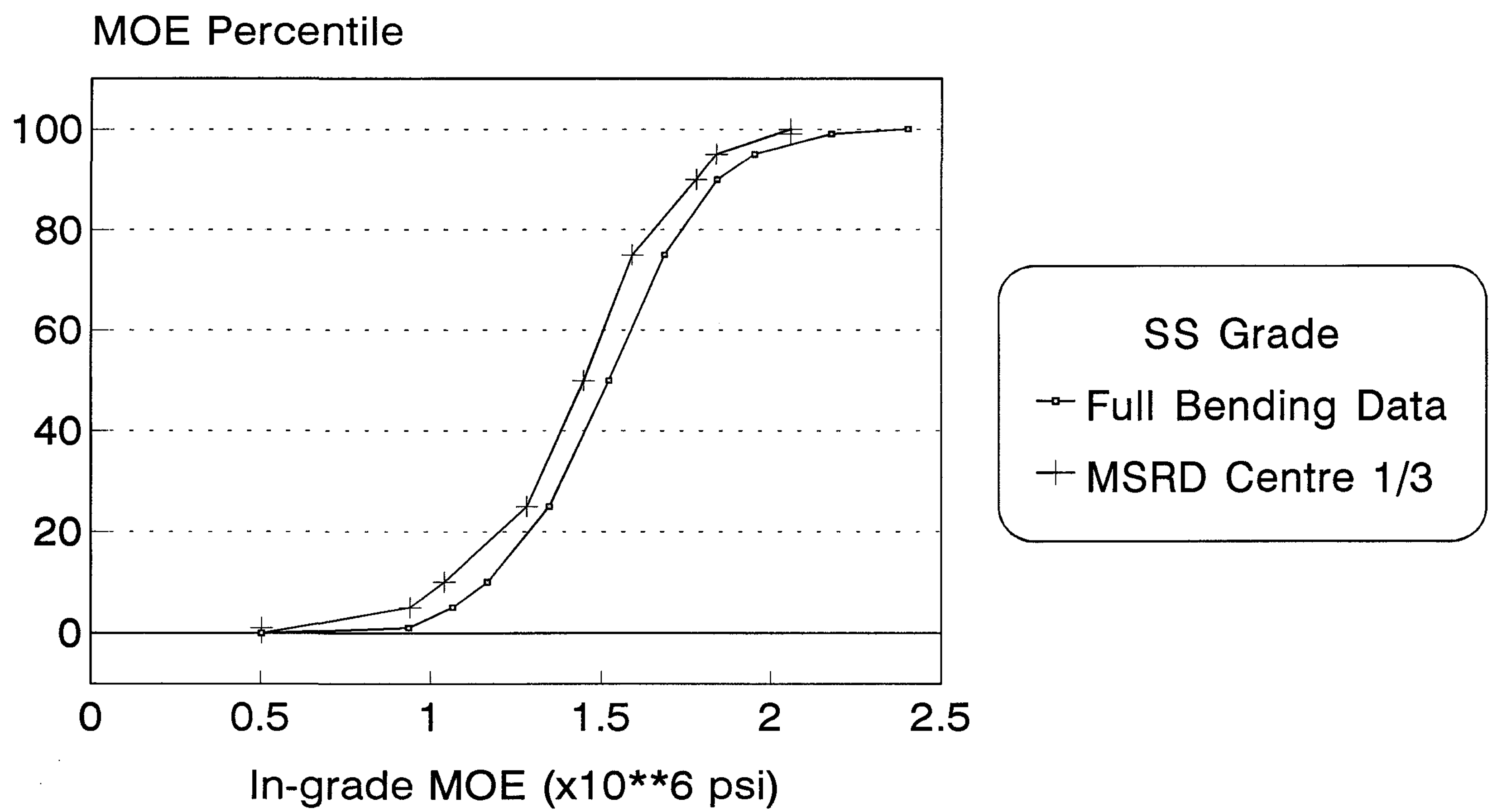
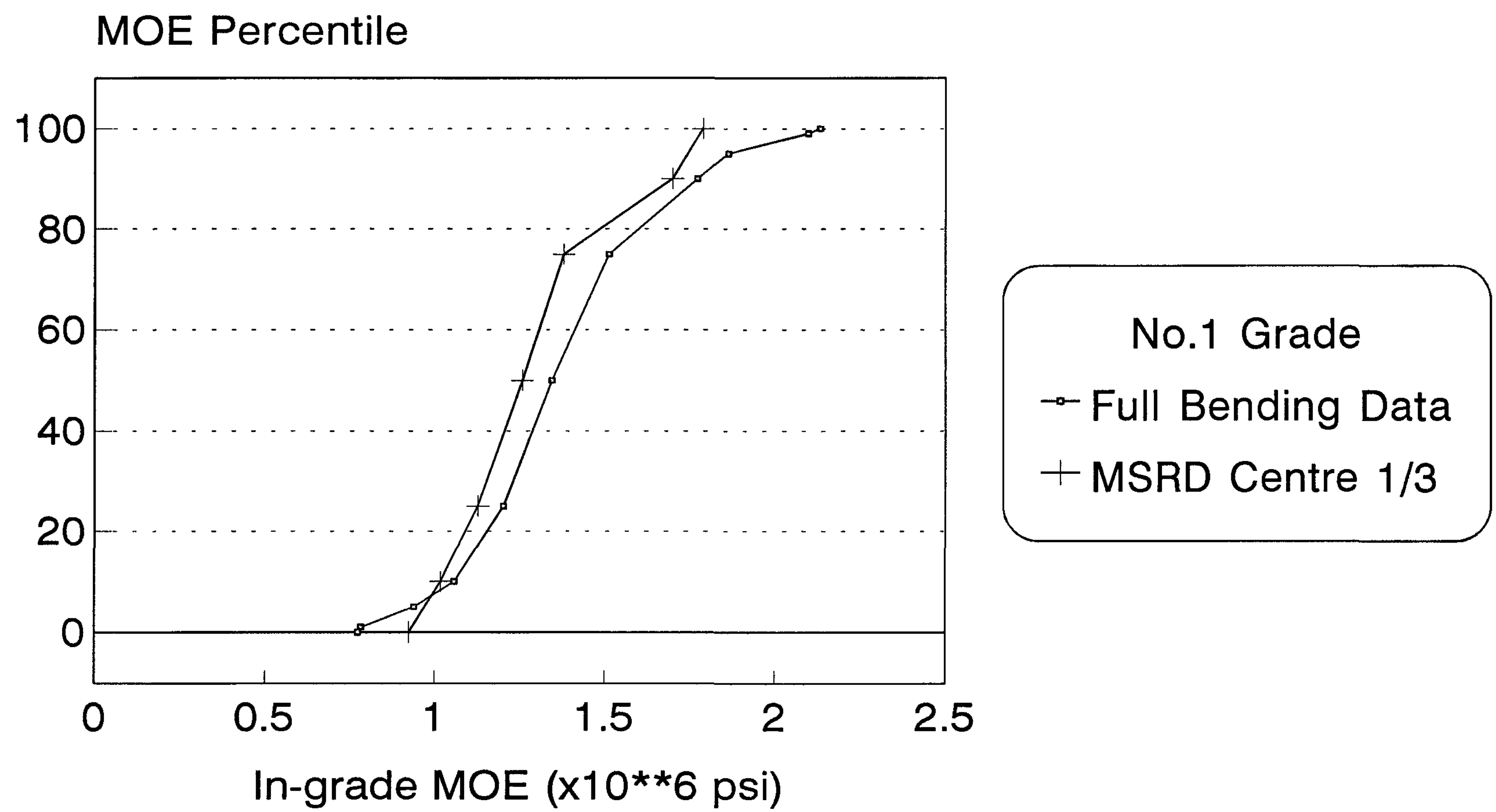


