METHODOLOGY TO PREDICT THE STRENGTH AND STIFFNESS OF RED ALDER BLOCK PALLET CONNECTIONS FASTENED WITH HELICALLY THREADED NAILS

by

Hector M. Sosa

Thesis submitted to the faculty of

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Wood Science and Forest Products

APPROVED:

Dr. Joseph R. Loferski, Chairman

Dr. Marshall S. White

Dr. James D. Dolan

November 11, 1994

Blacksburg, Virginia

METHODOLOGY TO PREDICT THE STRENGTH AND STIFFNESS OF RED ALDER BLOCK PALLET CONNECTIONS FASTENED WITH HELICALLY THREADED NAILS

by

Hector M. Sosa

Dr. Joseph R. Loferski, Chairman

Department of Wood Science and Forest Products

(ABSTRACT)

The objective of this project is to develop a methodology to measure and predict the strength and the stiffness of red alder (Alnus rubra) nailed pallet connections subjected to repetitive loading. Joint tests were conducted to define the mechanical properties of bottom block pallet connections. The primary tests were conducted to define the strength and stiffness of joint specimens tested in cyclic lateral loading, using three different side member thicknesses and four types of nails. Also the influence of other specific variables on joint performance was evaluated including friction, pattern, moisture content, number of nails per joint, specific gravity, and rate of loading. In total, 23 sets of nailed joint specimens, with 15 replications each, were constructed and tested. The use of a reversing cyclic lateral loading procedure permits documentation of the effect of dynamic loading on the load-slip response of the connection. Analysis of the data included the creation of two envelope curves, the initial and the final (stabilized) curve. The data obtained from the two curves was used to find the "best" model for predicting the strength and stiffness of the connections. Four models were identified but only one of these was found useful for prediction purposes. Finally, experimental capacity loads were found to be at least three times greater than the national design specification allowable design loads.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the U.S.D.A. Forest Service for the financial support of this project provided through Contract No. FP-92-1859. Special thanks go to Diamond Wood Products, Inc. in Eugene ,Oregon and Northwest Hardwoods (A Division of Weyerhauser), in Portland, Oregon for supplying the red alder used in this research. My appreciation and gratitude to Dr. Geza Ifju, Head of the Department of Wood Science and Forest Products, for his understanding and support all these years.

I would like to express my sincere gratitude to my graduate committee members for leadership, encouragement and guidance through this study. Special thanks to Dr. Joseph Loferski for his advise and patience. His fast editing and thoughtful suggestions were very important to bringing this thesis to this stage. His continuous support and guidance was vital in my completion of this study, I am deeply gratefull Thanks to Dr. Raymond H. Myers for his invaluable statistical expertise.

The author's gratitude goes to all the staff members of the Brooks Forest Products Center at Virginia Tech for help. Special thanks goes for Mr. J. W. Akers, Mrs. Charlotte Barnett, Mrs. Roza Podkovyrova, Mr. Bob Carner, and Mrs. Sharon Daley for their assistance in the preparation of specimens, equipment, plots and spreadsheets used in the experiments and analysis of the data develop by this study.

Extension of my gratitude goes to all my fellow graduate students for their support and friendship. Special thanks to Kathryn Schueler for all her support in editing and typing, to my good friends Alfredo Lopes, Jaime Acosta, Ronan Roudik, Vijai Reddy, Tim Stiess, and Terry Platt for their encouragement and support.

Finally, the author wishes to thanks the support of his mother, Valeria Villanueva and sister Blanca Sosa. Deep gratitude is express to the author's children, Sayeli, Hector, and Irais Valeria for their patience and to his wife Graciela, for her support and understanding.

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.0 Background

Pallets are one of the most cost effective methods of shipping and handling of materials, and are used as platforms to transport a wide variety of products that are moved in volume, or require special care. There is an increasing tendency by pallet users to adopt block pallets. The versatility and low cost of this type of pallet have caught the attention of the Grocery Manufacturer's Association and manufacturers of pallets (Cristoforo, et al., 1992). Additionally, block pallets are more adaptable to individual situations, because they readily accommodate four-way entry by the tines of a fork-truck. This survey is already showing the trend in the grocery industry to use the block style pallet. Historically, the grocery industry has purchased close to 15% of the pallets manufactured annually. In 1992, the approximate wood volume used in wood pallet production in the USA was 9.6 billion board feet. The percentage of wood type used in pallet construction was 79.45 percent hardwood , and 20.55 percent softwood species. From the 1992 volume, 52.92 percent was used in the production of multiple use (warehouse or returnable) pallets and 47.08 percent was used in the construction of single use (expendable or shipping) pallets

(National Wood Pallet Container Association (NWPCA), (1993). The Center for Forest Products Marketing reports, from a mail survey of the U.S. pallet and container industry, a consumption in 1993 of approximately 4.82 billion board feet of solid hardwood (lumber, cants, parts and shook). The study highlights in the same year a total consumption of 2.12 billion board feet of solid softwood (lumber, cants, parts and shook) (Bush, et al. 1994).

Until now, the models developed for estimating the deformations of laterally loaded nail joints in the block and stringer versions of the Pallet Design System (PDS) were restricted to deformations well below the proportional limit. No model for high deformations (beyond the proportional limit) has been developed for pallet joints. The existing model predicts deformations up to 0.015 inch and is based on models developed by Wilkinson (1971). It has been found that block pallets with perimeter and cruciform bottom deck constructions (Figure 1.1) supported in rack frames on both bottom lead boards produce high deformations (more than 0.1 inch) in the end-butted connections of the bottom boards. These deformations exceed the limits of prediction for the reliability-based design model (PDS), and could lead to under-designed pallets. Under-designed pallets can create safety and serviceability problems to both producers and consumers, leading to catastrophic failure, or damage to the unit load products, and/or danger

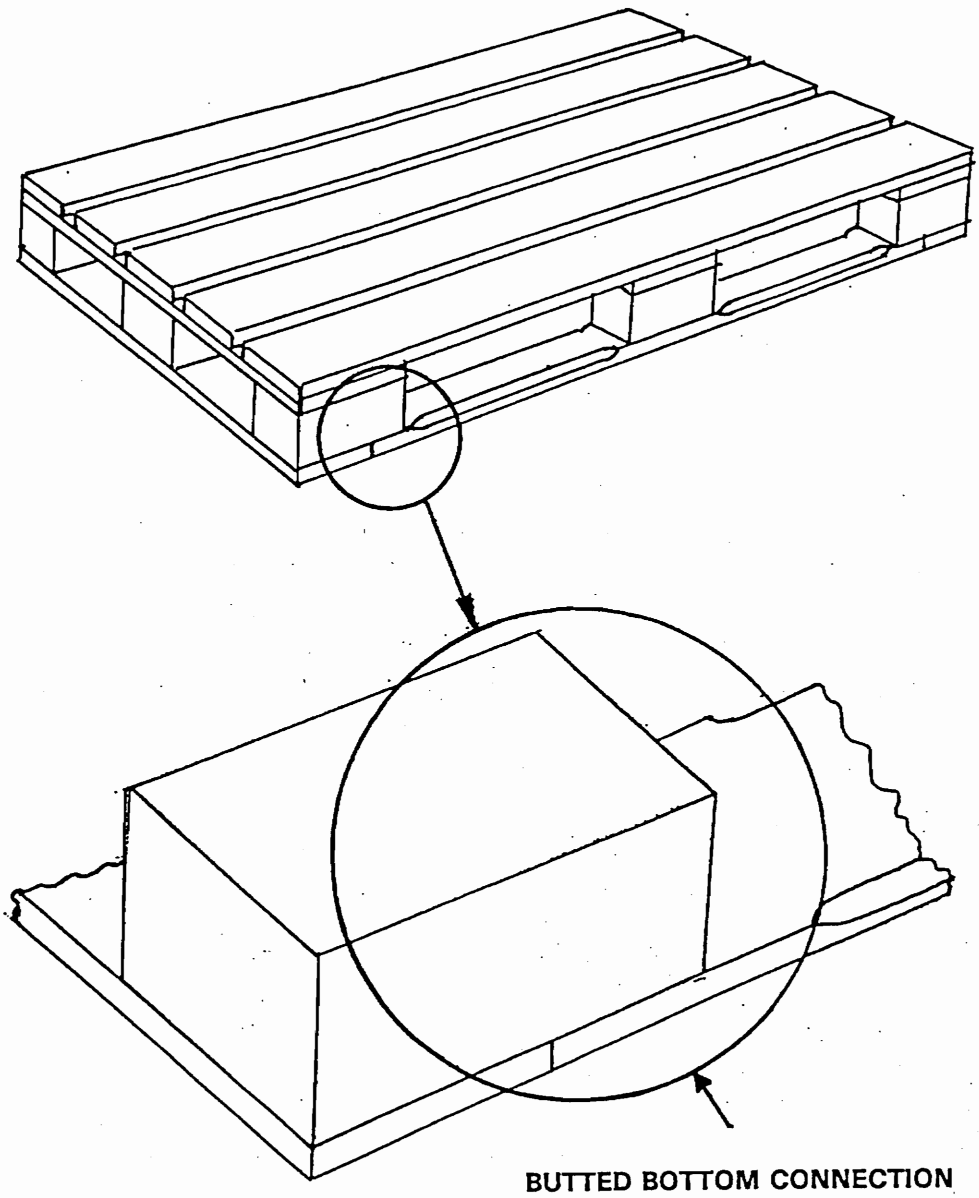


Figure 1.1 Diagram of a block pallet and the butted connections.

to workers. Developing accurate models of the behavior of pallet joints is important because approximately 77% of the structural damage in pallets is at the connections between components (McLain and White, 1992). A methodology that predicts the strength and stiffness of butted board pallet connections will help in the construction of effective and safe pallets.

The most important hardwood species in the Pacific Northwest is red alder (*Alnus rubra*) (Powell, et al., 1992). This species thrives in a wide range of latitudes, from Alaska to Southern California. The wood has intermediate mechanical properties, relatively low shrinkage, and properties that make it easy to work. On the west coast of the US, because of the increasing scarcity of softwood timber for the industry in the area (due to changes in national government policy), the red alder species has became more important for the producers of furniture, cabinets, case goods, pallets, and novelties. In order to contribute to the knowledge and industrial development of this species, the present study is focused on the performance of red alder nailed connections as typically found in block pallets. Two more species were also studied to provide a validity to the theoretical model for multiple species.

1.1 Objective

The global objective of this research was to evaluate existing methods for predicting the strength and the stiffness of block pallet connections and, if found inadequate, to develop a methodology to predict the strength and the stiffness of laterally- loaded butted-board nailed pallet connections. This project is focused on red alder, but two other species were also tested to cover the range in density of species commonly used in the pallet industry.

Hypotheses: (1) The strength and stiffness of a butted joint can be modeled by Foschi's (1973, 1977) equation, or a new model can be developed using a commercial statistical software; (2) The European Yield Theory can be used to predict connection design values; (3) Multiple linear regression analysis can be used to develop a model to predict the stiffness of joints from materials and geometric characteristics of the connections. To accomplish the primary objective the following specific subobjectives were generated:

1. Develop methods to measure the deformation created in the butted connection when the joint is subjected to cyclic testing. Using the modified sequential phased displacement procedure that was proposed as an ASTM standard test procedure for dynamic testing of connections with mechanical fasteners (Dolan, 1993), the results were compared to data obtained from the monotonic ASTM standard test procedure (ASTM D 1761-88 (1993)). This new cyclic testing procedure is expected to account for the fatigue created when the pallets are subjected to the repeated loading and unloading typically found in service.

2. Determine the effect of selected test conditions on the load-slip relationship of nailed connections in red alder subjected to lateral loading. The factors investigated in this experimental program are:

   A. Three deckboard thicknesses (1/2-, 5/8- and 3/4-inch),
   B. Four types of threaded pallet nails,
   C. Connections with one, two, and three nails per joint,
   D. Connections with three nails in two different layout patterns,
   E. Connections tested with and without friction,
   F. Connections with different moisture contents: joints assembled green and tested green; joints assembled green and tested dry; and joints assembled dry and tested dry,
   G. Connections tested with different rates and types of loading.

3. Develop mathematical models of the load-slip relation as related to the factors described in subobjective 2, parts A and B.

4. Define yield equation parameters (experimental)

   A. Dowel Bearing Strength for green and dry red alder wood,

B. Nail Bending Yield Moment for the four types of threaded nails.

Chapter 2 contains general background literature related to the methods for predicting the stiffness and the strength of nailed joints. This includes several equations used to predict the stiffness and the strength (capacity) of joints, methods and apparatus used to test these connections in shear, and other relevant information about the topic. Chapter 3 describes the materials and methods used in the testing of the joint specimens. It explains the testing equipment and computer programs required for the testing, as well as the computer equipment and type of analysis that was done with the collected data. In chapter 4, the results of the research project are presented together with the discussion of these results. Tables and figures are included to give the reader a visual presentation of the results. Chapter 5 presents the conclusions and recommendations for further research.

Finally, appendix A enlists the tables containing the general data collected for the different sets of connections; appendix B describes the statistical programs used in the study for analysis, and appendix C enlists the curve fitting for each set using the commercial software and Foschi's model.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

In this section a brief summary of some of the most relevant information related to the topic of nailed wood connections will be described. Since joints are one of the weakest points in the structure, systematic research in this area has been conducted for years. As with the building industry, other industries have had the need to study specific joints. In the case of the pallet industry, the nailed joint is still the most common. Some concepts and results of previous lateral load joint studies are included, covering topics such as structural analysis of nailed joints in lateral loading, pallet shook properties, and modelling load-slip behavior of timber joints. In addition, some of the results of the performance of nails and nailed joints in pallets will be described, especially those related to the strength and stiffness of the red alder block pallet connection.

2.1 Prediction of Nailed Wood Joint Properties

The ultimate prediction of the performance of a wood structure is dependent on the performance of the nailed joints. The prediction of the mechanical properties of nailed joints will be influenced by a significant number of variables, especially when they are tested in lateral loading.

Three of the more significant factors in nailed joint behavior are: properties and dimensions of nails and members of the connection, the connection geometry, and the loading conditions.

2.1.1 Fastener

The type of fastener will define the way the force is transmitted in the connection. There are three main forces transmitted through a connection for a dowel-type fastener - (1) shear (lateral load), (2) parallel to the dowel axis (withdraw or axial load), and (3) a combination of the two. DeBonis and Bodig (1975) studied the effect of the combined axial and lateral loading on nailed wood connections. They used a common wire nail, with different depths of penetration in the main member, and three wood species with a wide specific gravity range. They found that the lateral stiffness was influenced by an additional axial load. That is, the initial stiffness was higher when the load was applied in the direction of the nail axis (withdrawal or compression).

McLain and Carroll (1990) conducted research to find the influence of the combined axial and lateral loading in wood connections using threaded fasteners such as lag screws and wood screws. They found that relatively small deviation from pure lateral loading or pure withdrawal loading may be conservatively ignored. They derived design values from the application of different safety parameters to either the test load, defined lateral deformation, or the ultimate withdrawal load.

The performance of a nailed wood connection is affected by the materials from which the nail is made, the way the nail is treated and finished, and its dimensions. ASTM Standard F547-77 indicates that the wire used for nails can be of regular-stock steel (a bright low-carbon steel with $C \leq 0.15\%$), medium low-carbon steel ($0.15 < C \leq 0.23\%$) or stiff-stock steel (a bright, non-hardened, medium low or medium high-carbon steel ($0.23 < C \leq 0.44\%$). Stiff-stock steel is harder, tougher and stiffer than regular steel. Nails made of stiff-stock steel can be heated above the critical temperature, quenched and tempered to increase the hardness, toughness and stiffness at high flexural loads (Ehlbeck, 1979).

Pallets are manufactured with driven nails and staples, bolts, wood screws and lag bolts. Driven fasteners include nails, and double legged staples. The nails used in pallet manufacturing are classified as plain shank, helically threaded, annularly threaded, fluted, and twisted square wire. The National Wooden Pallet Association (NWPA), in its Uniform Voluntary Standard for Wood Pallets, 1994, recommends that the driven fastener length should be sufficient to provide a minimum penetration of 1.25 inch (32 mm) into the stringer or block for all deckboard thicknesses of 0.5 inch (13 mm) or less. This manual specifies the minimum acceptable quality of driven fasteners, as well as the minimum number of driven fasteners per connection for limited use or multiple use pallets.

The present work is focused on the performance of four common types of threaded nails used in the pallet industry (description given in Chapter 3). As explained by Ehlbeck (1979), treated nails are manufactured "by rolling annular, helical or longitudinal deformation onto the shank of the nail after its heading and pointing." Helically threaded nails have continuous multiple flutes which are rolled onto the nail shank.

2.1.2 Wood

A second important factor impacting the performance of the connection is characteristics of the joint members. Properties such as dowel bearing strength and compressive strength, both related to specific gravity, and characteristics such as grain direction, moisture content, member dimensions and wood defects critically influence on the behavior of the connection. Strength and stiffness of a nailed wood connection has been found to be directly related to the specific gravity of the wood members (McLain (1975), Stern, et al, (1973), Wilkinson (1972a), (1972b), (1974a), (1974b), (1991)). McLain (1975) found that the specific gravity of both side and main member influenced the behavior of the load-slip relationship. Wilkinson (1991) studied the dowel bearing strength, one to the inputs of the European yield model, adopted in the NDS manual for setting design values of laterally loaded dowel-type connections. He investigated the effects of specific gravity, dowel diameter, and loading direction for dowels and nails. He found that the dowel bearing strength for nails is related to specific gravity only. In general, the loading direction affects the performance of wood joints because of the orientation of the structural elements in wood. In lateral loading, wood is stronger parallel to the grain than it is perpendicular to the grain.

Wood moisture content influences structures or joints manufactured green (more than 30% moisture content, oven-dry basis), if they are seasoned, or have cyclical changes. Stern (1964) documented the loss of the initial holding power of plain-shank nails when they were driven into green wood with subsequent seasoning. He also found that for helically and annularly threaded nails, the withdrawal resistance increases or decreases with a decrease or increase in moisture content, respectively. Moehler and Ehlbeck (1973) pointed out that helically threaded nails are not subject to the relaxation effect of the wood fibers and the shrinkage effects of wood, so they do not lose their initial holding power when wood is seasoned. When wood is nailed green and tested dry the opposite holds true; the wood fibers became stronger, so an increase in the withdrawal resistance of threaded nails was observed. To account for the influence that wood defects have on the performance of two member wood connections, it is required that the selection of representative materials be on an objective and unbiased basis. Variables such as species of wood and defects such as knots, cross grain, or other natural or manufacturing characteristics, should be avoided to decrease their effect on the joint behavior.

2.1.3 Joint Geometry

The geometry parameters found to influence the performance of laterally loaded nailed wood joints were single, double or multiple shear, member thickness, number of nails, nail clinching, pre-drilled holes, end and edge distances, spacing of nails, angle between nail axis and wood surface or wood orientation, and depth of penetration, Ehlbeck (1979), Colclough (1987), SáRibeiro (1991).

2.1.4 Loading Conditions (rate and range of loading)

The strength of wood connections can be affected by many factors. Least studied of these is the interaction between time and load duration. The behavior of nailed joints is based on the method of application of the load, the time length of application, and whether the load is static or dynamic. Most of the time, these three factors occur together, and the response of the connection will depend on individual factor variation, with the others held constant.

The National Design Specification (NDS) (NF&PA, 1991 edition) established "normal loading" as the load duration basis for wood design values. This normal loading is defined as a load in which a member receives maximum stress to the limit of its allowable design value for a cumulative period of ten years (cumulatively or continuously). It is known that wood structural members are better able to carry a greater maximum load for short periods of time, than for long periods. When maximum load is carried for a year or more, 30-40% reduction in strength has been reported.

Length of time and rate of loading are also important aspects of the design criteria for structures. The design criteria for lateral resistance of nail joints are based on static load tests. These values may not reflect the behavior of a structure under dynamic stress. A more accurate procedure to define structural design values for wood connections subject to dynamic loading has been submitted for approval by Dolan (1993) to ASTM in draft form . Historically, the design criteria for earthquakes and wind have not been defined from dynamic testing. It has been necessary to use values with high safety factor to predict the behavior of structures subject to these forces. Research comparing static and dynamic testing has shown that at small deformations, the joint capacity increase from the higher rate of loading is offset by the joint capacity decrease from load cycling. The variations between statically and dynamically loaded joints are not significant at small deformations and low number of load cycles. Since most code values for connections are based on small deformations and these values have not been changed, this reduction in strength must be considered for design values close to capacity (Soltis and Mtenga, 1985). The evaluation of static and dynamic testing of wood connections with thin and thick member joints, with parallel and perpendicular load and grain directions, have shown important increases in dynamic strength over static strength when the rate of deformation is increased. Girhammer and Andersson's (1988) study showed that the increment of strength increases more substantial in the wood than in the nail.

There are very few studies which define clearly the relationship between time and load. Most remark on the influence of three factors (rate of loading, time of loading, intermittent or constant load). The design criteria for wood structures is based mainly on static procedure testing, and on constant, short-term loads. All these studies call for new, appropriate procedures for defining design values for intermittent creep, damage accumulation (load history), time-dependent loading, and different rates of loading. In the present research, one of the subobjectives is to find how much effect the rate of loading has on the connection performance.

2.2 Evaluation of the Methods to predict the Load-Slip Relationship

One way to empirically obtain a measure of the strength and stiffness of a nailed wood connection is to use the load-slip curve method (Wilkinson, 1971), which consists of testing a sufficient number of joint specimens, and fitting a regression model to the data for numerical simulation to predict the behavior of the load-slip curve. Another empirical method proposed to predict the load-slip relationship of nailed wood joints is the use of an equation developed by Foschi (1973, 1977) to fit the experimental data. Equation 2.1 presents Foschi's three-parameter, nonlinear representation of connection performance, with the initial slope of the curve (K_o) as one of the parameters, the slope of the asymptote (K_2) and the load-intercept (P_o) as the other two. Next the Foschi's model is presented

$$|F_u| = (P_o + K_2 |\Delta|)(1 - e^{\frac{-K_o |\Delta|}{P_o}}) \tag{2.1}$$

Where: $\boldsymbol{\Delta}$ = displacement (in)

$\boldsymbol{F_u}$ = load (lb).

First, Foschi studied the non-linear behavior of the load-slip relationship assuming that the nail yields in bending and the wood under the nail fails in bearing. He developed a theoretical model using finite element approximations and concludes that "this elastic approximation is only acceptable to estimate initial stiffness for the fastening." The model was later improved using finite-element elasto-plastic analysis and describes the derivation of the load-slip characteristics of wood connections using common nails. He showed that his model is in agreement with the initial stiffness and ultimate loads obtained by Wilkinson's method (1971, 1972) and Larsen's methods (1973) as well as with experimental values. Foschi's equation is evaluated in this research to see how well it predicts the load-slip relationships of block pallet connections nailed with threaded fasteners. Kalkert and Dolan (1994) studied the effect of using Foschi's equation with only two-parameters (slope of the asymptote equal to zero), and how the amount of the data affect parameter estimation. They found that it is better to use the three-parameter equation ($K_2 \neq 0$) since the two-parameter equation underestimate the capacity of the connection.

An additional alternative assessed to estimate the strength and stiffness of a nailed wood connection was the method developed by SáRibeiro (1991). He studied the possibility for expanding and improving the load-slip equation [P = A log (1 + BA)] developed by McLain (1975) for nailed wood joints subjected to lateral (shear) loading with different species of tropical hardwoods. The principal variables included in the model were 1) specific gravity of joint members (SG), 2) side member thickness (t), 3) nail diameter (d), and 4) moisture content (MC) of joint members.

He found that the parameter "A" of McLain's equation can be better predicted as a function of MC, SG, t, and nail diameter (d) using the equation,

$$A_{MC} = B_o + B_1\,(SG) + B_2\,(SG \times t) + B_3\,(SG^2 \times d) \qquad (2.2)$$

and that parameter B, can be better predicted as a function of SG, side member thickness and d, using the equation

$$B = B_o + B_1\,(SG) + B_2 \log(t) + B_3\,(SG^2 \times d) \qquad (2.3)$$

The use of the SáRibeiro improved model is restricted to a small range of moisture contents (from 6 to 18%) and since most of the wood tested in this study was over 30% (Fiber saturation point), it was not possible to apply the model to predict the load-slip relationship of the joint specimens in this study. However, the model could predict accurately the load-slip relationship of nailed wood connections manufactured and tested with wood with moisture content from 6 to 18%, using the joint members specific gravity.

2.2.1 Lateral Load (shear load). The theory on how to predict the strength of a laterally loaded nailed joint is known as Moeller's Theory or Yield Theory, since he was the first to apply it to this type of joint. Moeller assumed that the strength in the structure is dependent on the strength of the elements, that is the yield moment of the nail and the dowel bearing strength of the wood below the nail (Ehlbeck, 1979). This theory assumes that there is no deformation in the connection below the yield point. In 1991 the yield theory was adopted by the National Design Specification for Wood Construction (AF&PA, 1993) for dowel type connections.

Two basic types of failures can occur when wood nailed connections are laterally loaded (single shear connections):

1) The wood will fail first while the nail will remain stiff (Figure 2.1) .

2) The yield moment of the nail is reached first before the wood fails (Figure 2.1 Connection Yield Modes).

In both cases the wood member thickness will determine the type of failure in the joint (Ehlbeck, 1979).

After Moeller, several other scientists have contributed to the yield theory, as it is now known. These works are summarized by Aune and Patton-Mallory (1986). Their published work refers to these studies and their own contribution to the yield theory, and extends it to include steel-to-wood joints and joints with a layer of insulation (or gap) between joint members. Aune and Patton-Mallory (1986) also presented the formulas to

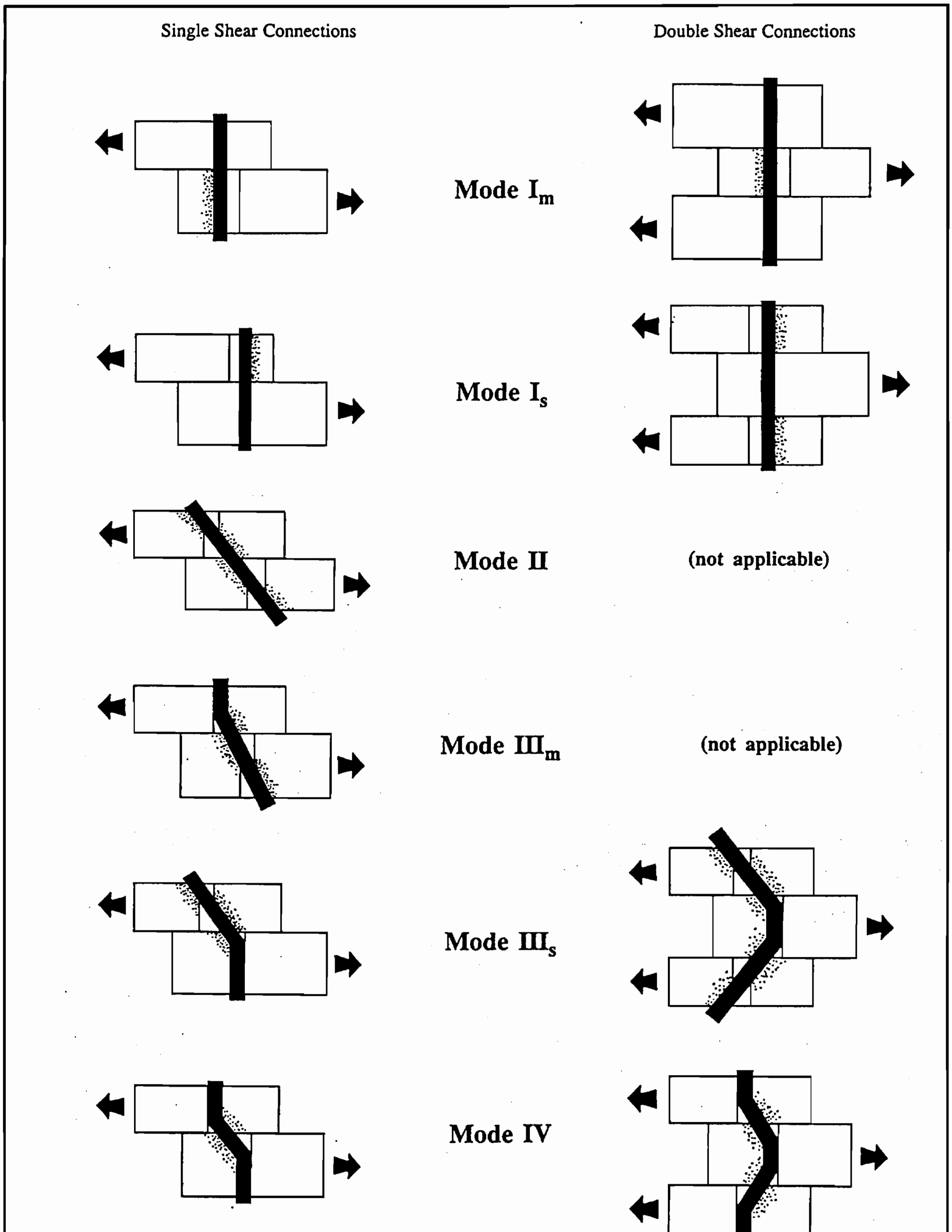


Figure 2.1 Connection yield modes (1991 NDS, AF&PA).

estimate the ultimate load for wood-to-wood and steel-to-wood joints and joints with unequal wood strength in the main and side members. A formula (based on the yield model) to predict the stress-deformation of the wood was developed by substituting a fourth-order curve for the traditional plastic embedment behavior (Aune and Patton-Mallory 1986).

Aune and Patton-Mallory (1986) did the experimental verification of the yield theory to predict the ultimate lateral stress using species and joint geometries typical of construction in the United States. The strength of different nailed joints under short-term loading was determined using the wood and nail properties and confirmed by experiments. The results showed very good agreement between predicted and experimental response. The application of the yield theory to predict the load-deformation of the connection was confirmed. However, the results show a good agreement above deformations of 0.12 inch (3 mm), but poor predictions in the first part of the curve.

As stated above, the two properties required to use of the yield theory are the dowel bearing strength of the wood and the nail yield moment. The dowel bearing strength is defined as "...the property of connection members that imparts resistance to embedding of a dowel" (Wilkinson 1991). Wilkinson investigated the effect of specific gravity, dowel diameter, and loading direction for bolts and nails. He established that the dowel bearing strength for nails is related primarily to specific gravity.

No standard method for evaluating dowel bearing strength existed until 1992, when a draft ASTM standard was proposed. This method sets the basic procedure for evaluating dowel embedding strength of wood and wood-based products. In this study, the nail yield moment was estimated by subjecting the nails to three-point bending tests following the procedure proposed by the draft ASTM Standard Test Methods for Determining the Bending Yield Moment of Nails (1993).

2.2.2 Stiffness of a Wood Nailed Joint. The stiffness of a nailed connection has been described for many years following the elastic theory, and all the developed equations assumed that deformations were elastic up to the proportional limit. It was also assumed that the curve remained linear in the range up to the proportional limit. However, this is often not true when there is no contact between nail and wood at the beginning of the test. The required condition of tight contact has been achieved by loading and unloading a number of times (Ehlbeck). Wilkinson (1971) used this procedure to perform the tests used to derive his load-slip relationship, which is only valid in the assumed linear load range.

Another approach to predict the load-slip behavior of a nailed connection is to use an empirical formula that fits the test data. This approach is described by Ehlbeck (1979). Of all these methods, the one suggested by McLain (1975) has been most commonly used (Pellicane, Stone, and Vanderbilt 1991), (SáRibeiro and Pellicane 1992), but, it is only valid for slip up to 0.1 inch (2.54 mm).

For slips up to 0.1 inch (2.54 mm), McLain's model [P= A log (1+BA)]can be used for prediction. In this model, the empirical parameters, A and B, will be predicted as a function of the specific gravities of the main and side members [McLain (1975), Pellicane, Stone and Vanderbilt (1992)]. The equation recommended by Pellicane et al. (1992) for solid wood members is:

$$A = 205.3 - (232.2/SGS) - [32.4/(SGS*SGM)] \qquad (2.4)$$

Where SGS, SGM = specific gravity (based on volume at 12 per cent moisture content) of the side and main member, respectively. This equation has a correlation coefficient (r) of at least 0.78. For the parameter B, Pellicane et al. (1992) suggested the use of McLain's equation and prediction of a point in the load-slip curve. Rearranging McLain's equation to solve for B results in the equation:

$$B = 10^{P/A} - 1/Deflection \qquad (2.5)$$

Because one of the objectives of this study is to predict deformations over 0.250 inch (6.35 mm), it is proposed that a combination of the Foschi's method, and the yield theory method described by Aune and

Patton-Mallory (1986) can be used for prediction of the entire curve of interest, Foschi's method would be used for prediction of the load-slip relationship and the yield theory method would be used for defining the maximum strength at capacity of the nailed wood connection.

2.3 Testing Methods

Several different testing methods were used in this research. For the Yield Mode Theory two methods were used: Dowel Bearing Strength and Nail yield Moment. To determine the strength and stiffness offered to lateral cyclic movement, a Modified Sequential Phased Displacement Testing Procedure (SPD) was used. Supporting the SPD two additional methods were used, the monotonic lateral test and the fully-reversal cyclic test. These tests are explain in more detail in chapter 3.

CHAPTER 3

MATERIALS AND METHODS

3.0 Introduction

Research in wood connections with threaded nails was conducted using a dynamic, modified sequential-phased displacement procedure. The details of the testing program are described in this chapter. The focus of testing was to appraise the strength and stiffness of two-member, three-nail connections, tested in shear. The main species used in the construction of the joint specimens were red alder (*Alnus rubra*), southern yellow pine (*Pinus sp.*) and white oak (*Quercus sp.*).

The determination of strength and stiffness was accomplished by the use of a modified half-reversal cyclic shear testing of the joint specimens. The theoretical yield mode equations were also used to predict the capacity or strength of the connections. In order to determine the material properties for the equation, tests of dowel bearing strength and nail yield moment were performed. These tests are described in detail in the following pages. This chapter also describes the equipment and techniques used to test the specimens, the specimen geometry, and the methods developed for analysis of the data.

Definitions of frequently used terms in this thesis are:

Strength or Capacity -Measure of maximum load that the connection can carry before failure, or the load associated with a 0.7 inch displacement. This displacement was chosen as "capacity" because the maximum gap found in the standard test of block pallets was smaller than this distance, and because it was found that most red alder nailed wood connections tested failed at deflection less than 0.7 inch.

Stiffness (initial stiffness) -Measure of the slope of the load/slip ratio given by the tangent line drawn over the initial linear part of the curve.

Deckboard or Side Member -Element or component of pallet top and bottom deck, perpendicular to stringers or stringerboards (Uniform Voluntary Standard for Wood Pallets [UVSWP], edited by the National Wooden Pallet and Container Association [NWPCA] 1994). For these connection specimens, it was the thinner element of the two wood members.

Block or Main Member -Rectangular, square, multisided, or cylindrical deck spacer, often identified by its location within the pallet such as a corner block, end block, edge block, inner block, center, or middle block (UVSWP [NWPCA] 1994). For these connection specimens, it was the thicker element of the two wood members.

3.1 Materials

All the red alder wood was obtained green from the inventories of two different pallet manufactures in Oregon and Washington, while the southern yellow pine and white oak were collected from a sawmill located in the western Virginia area. The wood was received as 7/8 inch and 1/2 inch thick by 6 inch wide by 48 inch long boards, and 4 inch thick by 6 inch wide by 8 and 10 ft long timbers. The 7/8 inch thick boards were planed to 3/4 inch and 5/8 inch thick specimens, and the 1/2 inch thick boards were used for the 1/2 inch thick side members. To keep the wood wet (above the fiber saturation point), one third of the wood was wrapped in polyethylene sheets, and stored in a cold room at 40°F (4.4°C), and the other two thirds were stored submerged in fresh water until specimen fabrication and testing. The deckboard (side member) specimens were sawn to 5.5 inches (139.7 mm) wide by 12 inches (304.8 mm) long. The blocks (main members) were sawn and planed to 3.5 inches (88.9 mm) in thickness, by 5.5 inches (139.7 mm) in width by 6 inches (152.4 mm) in length.

Four types of helically threaded nails were selected for the present work. They represent some of the most commonly used fasteners in the pallet industry. The properties of the nails (MIBANT angle, thread angle, difference between wire and thread diameter) define not only the strength and stiffness of the fastener but also its quality.