Figure 72. Cumulative Relative Frequencies
SS 2x4 S-P-F Visual Lumber In-grade Data



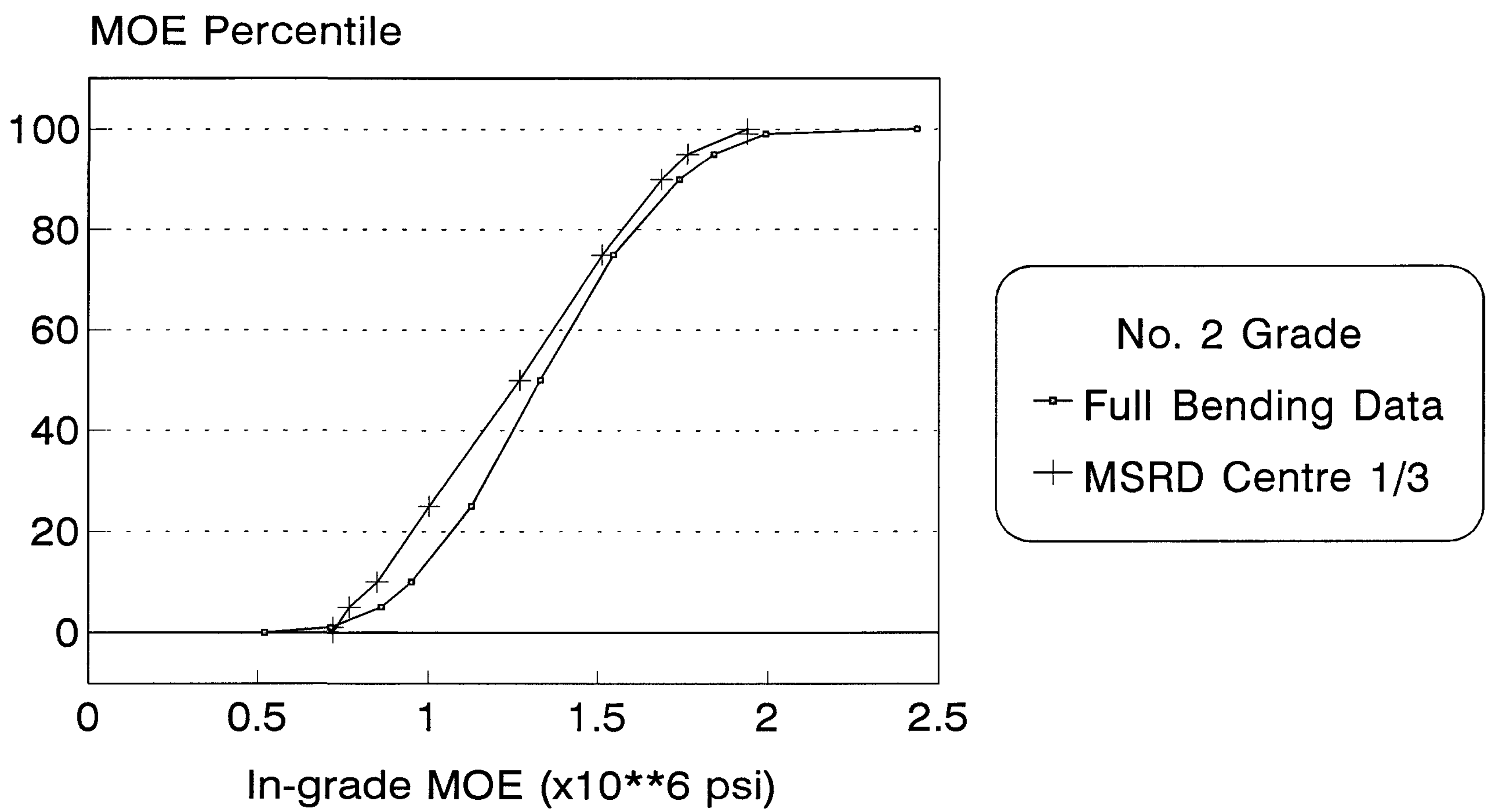
All data machine deflection adjusted

Figure 73. Cumulative Relative Frequencies
No.1 2x4 S-P-F Visual Lumber In-grade Data