3.2 Experimental Design (Test Procedure)

In this study, experimental testing of the isolated butted nail connection is used as a basis to analyze the strength and stiffness of a perimeter block pallet subjected to dynamic loads and deformations beyond 0.1 inch (2.54 mm). The visual analysis of block pallets during loading, has shown the following actions: 1) the nail embeds in both the wood of the deckboard and the wood of the block, 2) the nail head indents into the surface of the deckboard (side member), 3) the nail shank withdraws from the main member (block), and 4) the nail yields in bending under the action of the lateral force. In order to estimate the high deformation (gap) created in the bottom butted nail joints of block pallets, it is hypothesized that:

1. The pallet is racked across stringerboards (RAS).

2. Although lateral and withdrawal forces cause the high deformation (gap), the withdrawal force is small compared to the lateral force. Therefore, it is assumed that the butted nail joint is under pure lateral load. This idea has been experimentally investigated by McLain and Carroll (1990).

3. The lateral loading behavior is a function of fastener and wood characteristics.

For the definition of the stiffness and strength of this pallet connection a modified sequential phased displacement (SPD) procedure was used. This procedure was used, first, to account for the repeated loading and unloading that pallets endure throughout their normal life (this method simulates the effects caused by cyclic loading) and second, to define if there is any important difference in results that could be due to the method of testing (between the standard monotonic test and the dynamic test procedure used in this study). This dynamic testing method has already been used by Gutshall (1994), to determine if the seismic load duration factor was appropriate and to define the effect of previous load history from cyclic loading on connections. The latter portion of Gutshall's study is similar to what was used in this study.

It is assumed that the mechanical properties of this type of connection can be predicted from the mechanical properties of its parts, fastener and wood. Nail characteristics are illustrated in Figure 3.1 and described in Table 3.1. The description includes, hardness, length, head size, diameter, and thread characteristics. Wood characteristics include specific gravity, moisture content and deckboard thickness. Unless otherwise stated, all wood was assembled green and tested green. The analysis of this study is concentrated on the following points:

1) A main statistical block consisted of four types of nails and three different thicknesses of wood. These were tested with three nails per joint and one pattern to determine the connection strength and stiffness (Table 3.2)

2) Two sets of fifteen specimens each were tested with reduced friction to define the effect of friction on strength and stiffness of the connection (Table 3.3). To reduce the friction on the joint specimens, two sheets of polyethylene with lithium grease in the middle were put between the two wood members at the time of assembling.

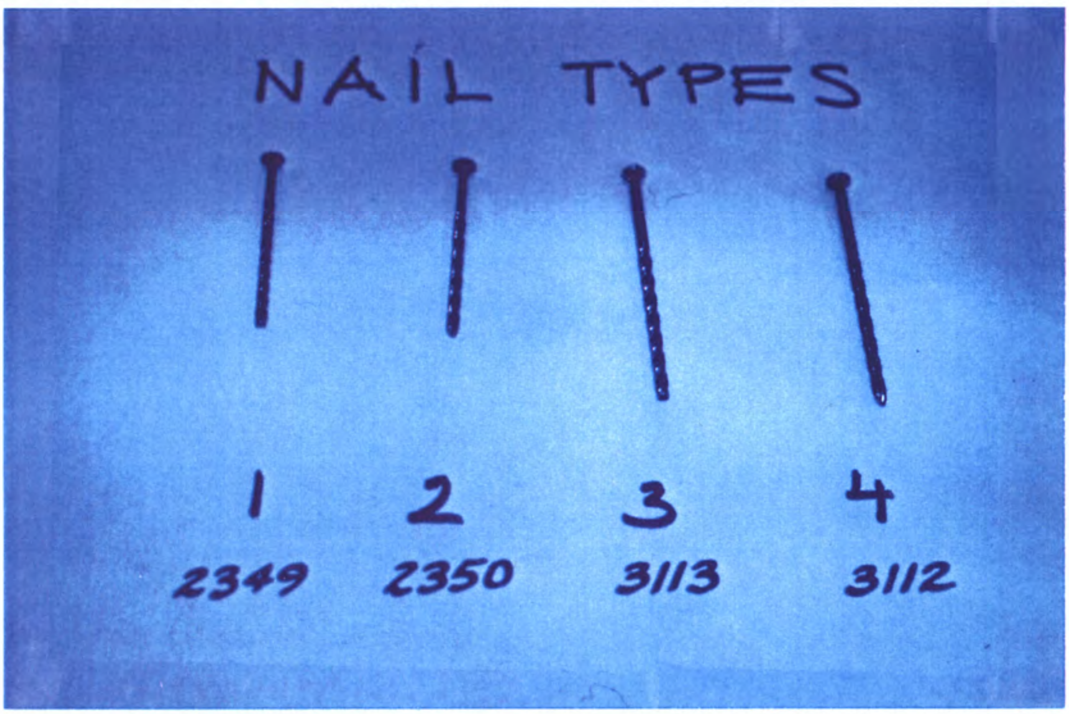


Figure 3.1 Types of nails used in the study.

Table 3.1 Average Properties of the Four Nail Types.

PROPERTY[1]	NAIL 1	NAIL 2	NAIL 3	NAIL 4
Length (in)	2.25	2.25	3.00	2.86
Wire diam (in)	0.111	0.111	0.120	0.121
Head diam (in)	0.281	0.276	0.272	0.276
ATD. (in)	0.127	0.126	0.135	0.138
T. angle (deg)	62	68	68	67
T. length (in)	1.75	1.625	2.00	1.81
No.helix	8/1.50	6/1.65	7.5	7.0
Flutes	4	4	4	4 & 5
MIBANT (deg)	27	48	28	18
VPI No.	2349	2350	3113	3112

1.The nail properties described are: nail length, wire diameter,head diameter, average thread diameter (ATD), thread angle, thread length, number of helices, number of flutes, and MIBANT angle.

Table 3.2 Cyclic Lateral Loading Test

Statistical Block Design

		Side Member Thickness		
		3/4"	5/8"	1/2"
NAIL TYPE	NAIL 1	n=15	n=15	n=15
	NAIL 2	n=15	n=15	n=15
	NAIL 3	n=15	n=15	n=15
	NAIL 4	n=15	n=15	n=15

Joint specimen characteristics: red alder deckboard (Side Member). Three thicknesses (3/4 inch, 5/8 inch and 1/2 inch). Four nail types. Pattern "A", three nails connections.

Table 3.3 Friction Effect[1]

		Side Member Thickness	
		3/4"	1/2"
NAIL	NAIL 3	n=15	n=15

[1]The comparison was done against two sets of specimens from the main statistical block design (Table 3.2).

3) Sets of specimens with one, two and three nails were evaluated to predict the effect of differing numbers of nails on the strength and stiffness of the connection (Table 3.4),

4) Two sets of fifteen specimens each, using white oak (*Quercus sp.*) and southern yellow pine (*Pinus sp.*), were tested and compared to the red alder results to determine the effect of differing specific gravities on the strength and stiffness of the connection (Table 3.5),

5) Two sets of fifteen specimens each, the first was assembled green and tested dry (15% MC), and the second was assembled dry and tested dry, were tested and the results compared to the assembled green and tested green results, to define the effect of moisture content (Table 3.6),

6) Fifteen specimens were tested using a different nailing pattern, to investigate any change in the response of the connection (Table 3.7 and Figure 3.2),

7) Fifteen joint specimens were used to define the effect of rate of loading on the strength and stiffness of the connection (Table 3.8)

These 23 sets of 15 specimens each comprised the target of 345 joint specimens for this research.

Table 3.4 Number of Nails Effect[1]

		NUMBER OF NAILS	
		ONE	TWO
NAIL TYPE	NAIL 2	n=15	n=15

Table 3.5 Species Effect[1]

		SPECIES	
		W. OAK	S. Y. PINE
NAIL TYPE	NAIL 3	n=15	n=15

Table 3.6 Moisture Content[1]

		MOISTURE CONTENT	
		GREEN-DRY	DRY-DRY
NAIL TYPE	NAIL 3	n=15	n=15

[1] The third set of specimens for Tables 3.4, 3.5, and 3.5 was taken from Table 3.2 for comparison.

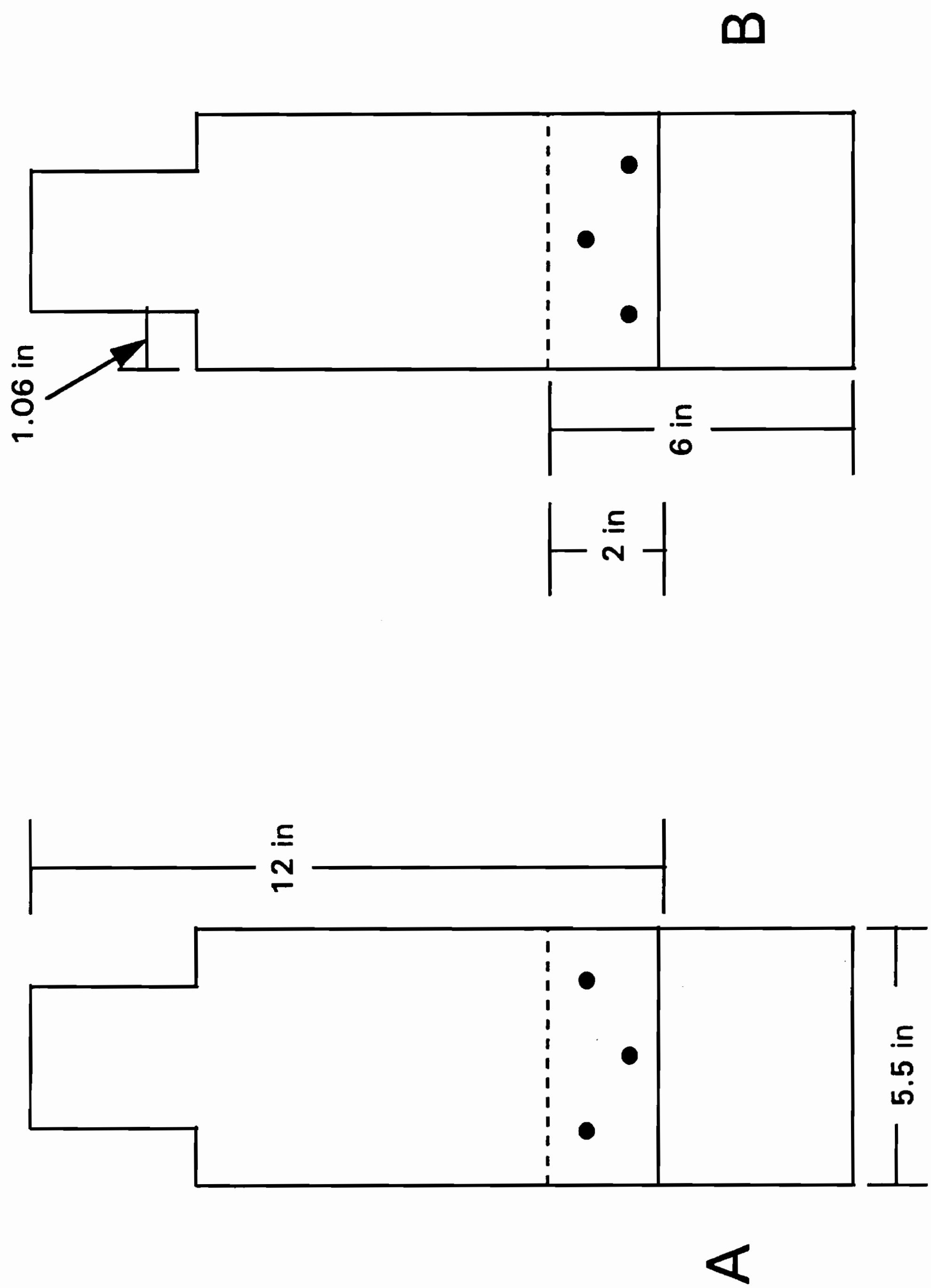


Figure 3.2 Types of nail patterns. Pattern B was used for comparison.

Table 3.7 Pattern Effect[1]

		Side Member Thickness
		5/8"
NAIL TYPE	NAIL 3	n=15

NOTE: All the previous tests were done at a rate speed of 1 hertz.
[1] Compared against the 5/8"-nail type 3 from Table 3.2.

Table 3.8 Rate of Loading[1]

		Side Member Thickness
		5/8"
NAIL TYPE	NAIL 1	n=15
	NAIL 3	n=15

NOTE: Both sets were done at a rate speed of 1/2 hertz.
[1] The comparison was done against sets from Table 3.2 and the set of specimens from the monotonic test.

3.2.1 Monotonic Testing

This study started with monotonic lateral tests with a rate of loading of 0.1 inch per minute in compliance with ASTM D 1761 "Standard Test Methods for Mechanical Fasteners in Wood" (1993). All joint tests were performed up to their ultimate capacity or a 0.700 inch (18 mm) slip, whichever occurred first. This displacement was set as capacity because 1) the desired observable deformation in this research fell securely within this range; 2) it was observed that most of the joint specimens failed before this displacement; and 3) it was simpler to create a program with 18 phases of the modified sequential displacement procedure than to modify the displacement in the original computer program. For the monotonic tests, the data was acquired at the rate of five readings per second. The monotonic tests were performed to:

1) Define the First Major Event (FME) for the Sequential Phased Displacement Testing, and

2) Compare the strength and the stiffness values of monotonic testing to the values found from cyclic testing.

One set of 15 nailed connections was tested using 5/8 inch thick boards and type 3 nails, and the design value was estimated using the values given in the National Design Specification (NDS) manual (NF & PA, 1991 Edition). The design load was found on the load-slip curve created from the monotonic test and the related displacement was defined as the first major event (FME) estimate for that type of connection. Figure 3.3 shows this concept graphically. The average FME value from the 15 replications was used as first major event (FME) for controlling the modified sequential phased displacement (SPD) procedure.

3.2.2 Cyclic Testing

In this study two types of cyclic tests were performed 1) fully-reversing and 2) modified sequential phased displacement. The fully-reversing tests used a rate of 1 Hertz (Hz) and consisted of a fully-reversing displacement-controlled test that produces 10 cycles each at ± 0.100 inch, ± 0.160 inch, ± 0.200 inch, ± 0.300 inch, and ± 0.400 inch displacements. These tests were conducted to determine the number of cycles required to produce a stabilized load-slip response. It was found that after the third cycle there was less than 5 percent difference between each subsequent cycle, so three was defined as the number of cycles required to obtain the stabilized response. The definition given by Gutshall (1994) explains the criteria followed to define the stabilized hysteresis curve; "The connection was considered stable when the decrease in peak load between successive cycles was less than five percent", see Gutshall (1994), Dolan (1993), and Dolan and Gutshall (1994). This number of stabilizing cycles was then used in the sequential phased displacement testing.

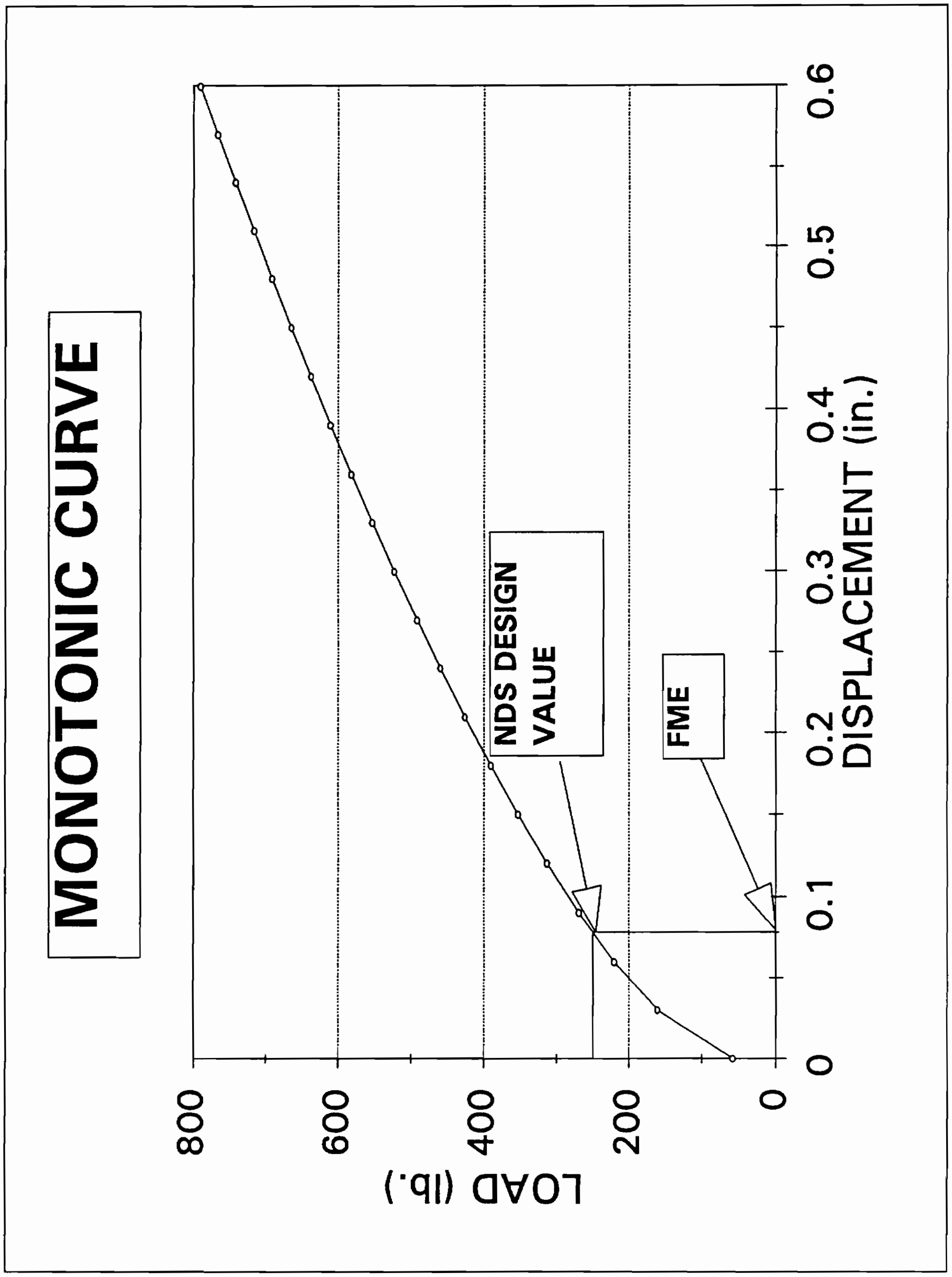


Figure 3.3 Definition of the First Major Event (FME).

3.2.3 Sequential Phased Displacement

The second type of cyclic testing used was the Sequential Phased Displacement Testing (SPD) procedure, this was the method used to test most of the joints in this study. This modified procedure is under consideration as an ASTM standard test procedure for dynamic testing of connections with mechanical fasteners, Dolan (1993). The procedure was modified for the particular requirements of this research. A similar procedure was followed, but the method differs from the full reversal cycling in that this study used only a one-sided cyclic test. While the displacement in Gutshall's procedure begins at zero with displacement in the positive direction, passes through the origin and continues in the negative direction to complete a loop at zero, the procedure used in this study was initiated at zero, reached a maximum displacement, and returned to zero (Figure 3.4). The pattern of this test procedure involves constant increments in displacement until a first major event (FME) occurs, then three relaxation cycles, followed by a series of cycles at the first major event level, until stabilization is reached. After stabilization, the displacement at the FME is doubled one cycle (the displacement goes from 100% to 200%), followed by the three relaxation cycles and the stabilization cycles are repeated. The process is illustrated in Figure 3.5. A total of seven cycles are conducted to produce one phase (one cycle at FME displacement, three decay cycles,

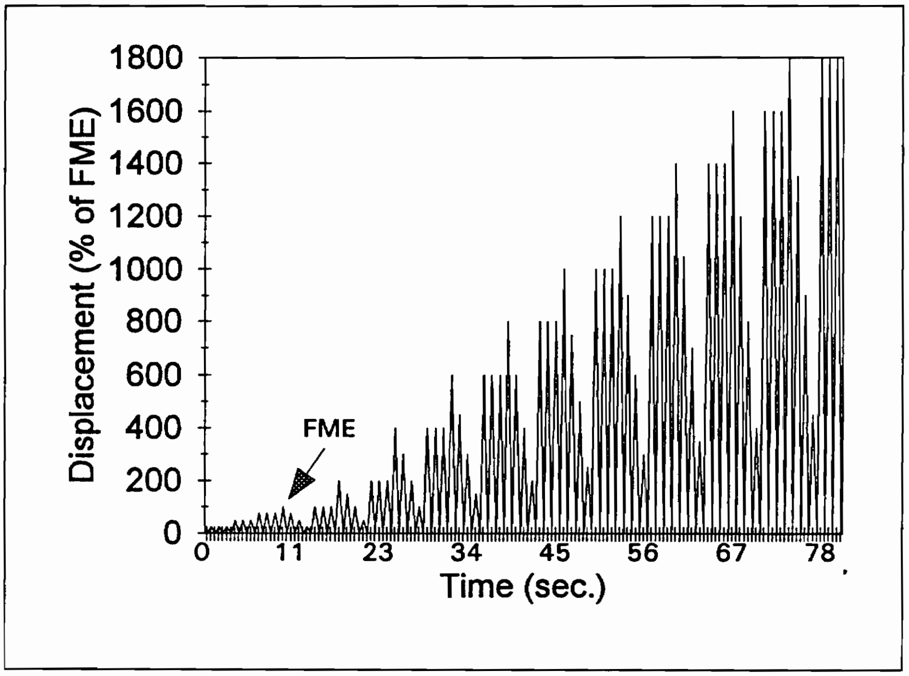


Figure 3.4 Sequential Phased Displacement Procedure used in this study.

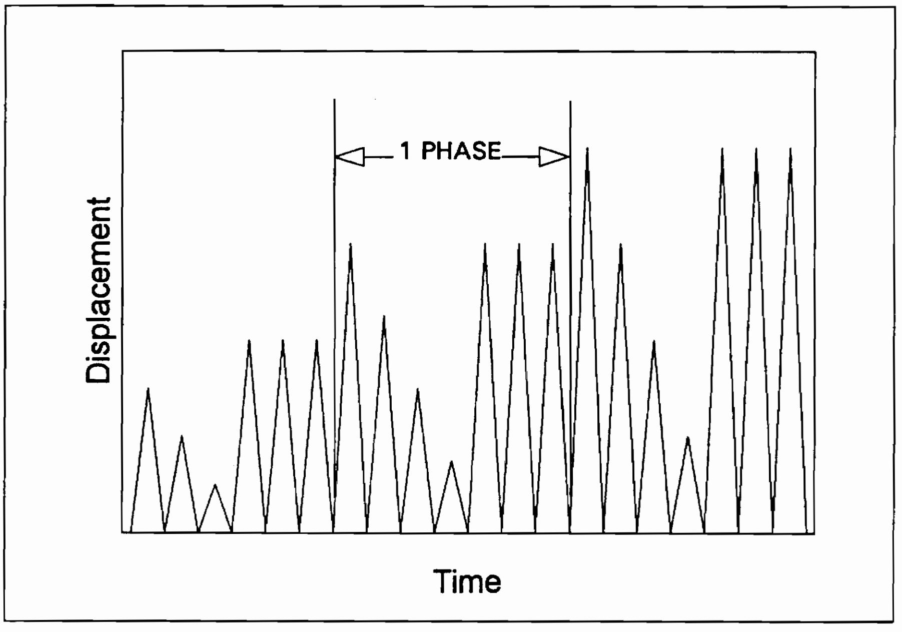


Figure 3.5 Displacement pattern for one phase of the sequential phased displacement procedure.

and three stabilization cycles at the initial FME displacement); hence the name of the procedure (sequential phased displacement). Gutshall (1994) describes the details of this procedure.

In this work a modified sequential displacement procedure was used instead of the monotonic ASTM procedure D 1761-88 "Standard Test Methods for Mechanical Fasteners in Wood" (1993) because it is believed that the modified procedure better describes the behavior of pallet connections that are exposed to repeated loading and unloading as well as dynamic work in service. Furthermore, the same test can be used to estimate the monotonic and stabilized hysteresis curves by using the first and final cycle peak points, respectively (Figures 3.6, and 3.7).

The sequential phased displacement procedure used in this study for the red alder, southern pine and white oak joints had 18 phases, from 100% FME to 1800% FME. The average displacement value used for all three thicknesses of red alder wood in the green state start with a first major event (FME) value of 0.039 inch and, after 18 phases, the last displacement was estimated to be 0.700 inch, which was accomplished by setting the span on the MTS test machine to 28 percent from a full displacement of 2.5 inches. The FME value was determined from the monotonic curve by finding the displacement that corresponds to the nominal design load value for that connection, as given by the National Design Specification (AF & PA, 1991

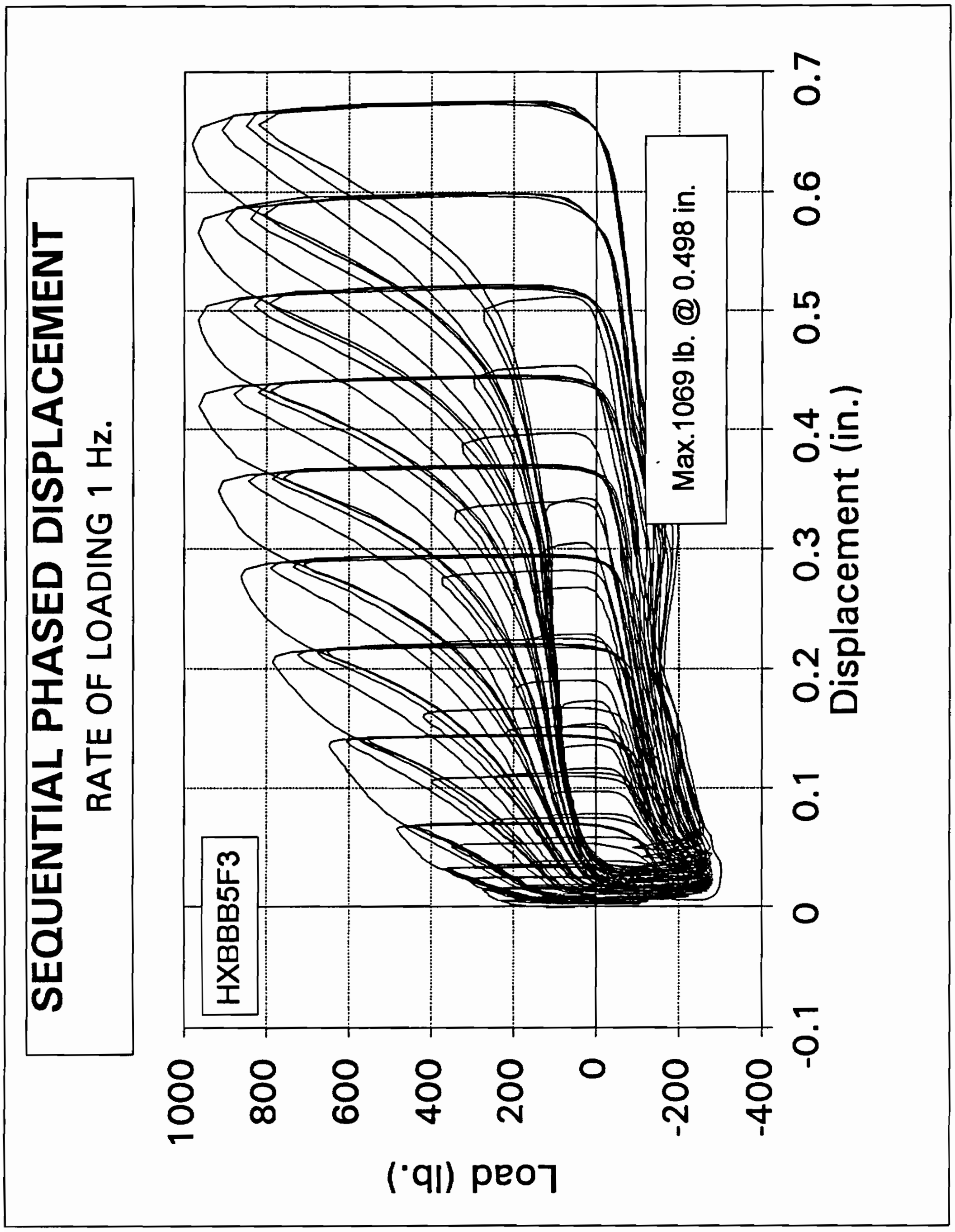


Figure 3.6 Typical load-displacement curve for the red alder nailed connections tested under lateral cycling using the SPD procedure.

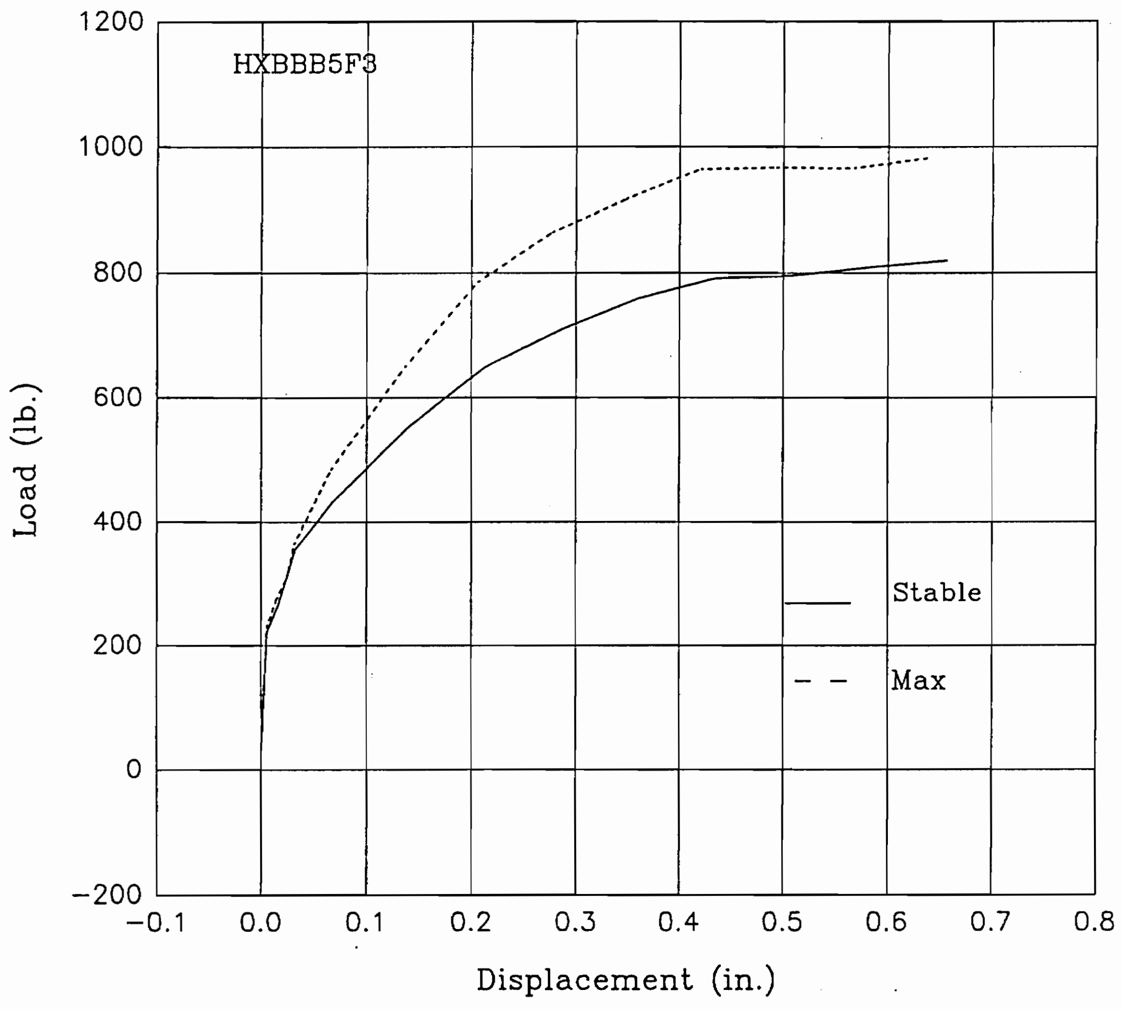


Figure 3.7 Backbone curves derived from the cyclic hysteresis curves.

edition). In the same way, the number of cycles for stabilization was found from the fully-reversing cyclic testing as explained in section 3.2.2. The same methodology was followed to define the FME value for white oak and southern yellow pine (monotonic tests to define the first major event [FME], cyclic test to define the number of cycles for stabilization). The estimated FME for white oak was 0.019 inch with a maximum displacement of 0.342 inch, for southern yellow pine the same FME as for red alder was used (0.039 inch).

Separate FME values had to be established for different connection geometries using one, and two nails per joint. The estimated FME value for red alder connections with one nail per joint was 0.031 inch, with a maximum estimated displacement at the end of the test of 0.558 inch. For two nails per joint the FME was 0.024 inch with a maximum value of 0.434 inch. The majority of the testing was done at a rate of loading of 1 Hz, however, two sets of 15 specimens each were tested at 1/2 Hz to estimate the influence of the rate of loading on the connection strength and stiffness. Data was collected at a rate of 98 points per second during the 1.0 hz test which took 94.2 seconds to complete. Data was acquired at a rate of 45 points per second for 178.5 seconds during the 0.5 hz tests.

3.2.4 Yield Mode Equation

A semiempirical model based on the yield theory was used for predicting capacity of two-member joints with all-wood members. It was found that the nail connection behavior can be described by one of the basic modes of joint yielding. To predict this capacity two properties were determined dowel bearing strength and nail yield moment.

3.2.4A Dowel Bearing Strength

The dowel bearing strength test provides the basis for determining the stiffness and embedding yield strength of the wood specimens. The test consists of embedding a fastener into a hole across the thickness of the wood specimen, so the fastener does not bend. The load and deflection are measured (Figure 3.8). The tests were conducted on a hydraulic universal testing machine, material test system (MTS), in such a way that a compressive load was uniformly applied to the fastener along its length. A constant crosshead movement rate of 0.025 in/min (0.635 mm/min) was used. This rate causes the maximum load to be reached in 2.5 to 5 minutes. The embedment was measured with the linear variable differential transducer (LVDT) built into the MTS machine.

The specimens were prepared following the proposed ASTM standard (1992). Configuration and dimensions of the specimen used are shown in Figure 3.9 and include a half hole bored perpendicular to the faces of the

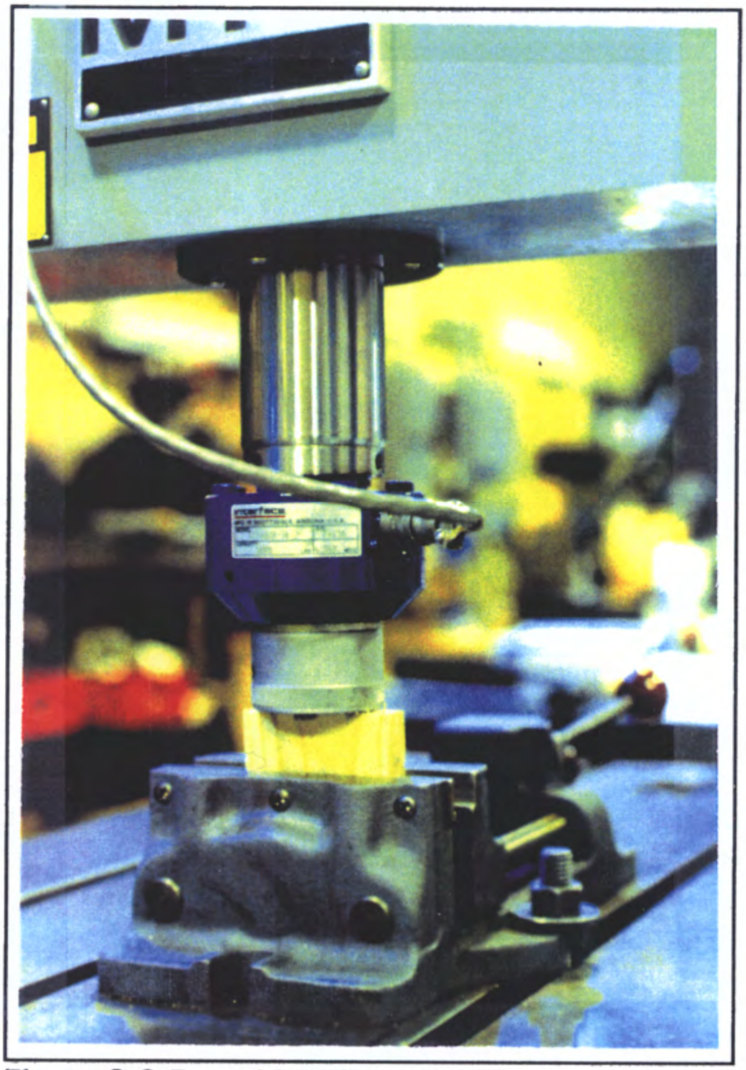


Figure 3.8 Dowel bearing strength test setup.