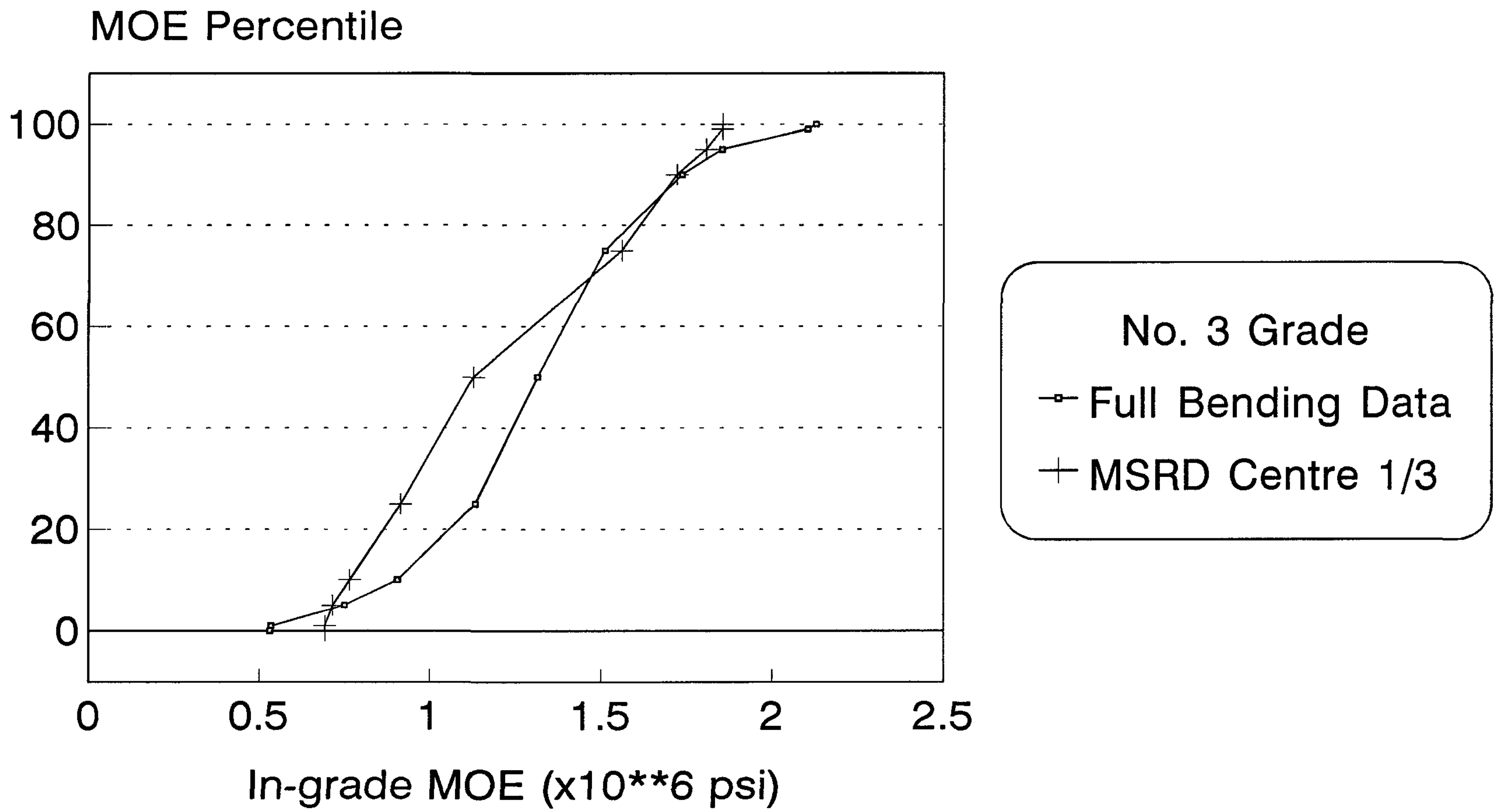
All data machine deflection adjusted

Figure 74. Cumulative Relative Frequencies
No.2 2x4 S-P-F Visual Lumber In-grade Data



All data machine deflection adjusted

Figure 75. Cumulative Relative Frequencies
No.3 2x4 S-P-F Visual Lumber In-grade Data



All data machine deflection adjusted

Figure 76. Cumulative Relative Frequencies
SS 2x4 S-P-F Visual Lumber In-grade Data

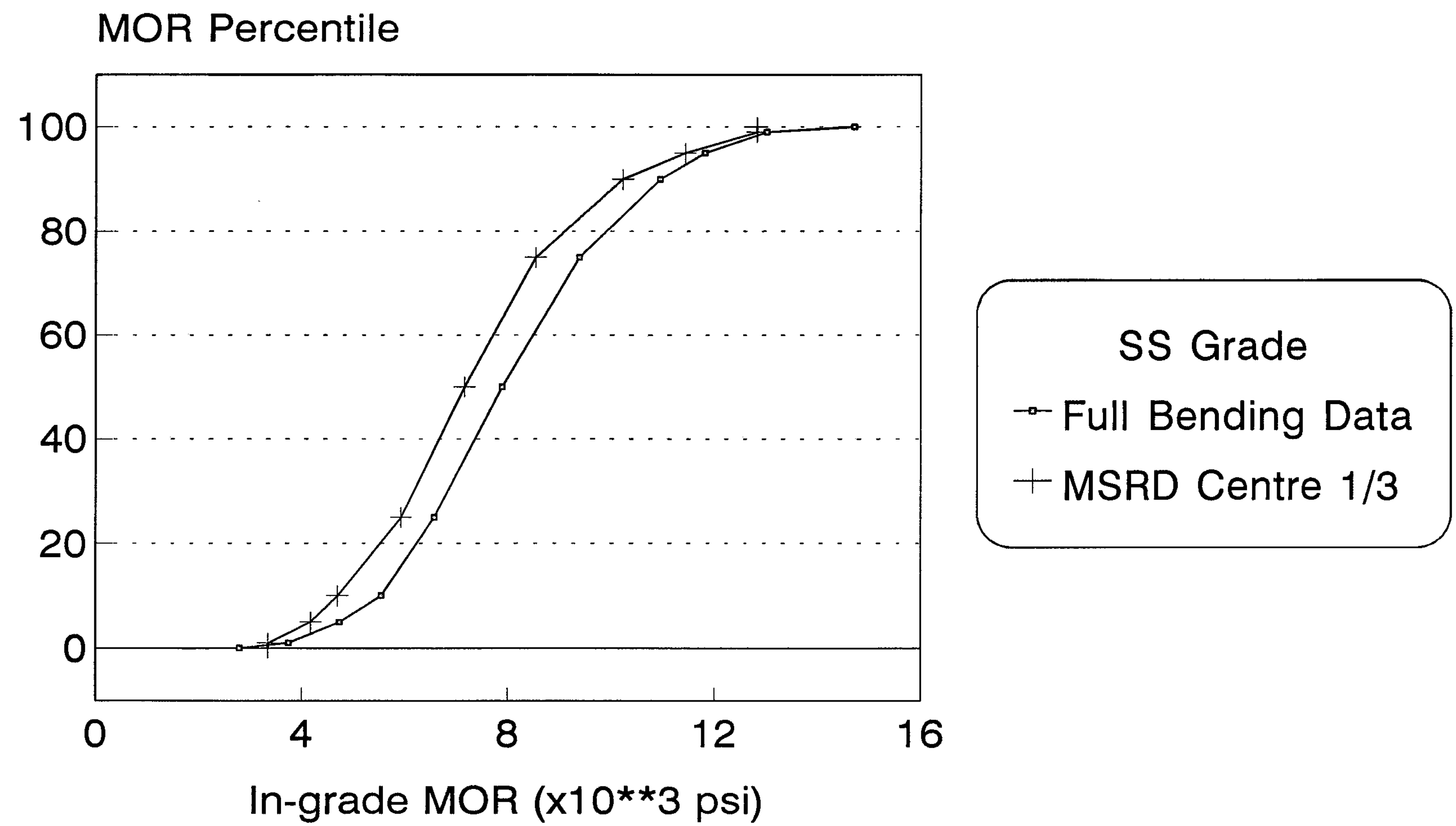


Figure 77. Cumulative Relative Frequencies
No.1 2x4 S-P-F Visual Lumber In-grade Data

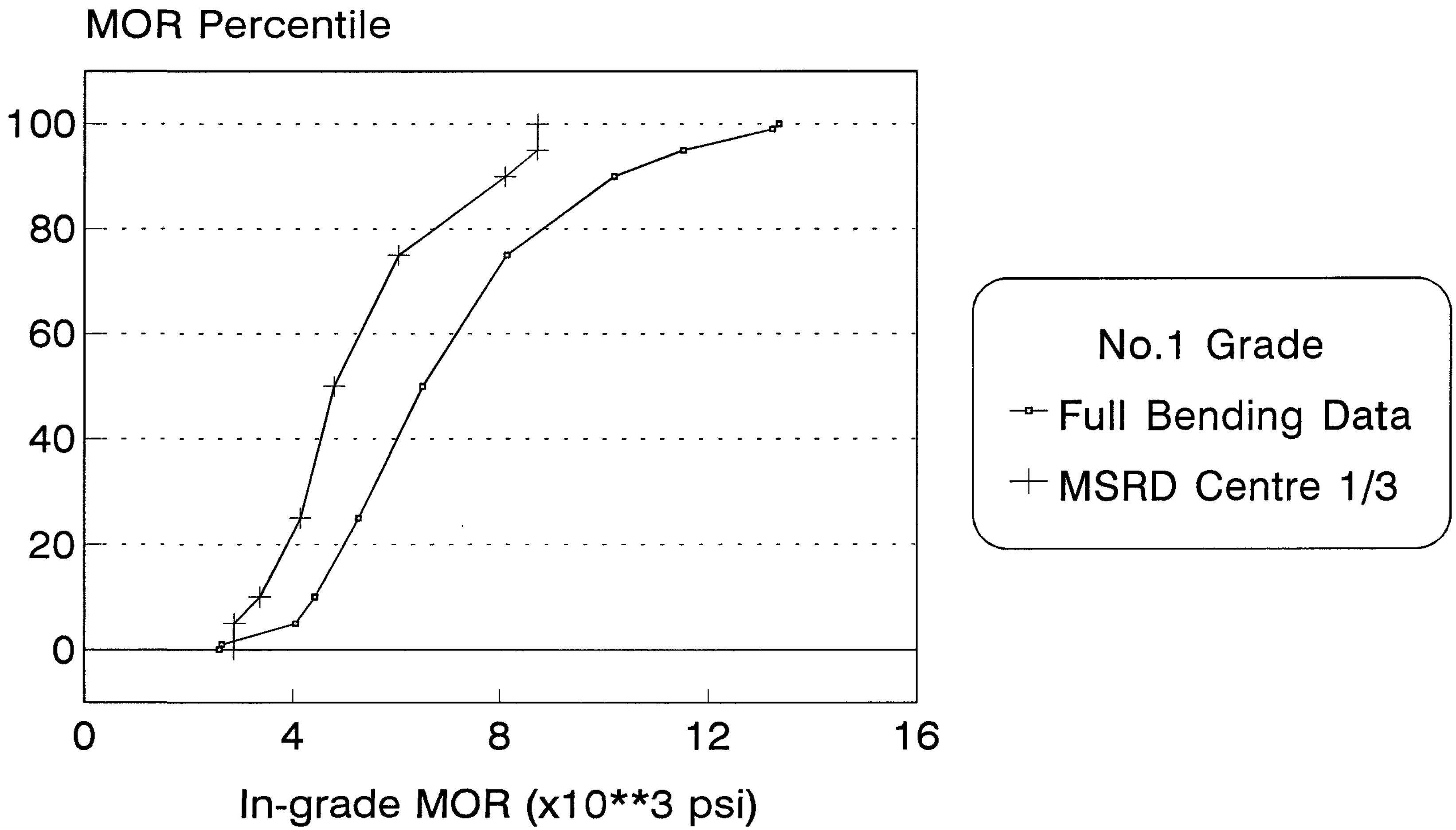


Figure 78. Cumulative Relative Frequencies
No.2 2x4 S-P-F Visual Lumber In-grade Data

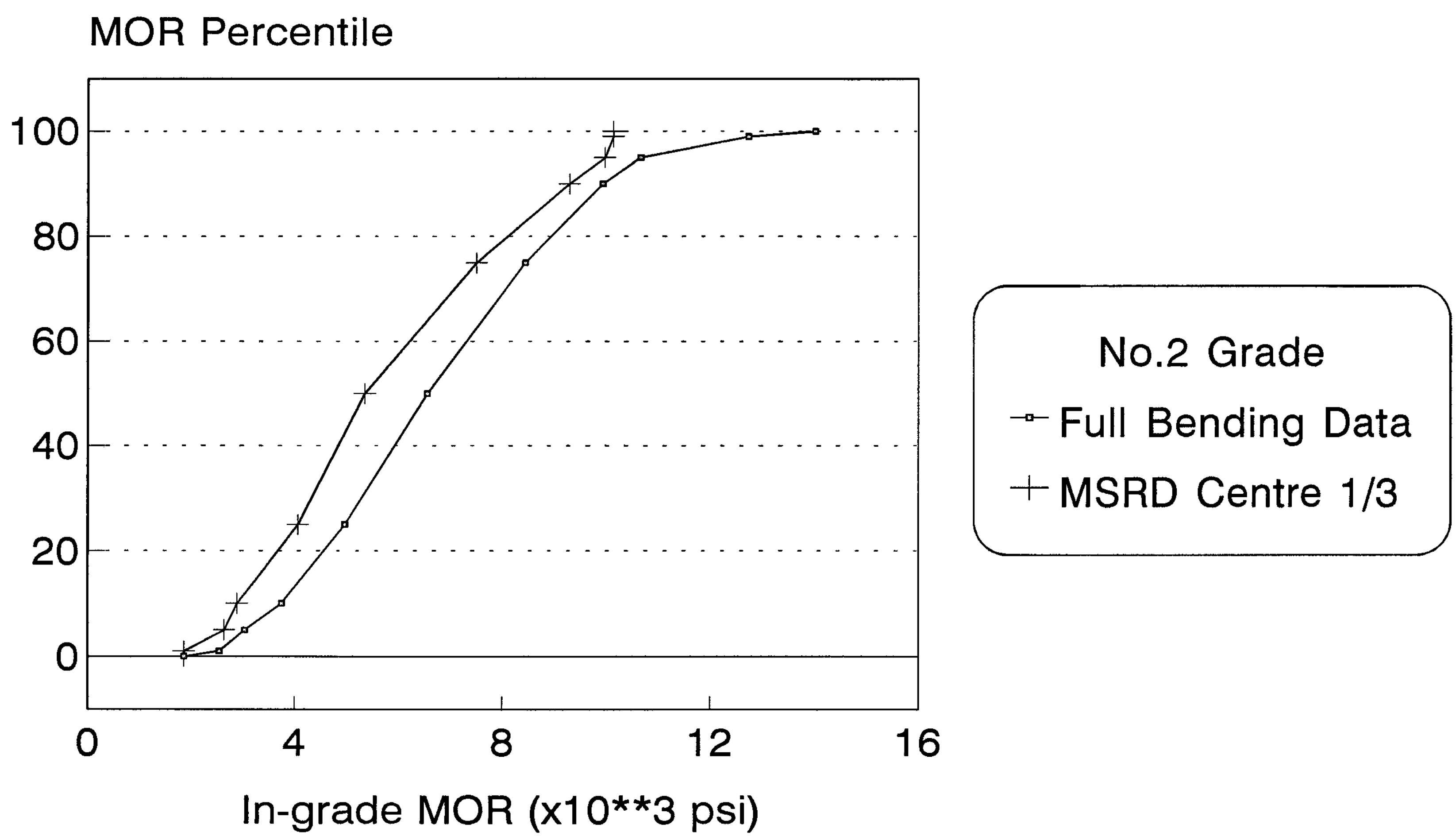


Figure 79. Cumulative Relative Frequencies
No.3 2x4 S-P-F Visual Lumber In-grade Data