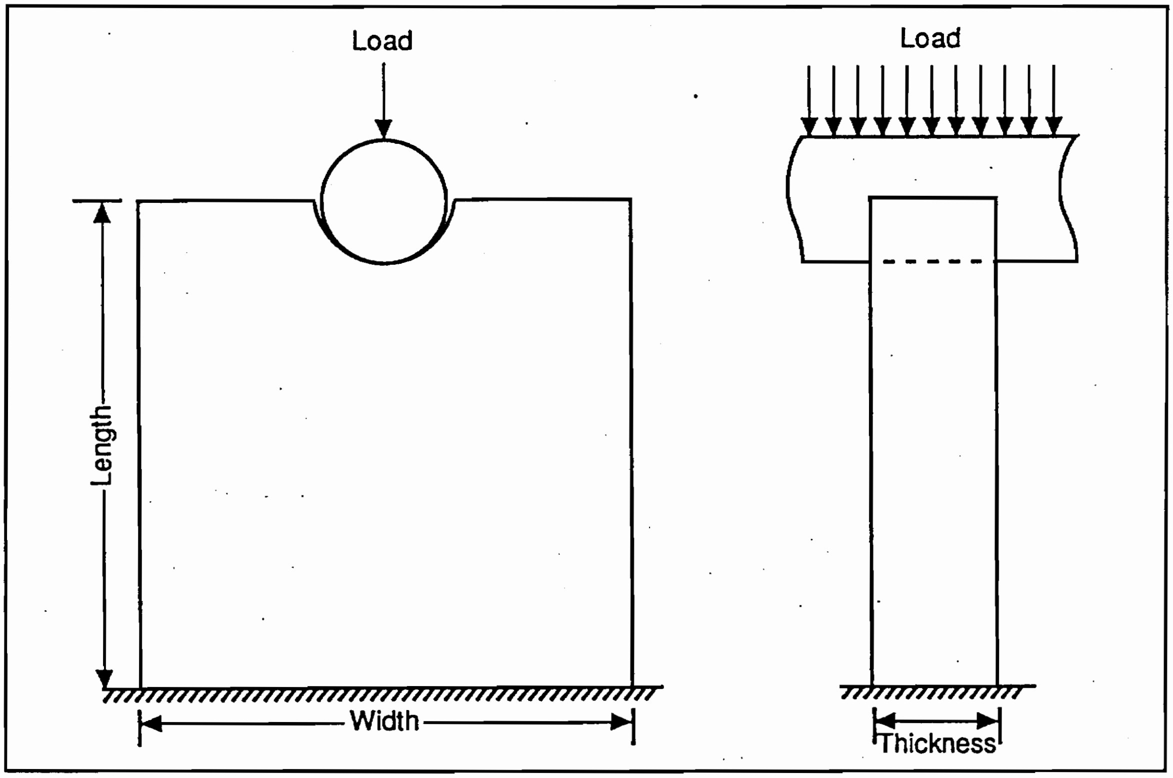


Figure 3.9 Schematic of the dowel bearing test used by Wilkinson (1991).

specimen to simulate the embedment hole of the driven fastener. The hole diameter bored in the wood was 75% of the nail diameter, or less. The moisture content and specific gravity of the material was measured after testing by the ASTM method B-Volume by water immersion, 1993 (ASTM standard D2395-83 "Standard Test Methods for Specific Gravity of Wood and Wood Based Materials").

All tests were conducted using 3/4 inch thick specimens and only nail type 3, because this nail type was determined to be the most representative of the four nail types tested. The rationale for this decision was that there is no significant difference between the test results for the specimens with nails of wire diameter 0.111 inch and specimens with nails of wire diameter 0.120 inch (Wilkinson, 1991). Red alder was tested with two moisture contents; green (moisture content higher than 30 percent) and with an average moisture of 15 percent. Southern yellow pine and white oak were tested green only. Table 3.9, illustrates the experimental design for each species. A total of 36 repetitions were tested.

Table 3.9 Dowel Bearing Strength Test

Statistical Block Design

		MOISTURE CONTENT	
		GREEN	DRY
SPECIES	RED ALDER	n=15	n=15

Characteristics: 0.75 in thick deckboard, 0.120 in nail diameter.

3.2.4B Nail Yield Moment

Four types of helically threaded nails were evaluated for nail yield moment and nail stiffness. Each test had 15 repetitions for each nail type. The nail yield moment was obtained by subjecting the nails to forces under the three point load set up as shown in Figure 3.10. The span was adjusted for each nail size so that the transition zone between shank and thread was

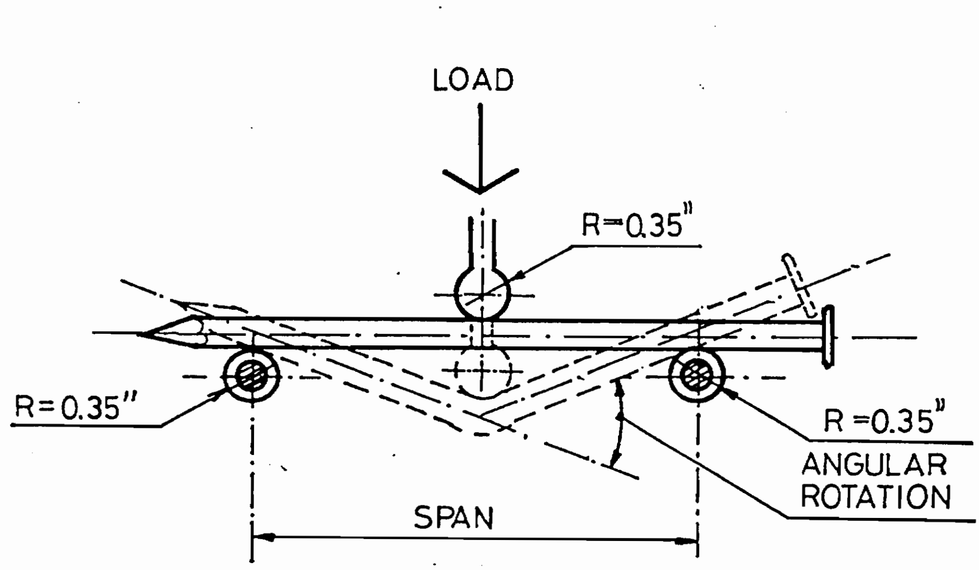


Figure 3.10 Center point nail yield moment test (Loferski and McLain, 1990).

as close to the midpoint between the bearing points as possible, but the load was never applied on the transition zone. The rate of loading was "such that the rate of deflection did not exceed one nail diameter per minute", Stern (1993); or less than 0.12 in/min for the 2.25 inches nail (wire diameter of 0.111 inch) and 0.16 in/min for the 2.86 and 3 inches nail (wire diameter of 0.121 and 0.120 inch, respectively). All the helically threaded nails were tested following the procedure described by Stern (1993) in the proposed ASTM standard. The block design of these tests is shown in Table 3.10.

Table 3.10 Nail Yield Moment

Statistical Block Design

NAIL TYPE	NAIL 1	n=15
	NAIL 2	n=15
	NAIL 3	n=15
	NAIL 4	n=15

3.3 Testing and Analysis Equipment

All testing in this study was done in the facilities of the Wood Engineering Laboratory of the Brooks Forest Products Research Center in the Department of Wood Science and Forest Products at Virginia Polytechnic Institute and State University, in Blacksburg, Va. Testing involved the use of a 22,000 lb capacity MTS (Material Test System) servo-hydraulic universal testing machine for the displacement-controlled monotonic, and cyclic connection tests,and for the dowel bearing strength and nail yield moment tests. In the two displacement-controlled tests, two linear variable differential transformers (LVDTs) were used to measure the displacement. The two LVDTs, mounted on opposite sides of the specimens, measured the average displacement of the deckboard relative to the block (Figure 3.11), and a 5,000 lb capacity load cell measured the load. The potential effect of rotation of the side member about the main member causing erroneous readings was eliminated by averaging the data from the two displacement LVDTs. Thus, the advantages of using two LVDTs connected to the members to measure displacement (instead of the one inside the MTS machine), are seen in the measurement of the real slip at the connection. In this way the reading does not include in the measurement the slippage of the grip holding the specimen, nor any rotational effect caused by the moment induced by variations in the three nail pattern of the connection (Figure 3.12). The test fixture used to test the nailed connections is the same as that used by Gutshall (1994) and is similar to the one used by Liu and Soltis (1984). The fixture is designed to eliminate the effect of eccentricity in lateral testing of two member connections. In the dowel bearing strength tests and nail yield moment tests, only the built-in LVDT of the MTS machine was used to measure displacement.

Two IBM microcomputers were used, one for function generation to control the Hydraulic actuator position, and the other for data acquisition. The first one used commercially produced software called Global Lab (registered trademark of Data Translation, Inc. 1991), to convert the digital information produced in the custom-designed Sequential Phased

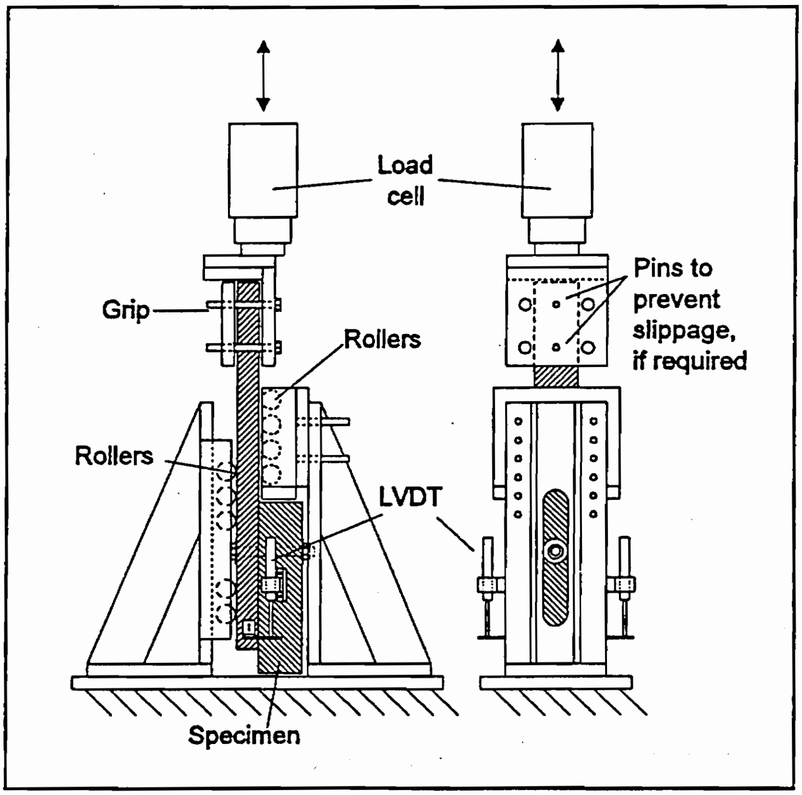


Figure 3.11 Laterally-loaded connection test fixture (Gutshall, 1994).

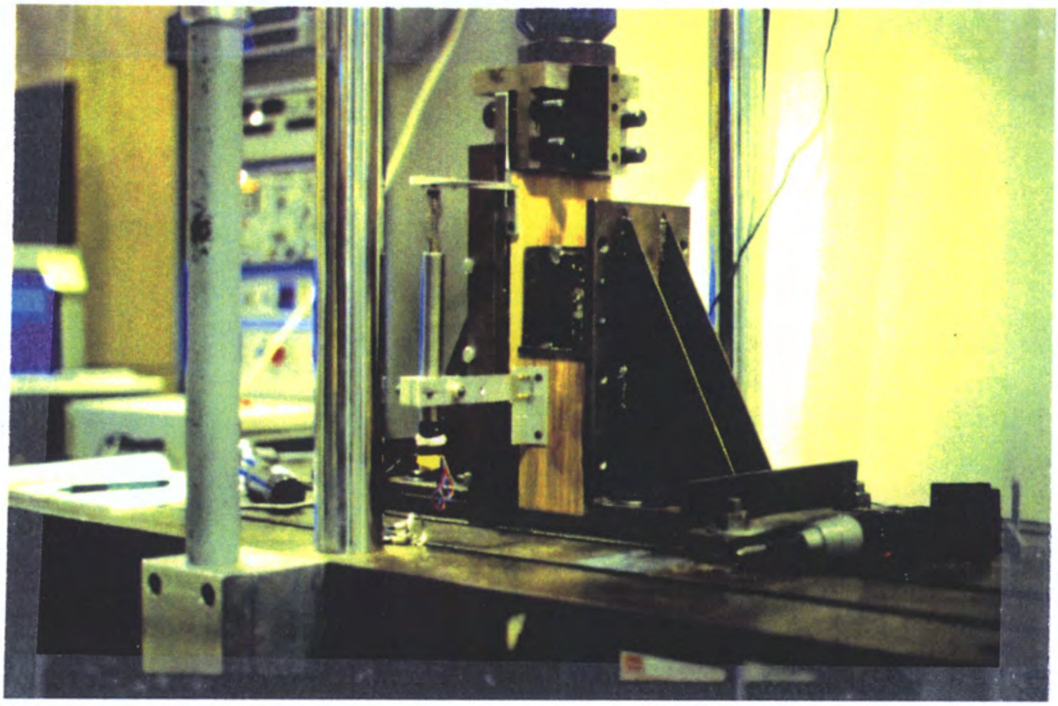


Figure 3.12 Test fixture and specimen at time of testing.

Displacement Procedure (SPD) program to the analog system of the MTS, for control of the testing. The second computer used ADAQ, (Analog Data Acquisition) a software developed at the department of Wood Science and Forest Products at Virginia Tech by Robert Carner (1994) for data acquisition.

The analysis of the data was done using several commercial software programs including Quattro Pro (Borland International, 1992), TableCurve (a registered trademark of Jandel Scientific,1991), and SigmaPlot (Norby, John, et al. 1992). The statistical analysis was done using SAS (SAS Institute, Inc. 1992) on the IBM mainframe at Virginia Tech.

3.4 Connection Geometry

Only one connection geometry was used for this study (Figure 3.13). It represents the nail butted connection that is found in the bottom of perimeter block pallets. A single shear connection specimen with one, two,or three nails per joint, using three different deckboard thicknesses (1/2 inch, 5/8 inch, and 3/4 inch) was used. There was no predrilling in the joint specimens made of red alder and southern yellow pine, but it was necessary to predrill holes before driving the nails into the oak joint specimens. This was because of white oak's high density (average ovendry specific gravity of 0.74) and splits formed when the nails are driven without predrilling holes. The nails were all driven by hand until the head was flush with the side member surface. The end and edge distances varied from 3/4 inch to 1 inch. All nails were placed in their respective patterns within the 2 inch by 5.5 inch area of the two member connection. The side member represents the deckboard and the main member represents the block in a block pallet. These joints were laterally loaded in single shear.

3.5 Data Analysis

Values obtained by analyzing the SPD data include the entire cyclic load-slip time-history curve, the points for the initial and final envelope curves, with their maximum load values. The peak displacement points from each phase were taken from the cyclic test curve to create the initial curve.

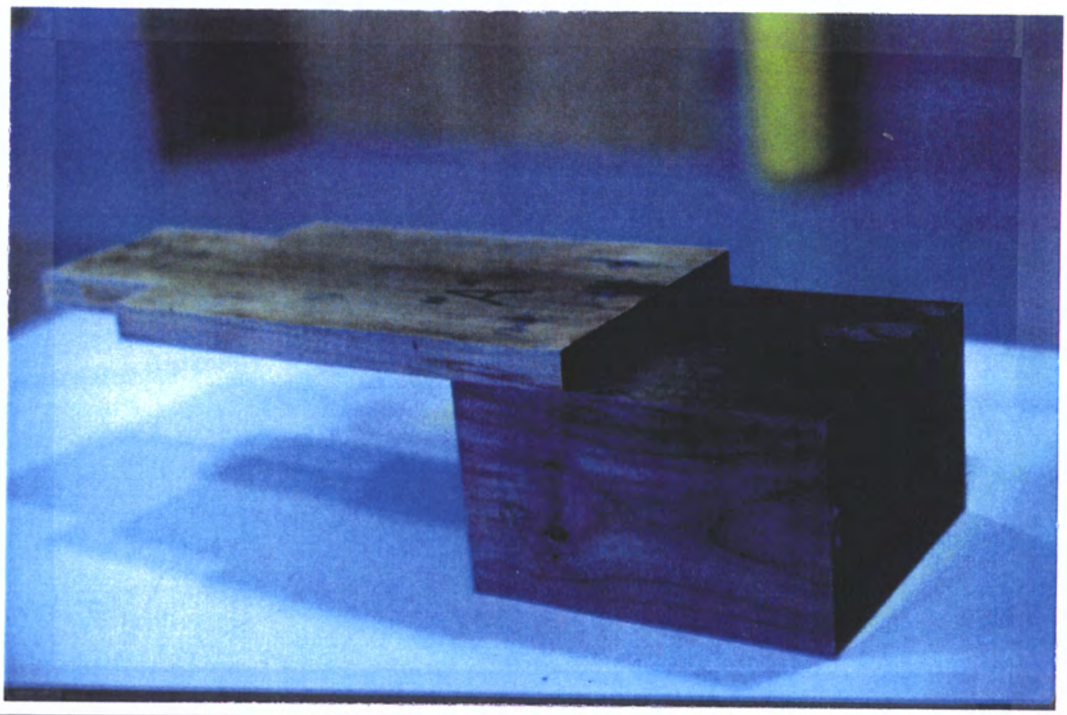


Figure 3.13 Typical connection geometry used for this study (Block = Main Member; Board = Side Member).

For the creation of the stabilized (final) curve, the values from the final cycle in the stabilization sequence were used (as it is explain in 3.2.3). Finally, from previous personal judgement and visual analysis of these two curves, the values for the variables of initial stiffness and load at 5% of the nail diameter offset were found (Figure 3.14). Table 3.11 shows the average values for a typical set of specimens and their respective coefficients of variation. The results and comments of this analysis are presented in the next chapter under the title "Results and Discussion".