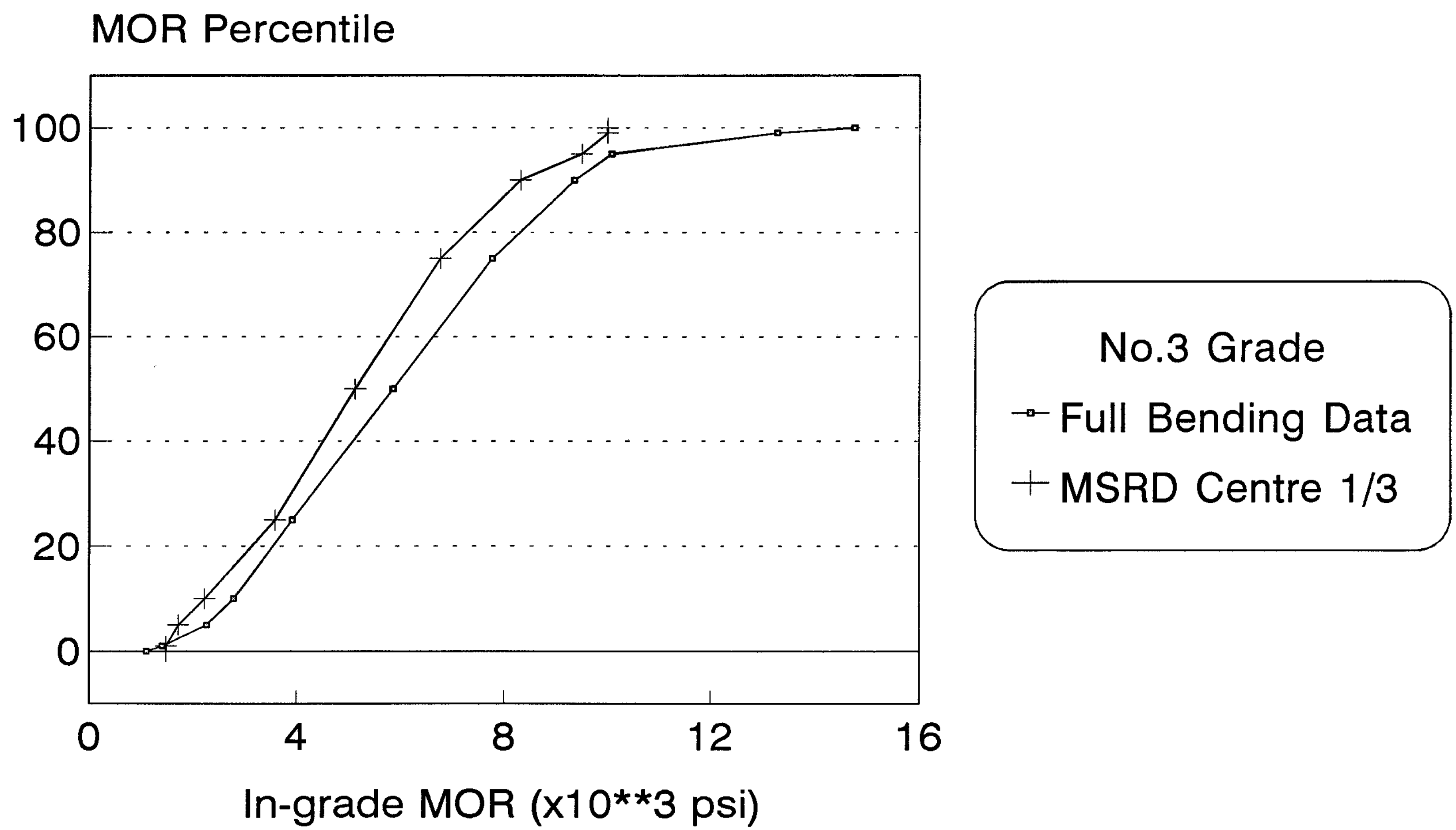


Figure 80. Plot of MOR with MSRD in the Centre Third

2x4 S-P-F Visual Lumber In-grade Data

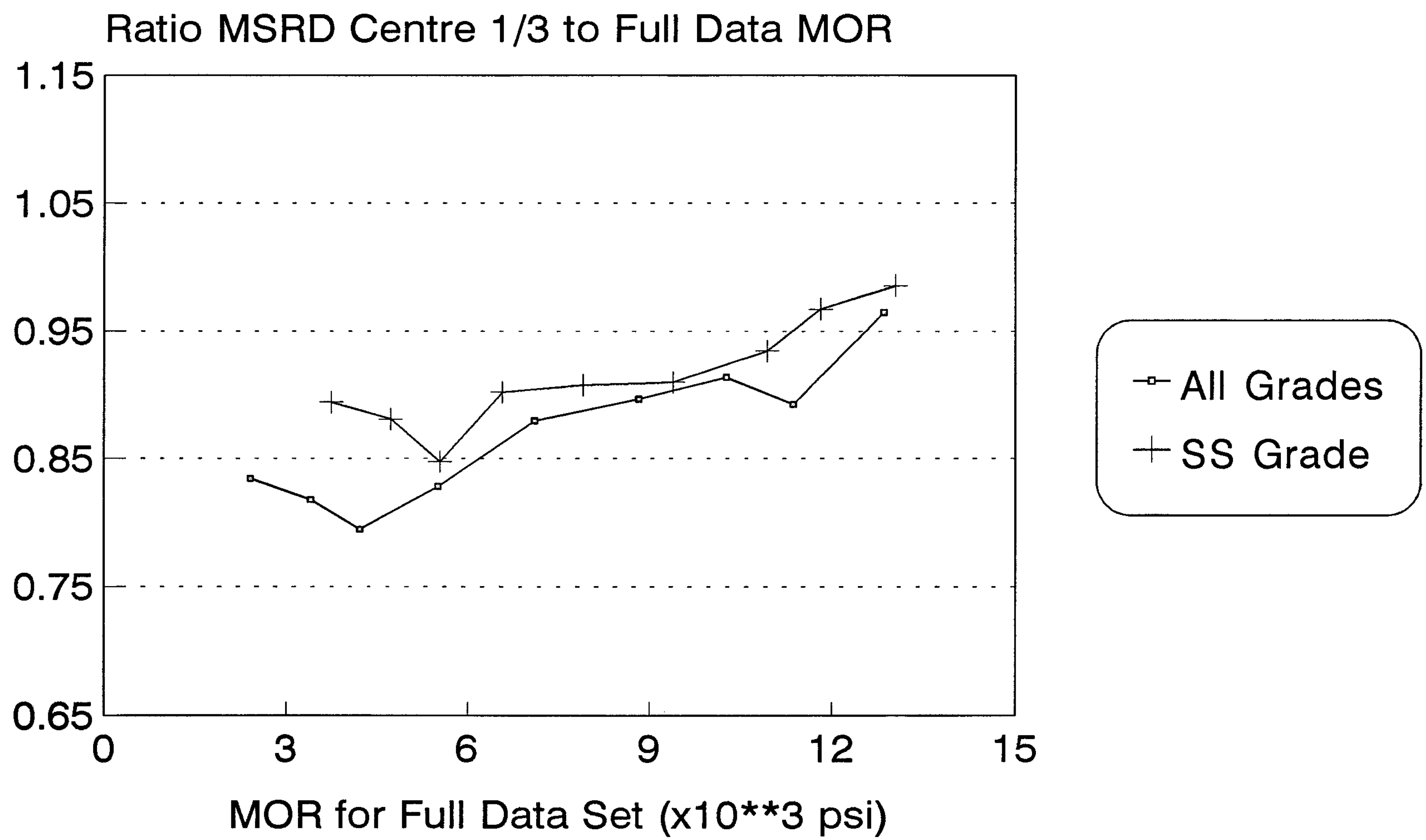


Figure 81. Plot of MOR with MSRD in the Centre Third

2x4 S-P-F Visual Lumber In-grade Data

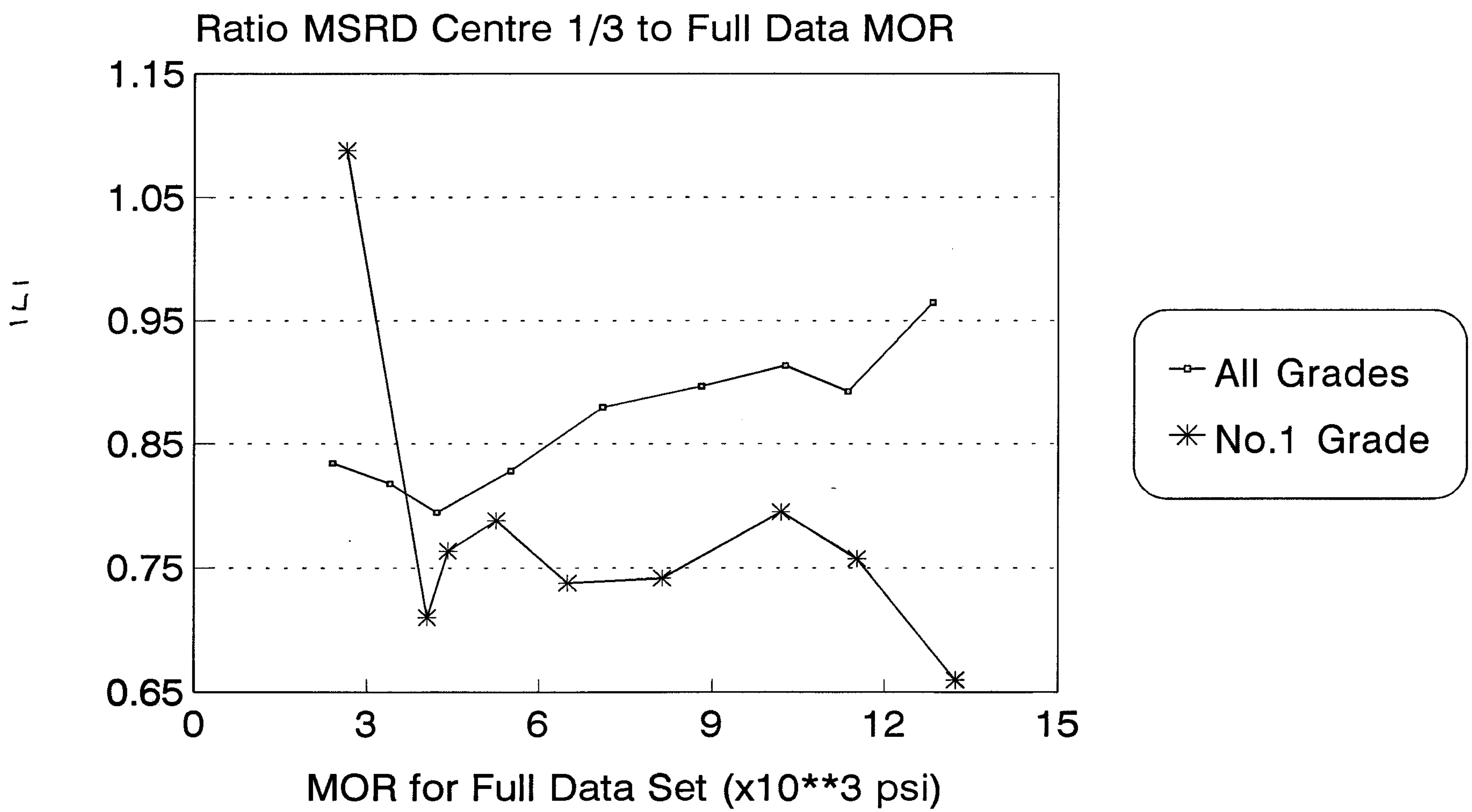


Figure 82. Plot of MOR with MSRD in the Centre Third

2x4 S-P-F Visual Lumber In-grade Data

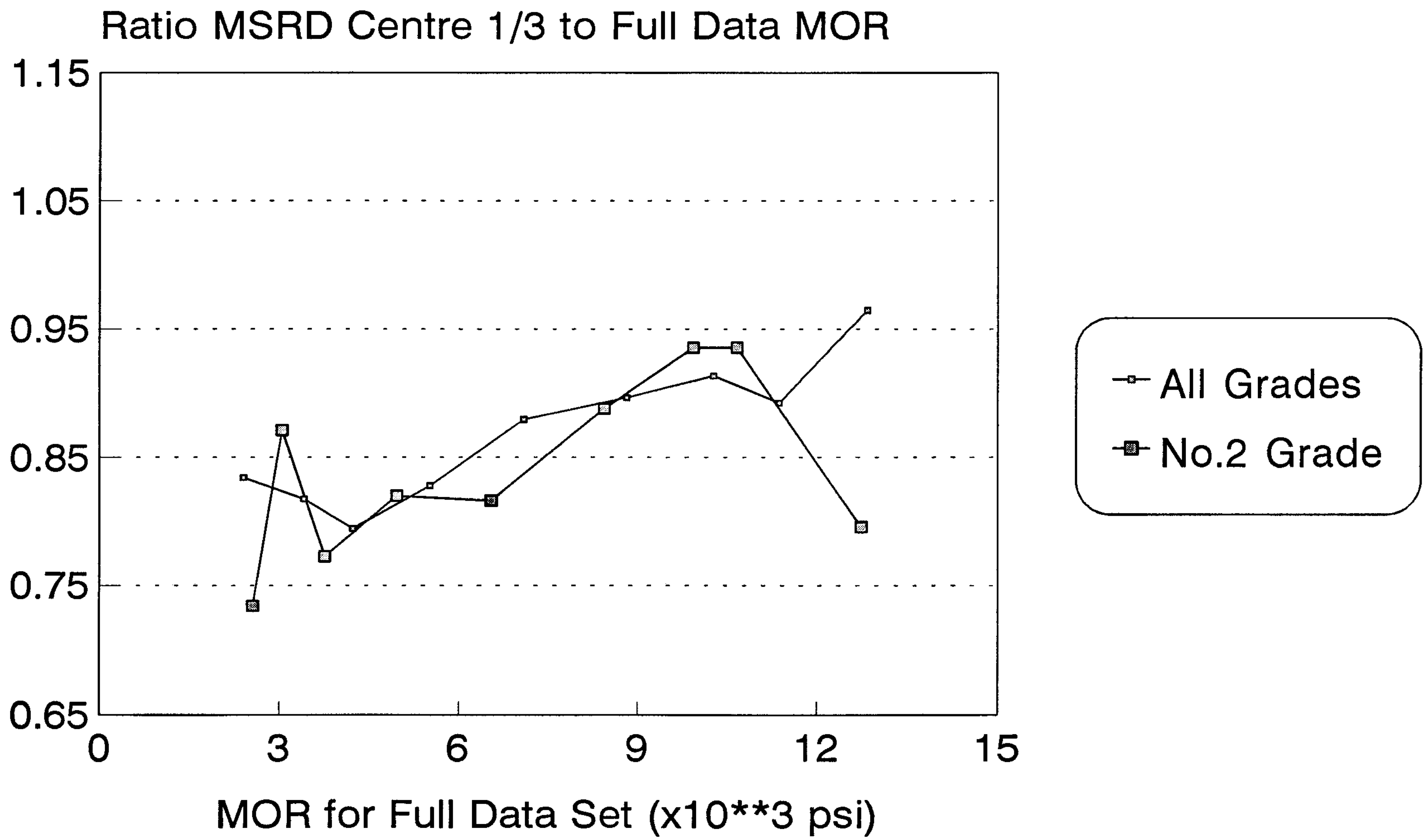
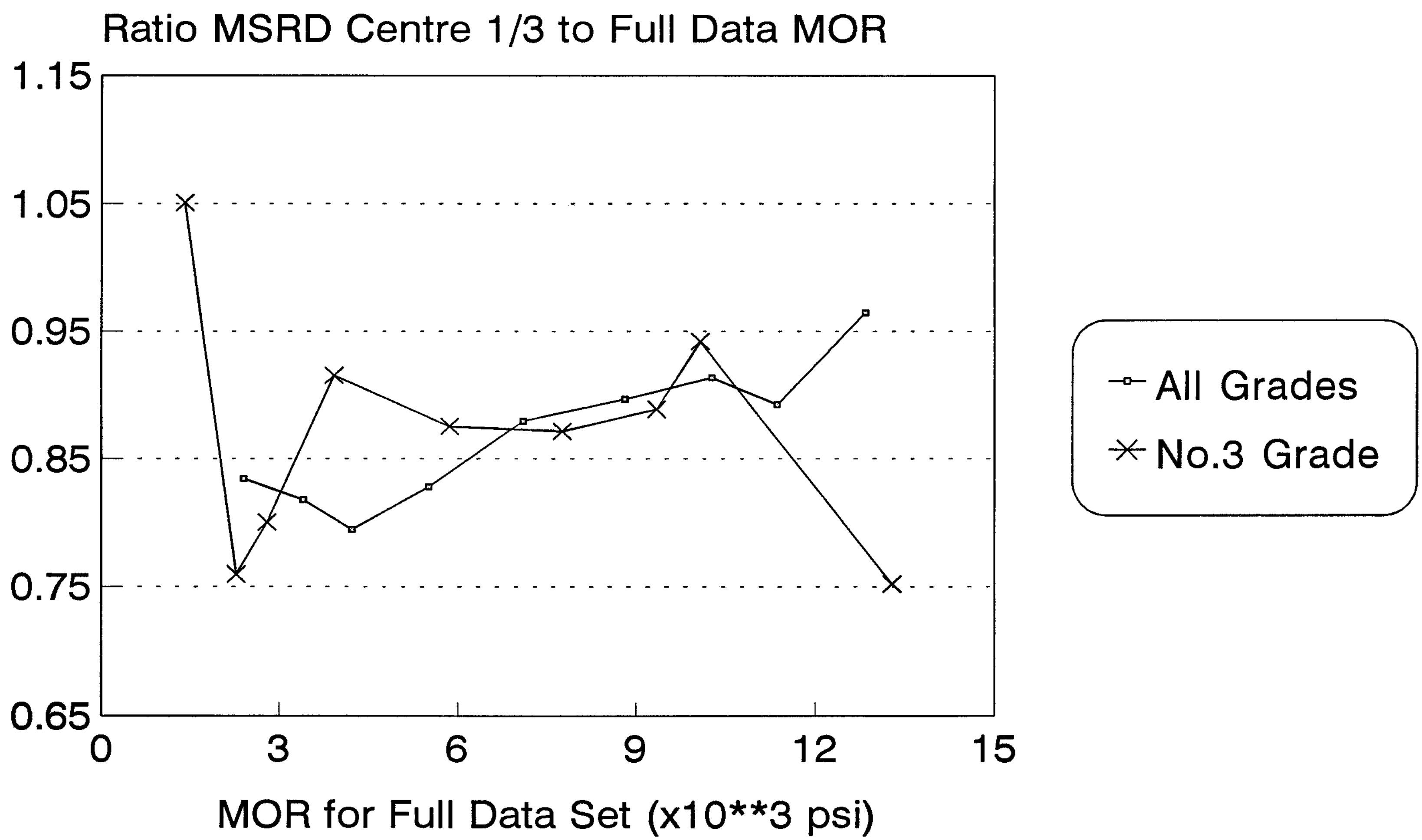


Figure 83. Plot of MOR with MSRD in the Centre Third

2x4 S-P-F Visual Lumber In-grade Data



APPENDIX C

FORINTEK KNOT AND FAILURE CODE

FORINTEK KNOT AND FAILURE CODE

The Forintek knot and failure coding system was developed to provide a rationale basis for analyzing and characterizing the cause of failure in dimension lumber which has been tested to destruction.

The code provides a system for describing and measuring the biological characteristics as well as the manufacturing and seasoning defects.

The system allows knots to be coded numerically with respect to size, orientation and location in the member cross-section using a minimum of measurements. All possible knot configurations have been incorporated into 10 knot "CLASSES", (Figure 1).

For knot classes, 1 through 9, the first digit designates the knot location on either the tension (0) or the compression (1) edge for bending tests. The second digit designates the knot class (1-9). The next 4 to 8 digits are used for the required knot measurements shown in Figure 1.

Lumber containing a boxed pith (designated as CLASS 10) may be dealt with using one of 3 methods.

1. Code as a CLASS 10 knot and determine the percent displacement of the knot(s) by using the lumber grading displacement measuring technique. This method does not allow reconstruction of the knot(s) geometry.

2. For this option, project the pith to the surface and treat as one of the other 9 classes. This method leads to a distortion of the geometry of the knot.

3. Measure knot as shown in Figure 2 (CLASS 10 supplementary). While measuring to the pith location is often difficult and extra coding (2 digits) is required, this method allows the knot geometry to be reconstructed accurately.

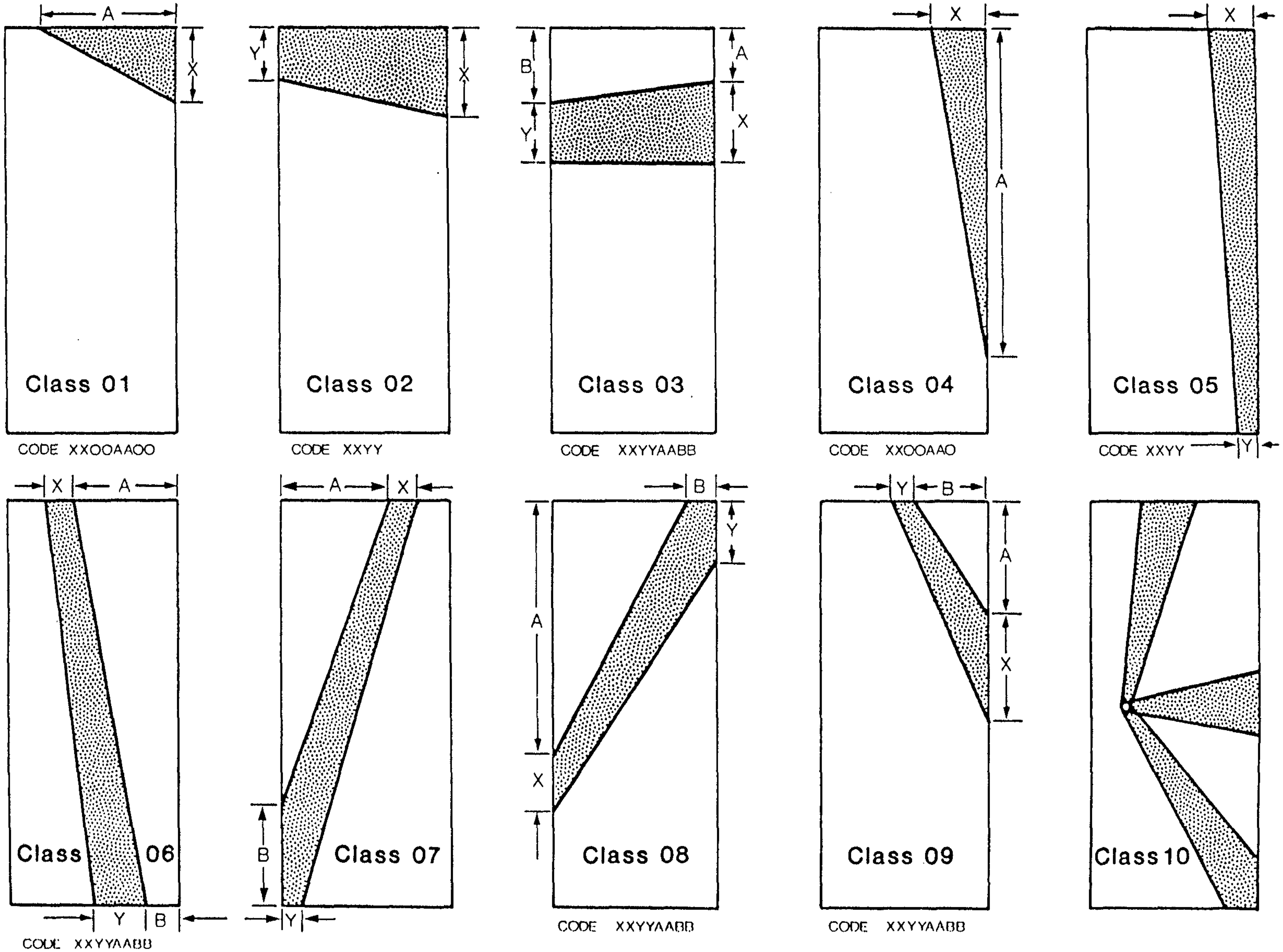
Knots may be measured in either millimeters or 1/16th's, or 1/8th's of an inch. Millimeters are not recommended for larger lumber sizes (2x8's, 2x10's) since measurements greater than 99 mm's are not compatable with the 2 digit coding system. Measurements in sixteenths of an inch are generally recommended since eighths of an inch may be too coarse for general purposes.

The codes for all failures other than knots are listed in Table 1 (Description of Failures for Dimension Lumber). These failures are defined and measured in accordance with, NLGA STANDARD GRADING RULES FOR CANADIAN LUMBER, with the following additions or changes:

1. Slope of grain - The slope of grain as measured on the wide face
2. Cross grain - The slope of grain as measured on the narrow face
3. Grain deviation - A localized grain deflection usually attributed to a large knot which itself is not present in the specimen
4. Deviated pith - The result of a sudden change of angle of the pith relative to the long axis of the piece.

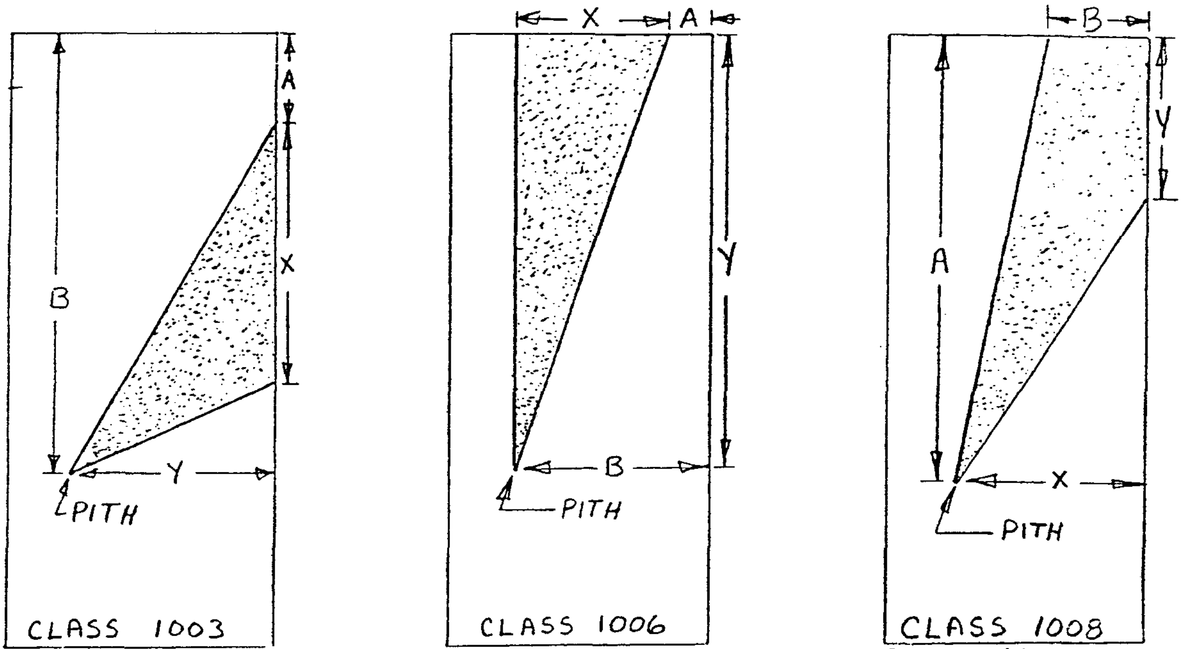
For a description of failures not associated with a defect, i.e., longitudinal shear, compression, tension and brash failures refer to ASTM D143, TYPES OF FAILURES IN STATIC BENDING.

Figure 1. WOOD ENGINEERING KNOT CODE



FIGURE

WOOD ENGINEERING KNOT CODE
CLASS 10 SUPPLEMENTARY



CODE XXYYAABB   CODE XXYYAABB   CODE XXYYAABB

DESCRIPTION OF FAILURES

for

DIMENSION LUMBER

CODE	CAUSE OF FAILURE	CODE	DETAILS OF CAUSE OF FAILURE
23	Knot cluster	00	% of x-section displaced
24	Slope of grain (wide face)	00	Actual slope
25	Grain deviation	00	% of x-section where deflection is greater than 1:4
26	Cross grain (narrow face)	00	Actual slope
27	Shake and checks	01	Not through and less than 2' long
		02	Not through and more than 2' long
		03	Through and less than 2' average
		04	Through and more than 2' average
		05	Shake breaks less than 2/3 the edg
		06	Shake breaks more than 2/3 the edg
28	Splits	00	Average length of both sides
31	Unsound wood	01	White specks
		02	Honeycomb
		03	Brown rot
32	Pinworm holes		
33	Grub holes		
34	Teredo holes		
35	Bark pockets		
36	Pitch pocket		
37	Wane	01	#1 wane
		02	#2 wane
		03	#3 wane
42	Compression wood	00	% of x-section
43	Burl	00	% of x-section
45	Machine damage	01	Saw cut through edge
		02	All other saw cuts
		03	Mechanical damage at edge
		04	All other mechanical damage
46	Falling breaks		
47	Breaks		
48	Deviated pith	00	Actual slope
50	Longitudinal shear		
51	Compression		
52	Tension and compression		
53	Tension		
54	Lateral buckling		
55	Brash		
58	Knot		
59	Rate of growth		
60	Clear wood or small defects		