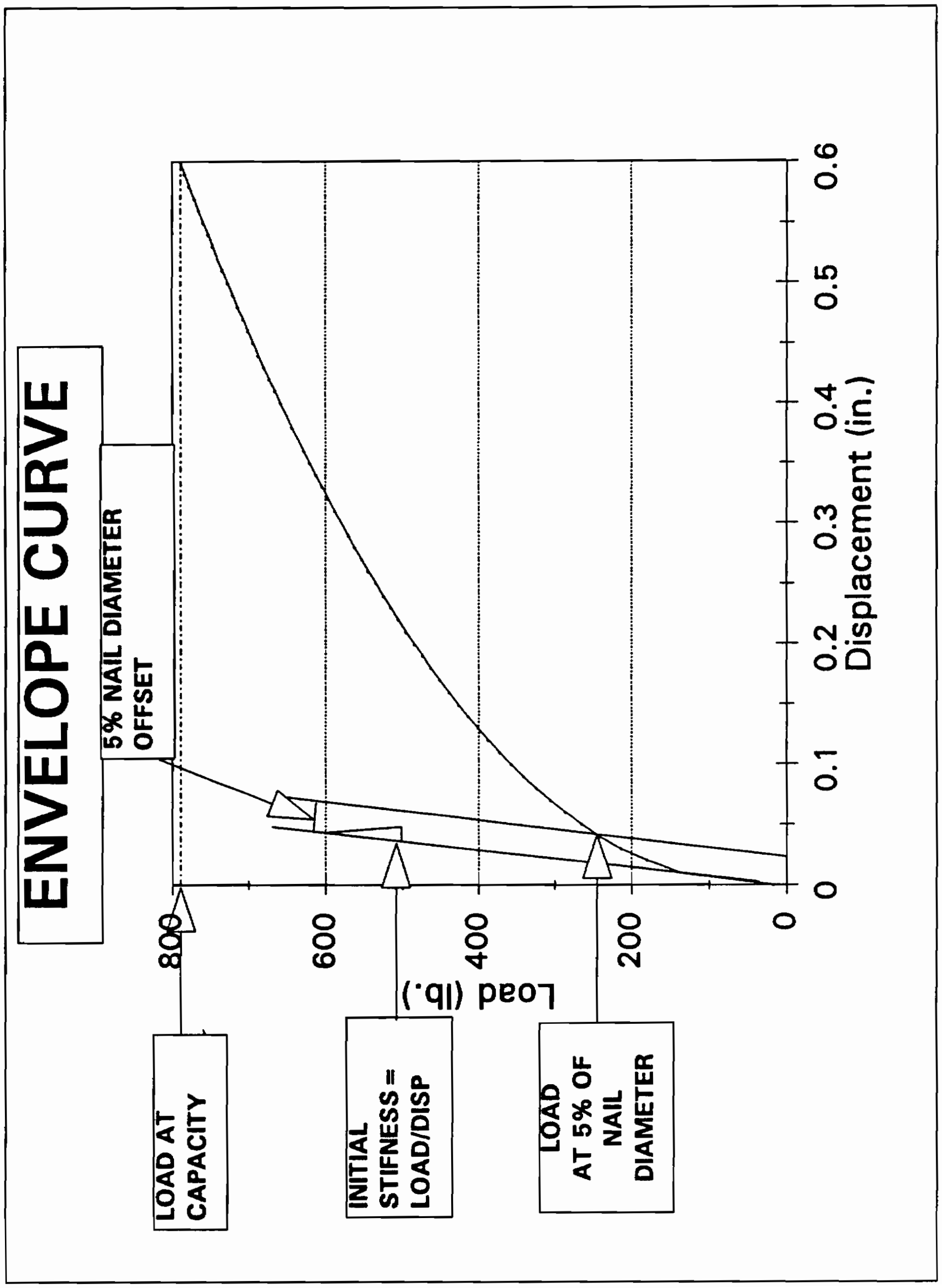


Figure 3.14 Analysis of the initial and final (stabilized) curves.

Table 3.11 Typical Table of Data Acquisition with the Average Values and Coefficient of Variation for Each Set of Nailed Wood Specimens.*

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	94	159	0.34	0.38	0.38	0.42	19500	23571	203	214	873	1027
2	128	148	0.35	0.38	0.39	0.43	21286	35833	265	265	865	1031
3	69	160	0.51	0.57	0.38	0.42	28250	28250	284	310	995	1203
4	71	126	0.34	0.38	0.37	0.42	49565	49565	250	250	772	908
5	81	157	0.35	0.38	0.35	0.40	29600	29600	214	214	790	921
6	64	154	0.36	0.39	0.38	0.43	26143	32000	262	262	894	1063
7	86	108	0.35	0.38	0.39	0.42	42400	42400	278	278	859	1032
8	82	137	0.48	0.53	0.37	0.41	70667	70667	310	310	1005	1188
9	80	158	0.33	0.37	0.37	0.41	46000	46000	220	220	770	908
10	52	163	0.46	0.51	0.37	0.41	56667	56667	246	246	927	1140
11	68	145	0.55	0.63	0.38	0.42	30833	31833	247	247	1026	1240
12	65	136	0.39	0.44	0.37	0.41	21750	22000	203	210	860	1002
13	89	83	0.36	0.39	0.44	0.48	44600	44600	287	287	917	1103
14	66	157	0.34	0.37	0.39	0.43	21875	22500	229	229	879	1035
15	82	145	0.33	0.36	0.38	0.41	33200	33800	202	202	805	938
AVG	78	142	0.39	0.43	0.38	0.42	36156	37952	247	250	882	1049
STDs	18	22	0.07	0.09	0.02	0.02	15004	13739	34	35	81	108
COV (%)	23	16	19	20	5	4	41	36	14	14	9	10

* See Appendix A for more details.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

Extensive data were generated from the testing program described in the previous chapter. This chapter presents and discusses the results of a semi-empirical model for estimating the strength and stiffness of the butted connection of block pallets. This model is designed to be used for estimating high deformations present in this joint when the pallets are loaded while racked. Assumptions and variables analyzed in the study are delineated, as well as the method for verification of the model, and the specific analysis done. This chapter is divided into five parts:

1. Factor effects on connection performance. Results derived from comparison of the different variables of the testing program are presented and discussed.
2. Description of the results obtained from the dowel bearing strength, nail bending yield moment, and the comparison of predicted yield equation values (NDS parameters, and experimental parameters) against experimental values for the joint performance.
3. Description of mathematical models of the load-slip relationship for the twenty four-different groups of nail-thickness combinations. This

task involves the analysis and presentation of the results of fitting equations to the data and showing the "best" models for the initial and the final (stabilized) envelop curves.

4. Fitting Foschi's model. Foschi's equation, equation 3.2, is fit to the data generated in this study, and the parameters for the regression analysis are presented.

5. Description of the "best" general multiple regression model to predict the load-slip relationship for the bottom butted block nailed connections. This model is generated using the variables from the main block design described in Chapter 3.

4.1 Effect of experimental factors on connection performance.

The variables tested in the experimental design described in Chapter 3 are discussed in the following sections. The base test conditions for the connection performance comparisons are: 1) Geometry: two-member three-nailed connections tested in single shear, 2) Moisture content: all the wood was assembled and tested in the green state, 3) Load rate: the rate of loading for all the testing was 1 Hz (one hertz), 4) Dependent variable: the value used for comparison is the load at capacity (maximum load for the connection) from the initial cycle envelop curve, 5) Material quality: the wood used for the construction of the joint specimens was grade # 4 common or better (pallet stock), and 6) Limiting criteria: for all the testing, the capacity of the connection was defined as the load at 0.7 inch displacement, or the load at failure if this happens first (refer to discussion in section 3.2.1).

It is important to emphasize the fact that the limiting displacement criteria influenced the value of the mean joint capacities that did not fail at this displacement. The connections were tested until a maximum 0.70 inch displacement, and in some joints the load was still increasing when the test was stopped. The displacement at 0.70 inch was set as the maximum displacement in the modified sequential phased displacement procedure (SPD) for these type of connections. For this study the limiting criteria affects the single and average capacity values for the different sets of specimens, as well as the shape of the predicted curve and parameter values of the mathematical model that fit this data. However, the effect is conservative since it results in a lower mean value for capacity than if all specimens had been tested to ultimate failure.

Tables 4.1, 4.2 and 4.3 presents the average values and coefficients of variation for the moisture content and specific gravity of joint specimens at the time of testing, for three board thicknesses. The average moisture content (MC) for 1/2 inch thick deckboard specimens ranged from 128 to 153 percent with an average specific gravity (SG) of 0.39 (oven dry specific gravity [ODSG] of 0.43), while the block component of the specimens had a

Table 4.1 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of moisture content and specific gravity for connections tested to determine the influence of thickness and nail type. (Species: red alder (green) Deckboard thickness: 1/2". Rate of loading: 1Hz).

Set Description		Moisture Content (%)		Specific Gravity			
		Block	Board	Bl G	Bl D	Bo G	Bo D
Nail type: 1	AVG	51	153	0.42	0.46	0.38	0.42
	STDs	7	14	0.06	0.07	0.02	0.02
	COV (%)	14	9	13	14	5	6
Nail type: 2	AVG	92	147	0.41	0.44	0.39	0.43
	STDs	27	15	0.02	0.02	0.03	0.03
	COV (%)	29	10	5	5	7	7
Nail type: 3	AVG	103	128	0.40	0.43	0.41	0.45
	STDs	29	16	0.02	0.02	0.03	0.04
	COV (%)	28	13	6	5	7	9
Nail type: 4	AVG	87	129	0.37	0.40	0.40	0.44
	STDs	28	18	0.02	0.02	0.02	0.03
	COV (%)	32	14	5	5	6	7

Note: Number of nails in the connection = 3; number of specimens in the set = 15.

Bl = Block G = Green volume basis

Bo = board D = Dry volume basis

Table 4.2 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of moisture content and specific gravity for connections tested to determine the influence of thickness and nail type. (Species: red alder (green) Deckboard thickness: 5/8". Rate of loading: 1Hz).

Set Description		Moisture Content (%)		Specific Gravity			
		Block	Board	Bl G	Bl D	Bo G	Bo D
Nail type: 1	AVG	122	157	0.38	0.41	0.39	0.44
	STDs	22	22	0.04	0.04	0.03	0.03
	COV (%)	18	14	10	9	7	8
Nail type: 2	AVG	94	170	0.40	0.43	0.39	0.43
	STDs	31	15	0.01	0.01	0.02	0.03
	COV (%)	33	9	3	3	6	6
Nail type: 3	AVG	127	156	0.38	0.42	0.39	0.43
	STDs	23	19	0.02	0.01	0.02	0.03
	COV (%)	18	12	4	2	6	6
Nail type: 4	AVG	83	160	0.39	0.43	0.39	0.44
	STDs	30	13	0.02	0.02	0.02	0.03
	COV (%)	36	8	5	5	6	6

Note: Number of nails in the connection = 3; number of specimens in the set = 15.

Bl = Block G = Green volume basis

Bo = board D = Dry volume basis

Table 4.3 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of moisture content and specific gravity for connections tested to determine the influence of thickness and nail type. (Species: red alder (green) Deckboard thickness: 3/4". Rate of loading: 1Hz).

Set		Moisture Content (%)		Specific Gravity			
Description		Block	Board	Bl G	Bl D	Bo G	Bo D
Nail type: 1	AVG	101	142	0.37	0.40	0.38	0.42
	STDs	44	26	0.03	0.04	0.03	0.04
	COV (%)	43	18	9	9	8	9
Nail type: 2	AVG	88	118	0.42	0.46	0.39	0.43
	STDs	24	34	0.04	0.05	0.03	0.03
	COV (%)	28	29	9	10	7	7
Nail type: 3	AVG	78	142	0.39	0.43	0.38	0.42
	STDs	18	22	0.07	0.09	0.02	0.02
	COV (%)	23	16	19	20	5	4
Nail type: 4	AVG	71	122	0.37	0.41	0.40	0.44
	STDs	30	14	0.02	0.03	0.03	0.04
	COV (%)	42	12	6	6	7	8

Note: Number of nails in the connection = 3; number of specimens in the set = 15.

Bl = Block G = Green volume basis

Bo = board D = Dry volume basis

moisture content between 51 and 103 percent with an average SG of 0.40. For 5/8 inch deckboard specimens the average moisture content values varied from 152 to 170 percent with an average SG of 0.39 (ODSG of 0.44), and the block components of the specimens had a MC changing from 83 to 127 with an average SG of 0.39 (ODSG of 0.42). The 3/4 inch deckboards, had an average MC ranging from 118 to 142 percent with an average SG of 0.39 (ODSG of 0.43), and the block component for the specimens had a MC ranging from 71 to 101 percent with an average SG of 0.39 (ODSG of 0.43).

The initial stiffness for the connections was estimated from the tangent line drawn to the initial straight segment of the load-slip curve. The load at five percent offset of nail diameter was defined by Gutshall (1994), as "the coordinates of the intersection of a line drawn parallel to the initial stiffness line that was offset along the displacement axis by 5% of the fastener diameter and the load-slip curve of the connection".

4.1.1 Effect of Type of Nail

To determine the effect of the nail type on the joint capacity, the mean capacity values (P_{max}) for the four types of nails described in the previous chapter were compared. For this analysis, a 3 X 4 factorial ANOVA test (three thicknesses vs. four types of nails) was performed using the software SAS. First, the null hypothesis of equality of the means was tested against the alternative hypothesis that they were not equal.

H_o: all the means are equal

H_a: at least one of the means is different

F=26.37; with Pr>F of 0.0001

The null hypothesis of equality of the sample means was rejected because the F value (test statistic) has a small probability of occurrence of type I error for an $\alpha=0.05$ (type I error is the probability of rejecting the null hypothesis when it is true). LSD and DUNCAN multiple comparisons were used to analyze the means, and it was found that the mean values for four nail types are significantly different from each other. It is also found that nail four is the strongest followed by nails three, one, and two respectively, as illustrated in Figure 4.1 and Tables 4.4, 4.5, and 4.6.

The ANOVA test of a completely randomized design was conducted for each of three thicknesses using an α value of 0.05. In this test, the null hypothesis of the equality of the means of the four nails in each thickness was proposed. The alternative hypothesis was that for each thickness the mean capacity of the four nail types are not equal.

H_o: the means of the four nails are equal in each thickness

H_a: at least one of the means is different

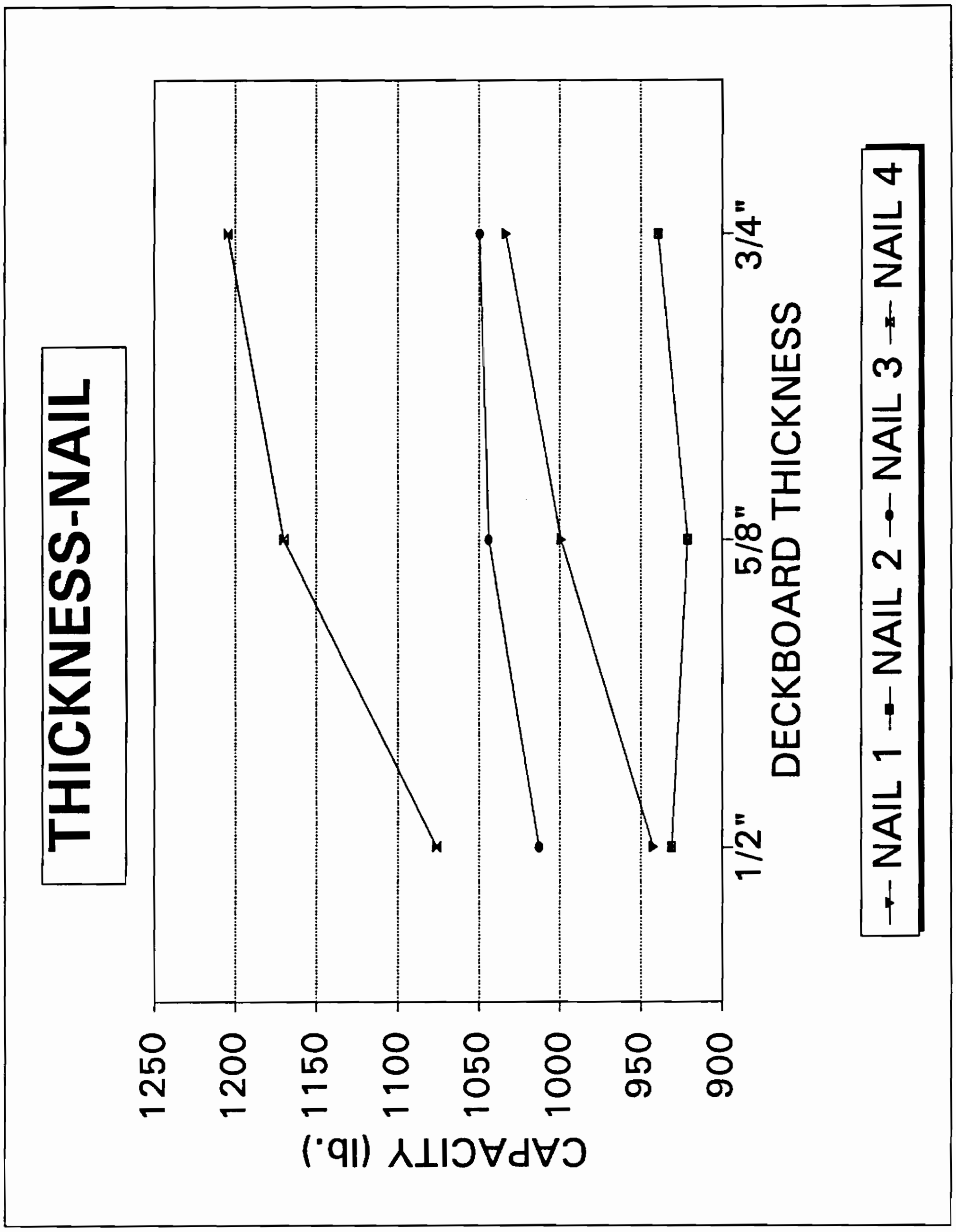


Figure 4.1 Comparison of the mean capacities of the four nail types by thickness.

Table 4.4 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of initial stiffness, yield load, and capacity for connections tested to determine the influence of thickness and nail type.

Species: red alder (green) Deckboard thickness: 1/2". Rate of loading: 1Hz.

Set		Initial Stiffness		Load at 5%		Load at Capacity		Diff*
Description		Final Curve	Initial Curve	Final Curve	Initial Curve	Final Curve	Initial Curve	%
Nail type: 1	AVG	33583 psi	34845 psi	203 lb	206 lb	773 lb	942 lb	18
	STDs	12027 psi	12671 psi	43 lb	45 lb	50 lb	49 lb	
	COV (%)	35.8	36.4	20.9	22.0	6.4	5.2	
Nail type: 2	AVG	39462 psi	41633 psi	252 lb	261 lb	762 lb	931 lb	18
	STDs	8970 psi	8224 psi	38 lb	36 lb	43	48	
	COV (%)	22.7	19.8	15.0	13.9	5.7	5.2	
Nail type: 3	AVG	47932 psi	50535 psi	245 lb	252 lb	822 lb	1013 lb	19
	STDs	8957 psi	8974 psi	41 lb	41 lb	73 lb	72 lb	
	COV (%)	18.7	17.8	16.9	16.2	8.9	7.1	
Nail type: 4	AVG	68931 psi	6938 psi	278 lb	283 lb	869 lb	1076 lb	19
	STDs	13349 psi	13647 psi	43 lb	41 lb	61 lb	68 lb	
	COV (%)	19.4	19.7	15.6	14.7	7.0	6.3	

* difference = [(Capacity of initial-capacity of final)/capacity of initial]*100

Note: Number of nails in the connection = 3; number of specimens in the set = 15.

Table 4.5 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of initial stiffness, yield load, and capacity for connections tested to determine the influence of thickness and nail type.

Species: red alder (green) Deckboard thickness: 5/8". Rate of loading: 1Hz.

Set		Initial Stiffness		Load at 5%		Load at Capacity		Diff*
Description		Final Curve	Initial Curve	Final Curve	Initial Curve	Final Curve	Initial Curve	%
	AVG	39877 psi	40835 psi	234 lb	241 lb	822 lb	999 lb	18
Nail type: 1	STDs	15052 psi	14929 psi	31lb	39 lb	77 lb	93 lb	
	COV (%)	37.7	36.6	13.1	16.3	9.4	9.3	
	AVG	33376 psi	33750 psi	240 lb	255 lb	768 lb	921 lb	17
Nail type: 2	STDs	8270 psi	7021 psi	25 lb	25 lb	49 lb	50 lb	
	COV (%)	24.8	20.8	10.4	10.0	6.4	5.5	
	AVG	32535 psi	36114 psi	238 lb	251 lb	855 lb	1044 lb	18
Nail type: 3	STDs	15423 psi	16828 psi	22 lb	21 lb	53 lb	58 lb	
	COV (%)	47.4	46.6	9.3	8.5	6.3	5.5	
	AVG	40119 psi	43617 psi	291 lb	315 lb	951 lb	1170 lb	19
Nail type: 4	STDs	11820 psi	14159 psi	30 lb	31 lb	68 lb	58 lb	
	COV (%)	29.5	32.5	10.4	9.9	7.1	5.0	

* difference = [(Capacity of initial-capacity of final)/capacity of initial]*100

Note: Number of nails in the connection = 3; number of specimens in the set = 15.

Table 4.6 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of initial stiffness, yield load, and capacity for connections tested to determine the influence of thickness and nail type.

Species: red alder (green) Deckboard thickness: 3/4". Rate of loading: 1Hz.

Set		Initial Stiffness		Load at 5%		Load at Capacity		Diff*
Description		Final Curve	Initial Curve	Final Curve	Initial Curve	Final Curve	Initial Curve	%
Nail type: 1	AVG	45131 psi	46933 psi	263 lb	265 lb	870 lb	1033 lb	16
	STDs	17606 psi	17191 psi	31 lb	31 lb	67 lb	82 lb	
	COV (%)	39.0	36.6	11.7	11.8	7.7	7.9	
Nail type: 2	AVG	43933 psi	45165 psi	289 lb	297 lb	788 lb	939 lb	16
	STDs	9238 psi	10512 psi	51 lb	49 lb	37 lb	51 lb	
	COV (%)	21.0	23.3	17.6	16.3	4.6	5.5	
Nail type: 3	AVG	36156 psi	37952 psi	247 lb	250 lb	882 lb	1049 lb	16
	STDs	15004 psi	13739 psi	34 lb	35 lb	81 lb	108 lb	
	COV (%)	41.5	36.2	13.9	14.2	9.2	10.3	
Nail type: 4	AVG	44930 psi	46724 psi	310 lb	320 lb	1011 lb	1205 lb	16
	STDs	8029 psi	7900 psi	30 lb	27 lb	57 lb	58 lb	
	COV (%)	17.9	16.9	9.7	8.6	5.6	4.9	

* difference = [(Capacity of initial-capacity of final)/capacity of initial]*100

Note: Number of nails in the connection = 3; number of specimens in the set = 15.

Since the test for 1/2" thickness has a F=19.04; with Pr>F=0.0001 (lower than α=0.05), the null hypothesis of equality was rejected. Multiple comparisons were developed to rank the sample means of the four types of nails. It was found that for 1/2" thick deckboard (side member) there is not a significant difference between nail types one and two, but they are significantly different from nail types three and four. It was found that nail type 4 was the strongest followed by nail type three; nail types one and two were the weakest types of nails.

The same test was used for the 5/8" side member thickness, and the null hypothesis was equality of the means of the four types of nails.

H_o: the means of the four nail types are equal

H_a: at least one of the means is different

F=36.21; with Pr>F value of 0.0001

The null hypothesis of equality was rejected for the alternative hypothesis that the sample means of the four types of nails were different. For 5/8" thick deckboards, the results showed that nail types four and two were significantly different from each other and from the other types of nails. The means of nail types one and three are not statistically different, but they were from nail types two and four. Nail type four was the strongest followed by nail types three, one and two respectively.

The next ANOVA test was conducted for 3/4" thick side member connections. The null hypothesis again was equality of the sample means, and, as in the two previous thicknesses, was rejected because the probability of occurrence of error type I is smaller than 0.0001 ($F=29.71$; with $Pr>F$ of 0.0001). Multiple comparisons were developed to rank the means of the four types of nails. The results of 3/4" deckboard showed that there is no significant difference between nail types one and three, but a significant difference exists between them and nail types two and four. Nail type four was the strongest, followed by nail types one and three, with nail type two, the weakest, see Figure 4.1 and Tables 4.4, 4.5, and 4.6. More details about data are given in Appendixes A, and B.

The results for all three deckboard thicknesses show that nail type four is the strongest follow by nail types three, one and two respectively. There is a disagreement between the 3x4 factorial and the randomized block design ANOVA tests. The first test shows significant difference between all the means of the four types of nails. The later test shows no significant difference between the means for nail types three and one for board thicknesses 3/4"and 5/8" and no significant difference between nail types one and two for a thickness of 1/2". This discrepancy in the test results is given because the difference between the means of the nail types is not the same in each thickness, as was explained previously, but the addition of these means in the 3x4 factorial changes the results. The average values of the variables for the four types of nails presented in Tables 4.4, 4.5, and 4.6 confirm that strength, diameter and length of the fastener are important factors that influence the stiffness and strength of nailed wood connections. It was observed during the testing that joints made with nail types one and three had similar capacites, but the withdrawal force produced at high deformations changed the mode of failure. Connections nailed with nail type three were stronger because the wood fails in embedding before the nail bends. Joints made with nail type one, however, fail not only in embedding of the fastener into the wood but also by bending and withdrawal of the nail. Therefore the capacity of connections built with these two nail types was not defined by diameter or strength (they have approximately the same MIBANT angle), but by length, because the shorter nail failed in withdrawal at high displacement levels. In general it is seen that for a given side member thickness, the strength of the fastener is the factor that most influences the capacity of these connections. This was appreciated in the results obtained from the cyclic lateral testing of wood nailed connections. Table 3.1 illustrates the difference between nails in terms of MIBANT angle, diameter and length.

Results for initial stiffness and load at five percent offset do not show the same consistency as the results for the capacity (strength) of the connections. This was mainly due to electrical noise in the MTS equipment at small levels of load and displacement, and to the inaccurate procedure used to define these values ("eye-balling"). The problems described above are reflected in the high coefficients of variation (COV) of the initial stiffness and load at five percent offset, as presented in the Tables in this chapter. However, even with this inaccuracy in the results, the general tendency of the initial stiffness for these connections indicates that the bending strength of the fastener is the most important factor that defines this value. Nail type four seems to make the stiffest connections, followed by nail types three and one, with nail type two making the least stiff connections. Comparisons of the monotonic response of connections constructed with the four nail types is presented in Figures 4.2 to 4.4. This set of figures focus on the first part of the load-slip curve (from zero to 0.1 inch) to illustrate the differences in the average initial stiffness of these connections. These figures are generated using the "best" model fitted to the experimental data, as described later in Section 4.2.

4.1.2 Effect of Thickness

To define the effect of the side member thickness on the strength and stiffness of the connections, the mean capacity values (P_{max}) for the three thicknesses (1/2 , 5/8, and 3/4 inch) were compared. The analysis of the

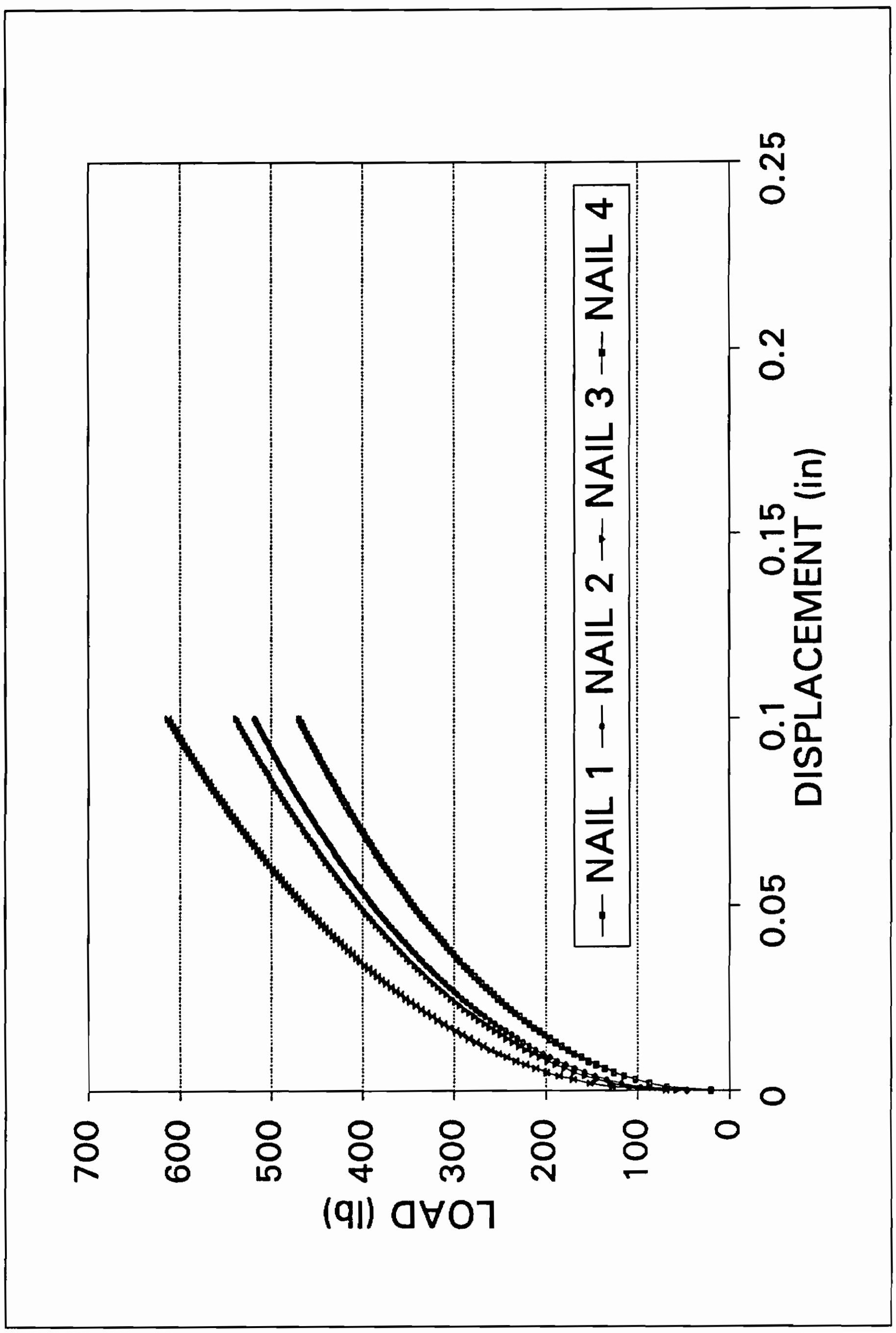


Figure 4.2 Comparison of the Initial stiffness for each nail type for joint specimens with 1/2" thick deckboards.

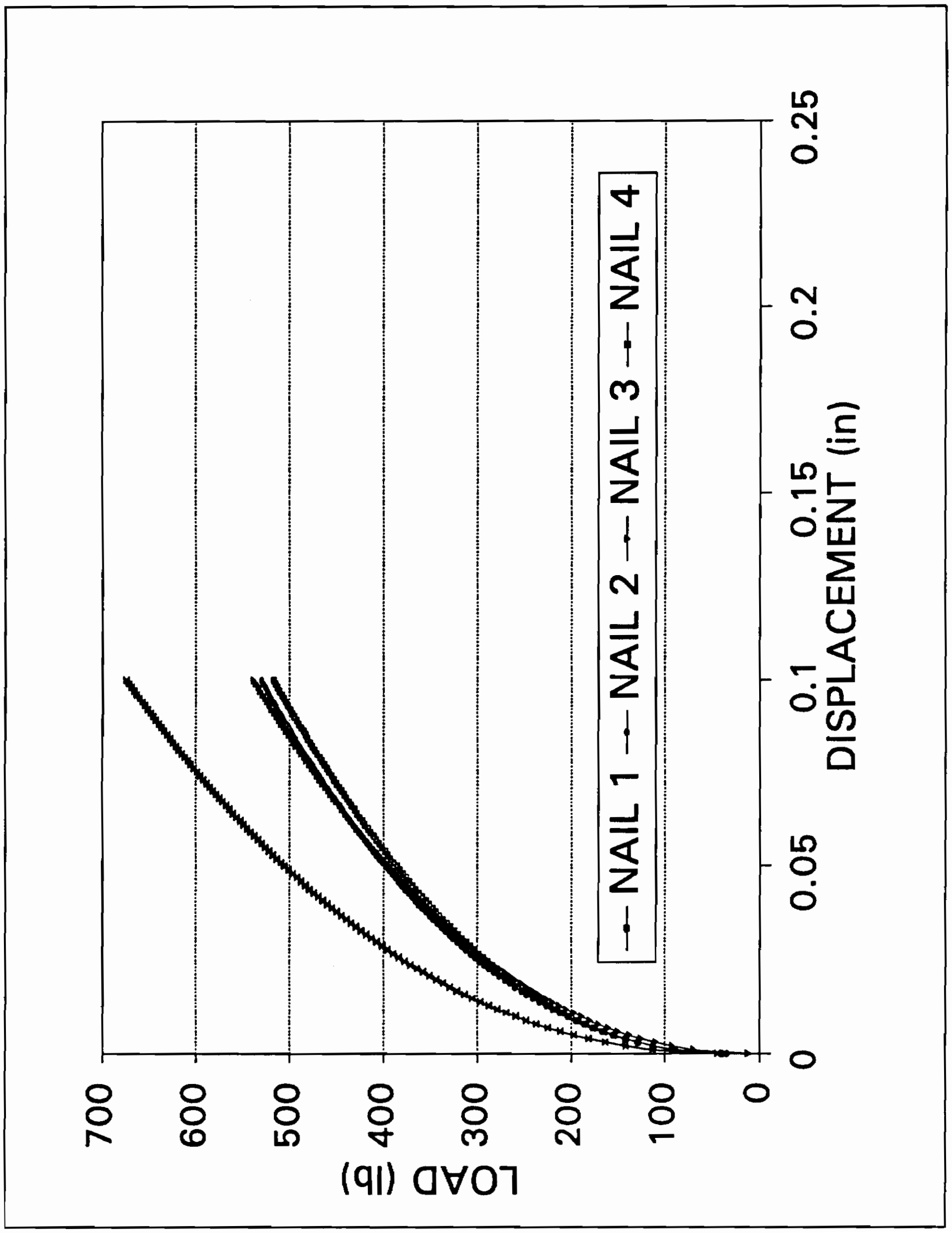


Figure 4.3 Comparison of the Initial stiffness for each nail type for joint specimens with 5/8" thick deckboards.

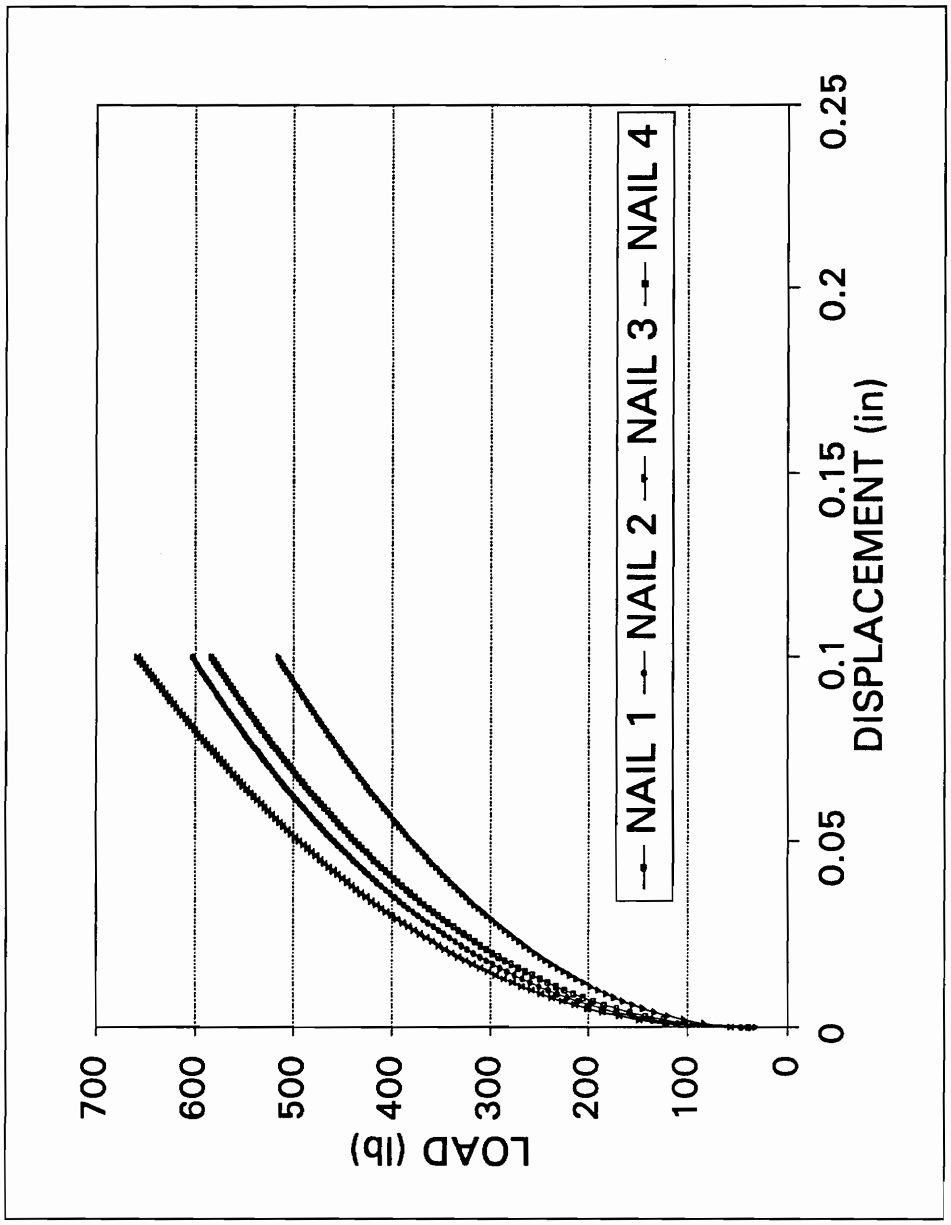


Figure 4.4 Comparison of the initial stiffness for each nail type for joint specimens with 3/4" thick deckboards.

three thicknesses was done using two types of ANOVA tests: 3x4 factorial for the three together, and a completely randomized block design for each thickness.

The 3x4 factorial ANOVA test was the same as that used for the four nail types, so it follows the same pattern (subsection 4.1.1).

H_o: all the mean capacities are equal

H_a: at least one of the mean capacities is different

F=26.37; with Pr>F of 0.0001

The null hypothesis of equality of the sample mean capacities was rejected because the probability of having type I error (rejecting the null hypothesis when it is true) is less than 0.01 percent, which is below the α value of 5 percent. Multiple comparisons (LSD and DUNCAN) revealed that the mean capacity values for thicknesses are significantly different from each other. It was found that there is no significant difference between the mean capacities of connection with 3/4 inch and 5/8 inch thickness side members, but there is a significant difference between these two, and the mean capacity of connections with 1/2 inch thick side members. Multiple comparisons indicate that the first two, connections with 3/4 inch and 5/8 inch thick side members, are stronger than the connections with 1/2 inch thick side members.

The completely randomized ANOVA test was conducted for each of the four types of nails using an α value of 0.05. The null hypothesis was proposed as the equality of the mean capacities of the three side member thicknesses for each nail type. The alternative hypothesis was proposed as the mean capacity of these three connection would be different for each nail type.

H_o: The mean capacities of the three connection are equal for each nail type

H_a: The mean capacity for each nail type is different

For Nail type 1: $F=5.3$ $Pr>F=0.0088$

For Nail type 2: $F=0.49$ $Pr>F=0.6134$

For Nail type 3: $F=0.87$ $Pr>F=0.4279$

For Nail type 4: $F=17.41$ $Pr>F=0.0001$

The null hypothesis of equality for nail type one was rejected, since the probability of the occurrence of error type I is smaller than 0.0088. Multiple comparisons showed that there is no significant difference in capacity between connections with 3/4 inch and 5/8 inch thick side members, nor between connections with 5/8 inch and 1/2 inch thick side members. Tthere is, however, significant a difference between connection capacities for 3/4 inch and 1/2 inch thickside members. There is a continuous increment of increasing capacity that is directly correlated to increasing side member thickness.

For nail type two, there was insufficient evidence to reject the null hypothesis, because the probability of the occurrence of error type I is very high (more than 61%). Therefore, the hypothesis that the mean capacities of all the thicknesses were equal was accepted. This was supported by multiple comparison testing. Although a constant increment of increasing strength was expected, it was not the case with nail type two. The mean capacity of the connection with a 5/8 inch thick side member was the lowest, indicating that this connection was the weakest. The strongest connection had a 3/4 inch side member, with the connection with 1/2 inch thick side member folling in between the other two connections. These results suggest that the mode of failure for these joint specimens was defined not by the side member thickness but by the nail yield strength and the nail length (failure in withdrawal). Nail type two had the lowest stiffness and bending strength value among the four types of nails (MIBANT angle=48° and bending strength=98,345 psi) and was 2.25 inches long. It was observed in joint specimens fastened with shorter nails that the deckboard was easily removed from the block after testing. This loosening of the connection suggests the failure of the joint was due to the withdrawal force exerted on the nails. The variation in the capacity obtained with this type of nail (nail type two) among the three side member thicknesses is not statically significant and is assumed to be in the typical range of nailed wood joints.

ANOVA test results for nail type three resembled those of nail type two. There was insufficient evidence to reject the null hypothesis that the mean capacities of the connectionc with three side member thicknesses were equal. Multiple comparison testing with an α value of 0.05 confirmed that there is no significant difference between the capacity of the three connections. Although there is not a statistical difference between the means of the thicknesses, there appears to be some increase in strength that is correlated to increasing side member thickness (Figure 4.5). A larger sample size may have provide sufficient information to show a statistical difference.

The ANOVA test for nail type four presents adequate evidence to reject the null hypothesis of equality of the mean capacities of the connections with three side member thicknesses. This was confirmed using multiple comparisons testing for the three mean capacities. The results indicated that the mean capacities for connections with side member thicknesses of 3/4 inch and 5/8 inch are not significantly different from each other, however, there is a significant difference between connections

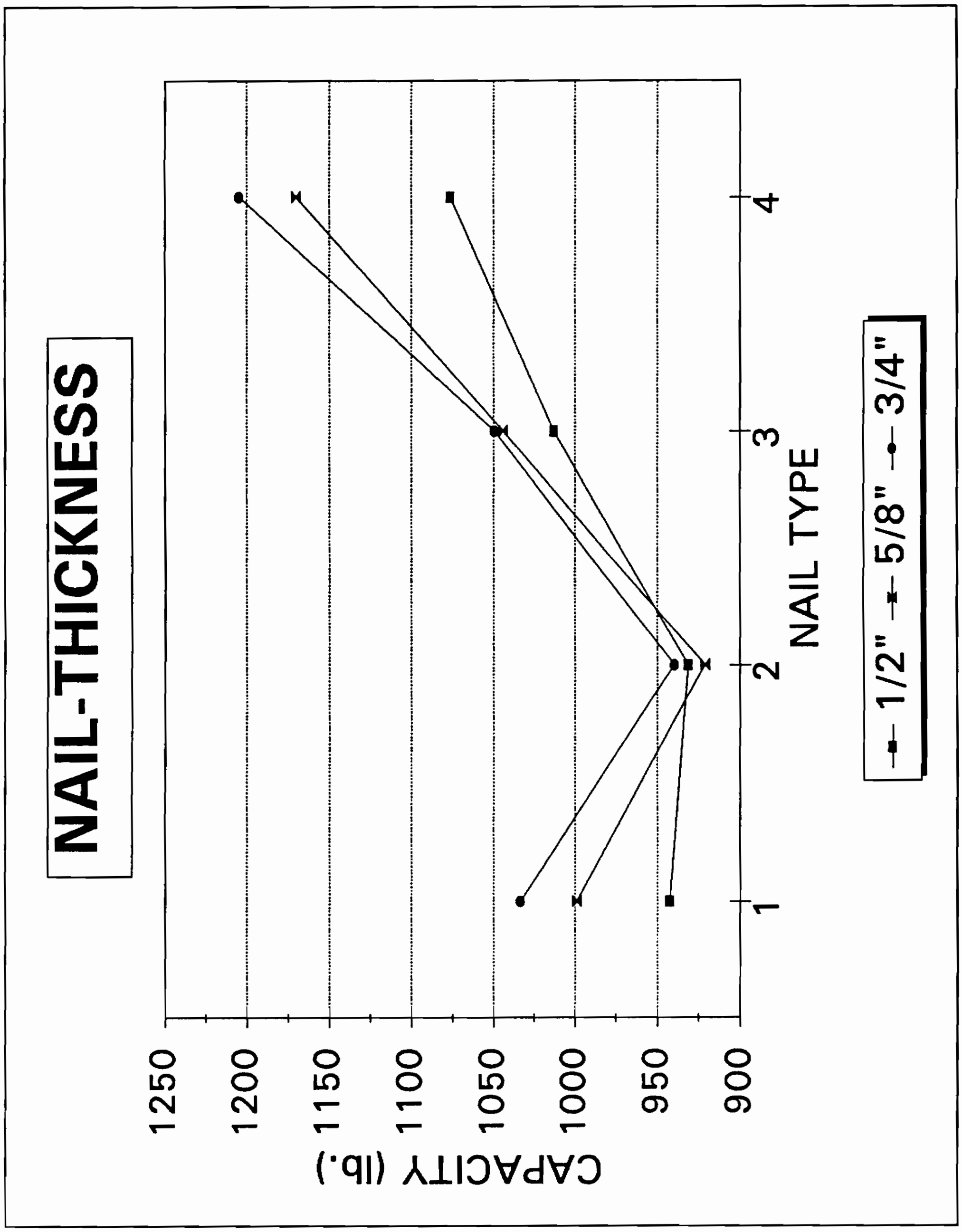


Figure 4.5 Comparison of the mean capacities of the three deckboard thicknesses by nail type.

with 1/2 inch side members and connections with both 5/8 inch and 3/4 inch thick side members.

It was generally observed that the capacity and stiffness of connections increased with an increase in thickness, as depicted in Tables 4.4, 4.5, 4.6, and Figures 4.5 to 4.9. In these connections, the nail strength was sufficient to cause a combined wood crushing and nail yielding failure mode.

4.1.3 Effect of Friction

Table 4.7 presents the average values and coefficients of variation for the moisture content and specific gravity of the joint specimens used to investigated the effect of friction at the time of testing, for the connections with 1/2 and 3/4 inch thick side members, respectively. Table 4.8 shows the results of the comparison between the connections tested with normal friction and those tested with reduced friction. It was observed that there is, on average, more than 20 percent difference in the capacity of joint specimens with friction and specimens with reduced friction. As would be expected, friction has an important influence on the capacity and stiffness properties of connections. This influence is due to the fact that wood in the green state (moisture content greater than 30 percent) has increased friction between members because of the roughness of the surfaces caused by raised grain and swollen fibers, even though all specimens were planed.

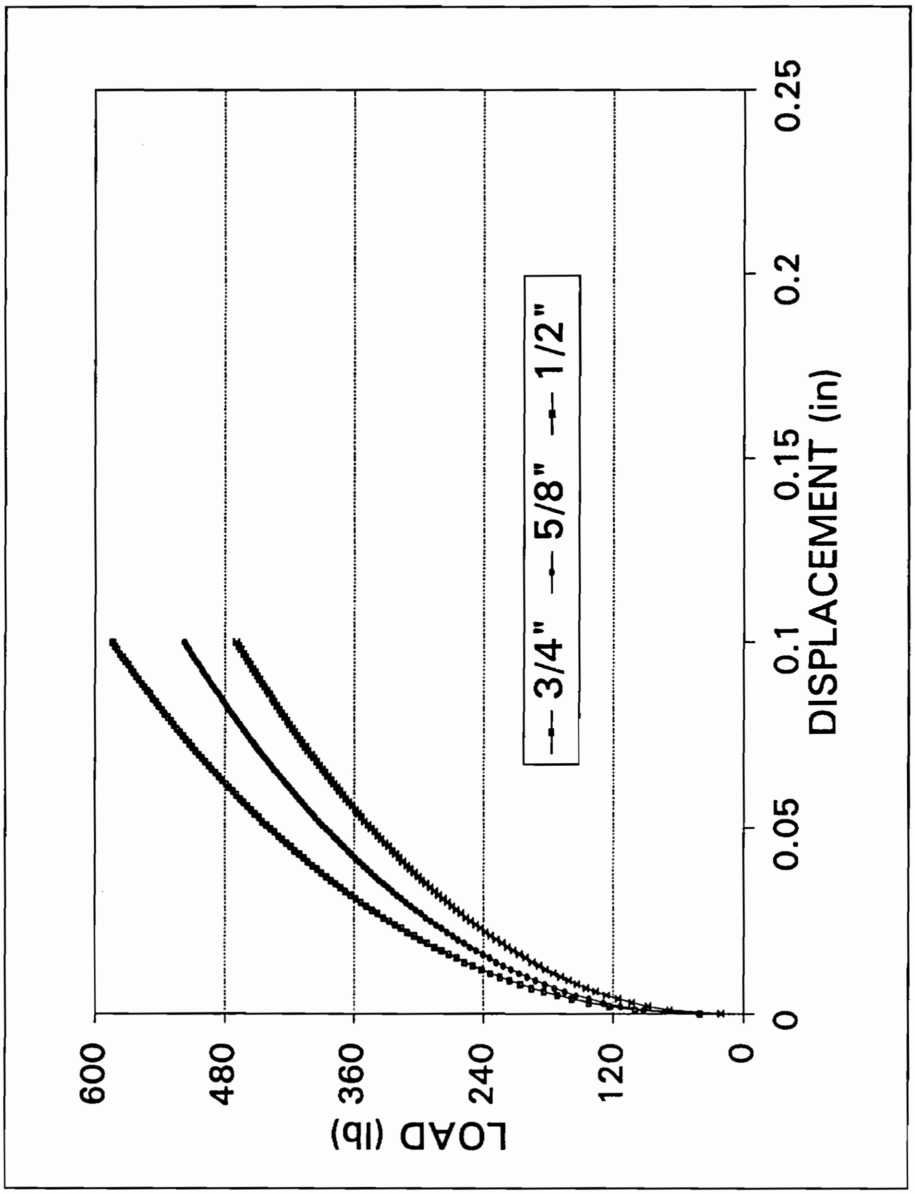


Figure 4.6 Comparison of the initial stiffness for each deckboard thickness for joint specimens fastened with nail type 1.

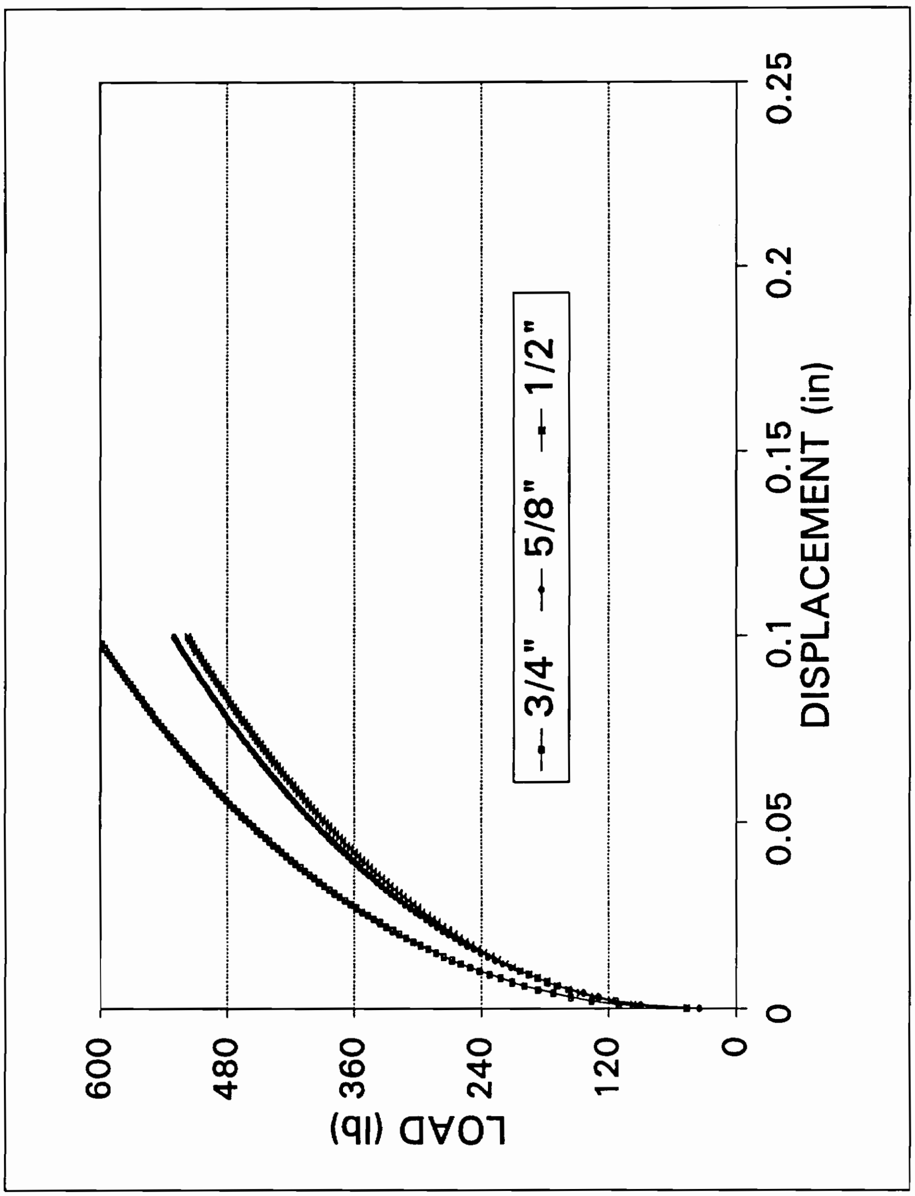


Figure 4.7 Comparison of the initial stiffness for each deckboard thickness for joint specimens fastened with nail type 2.

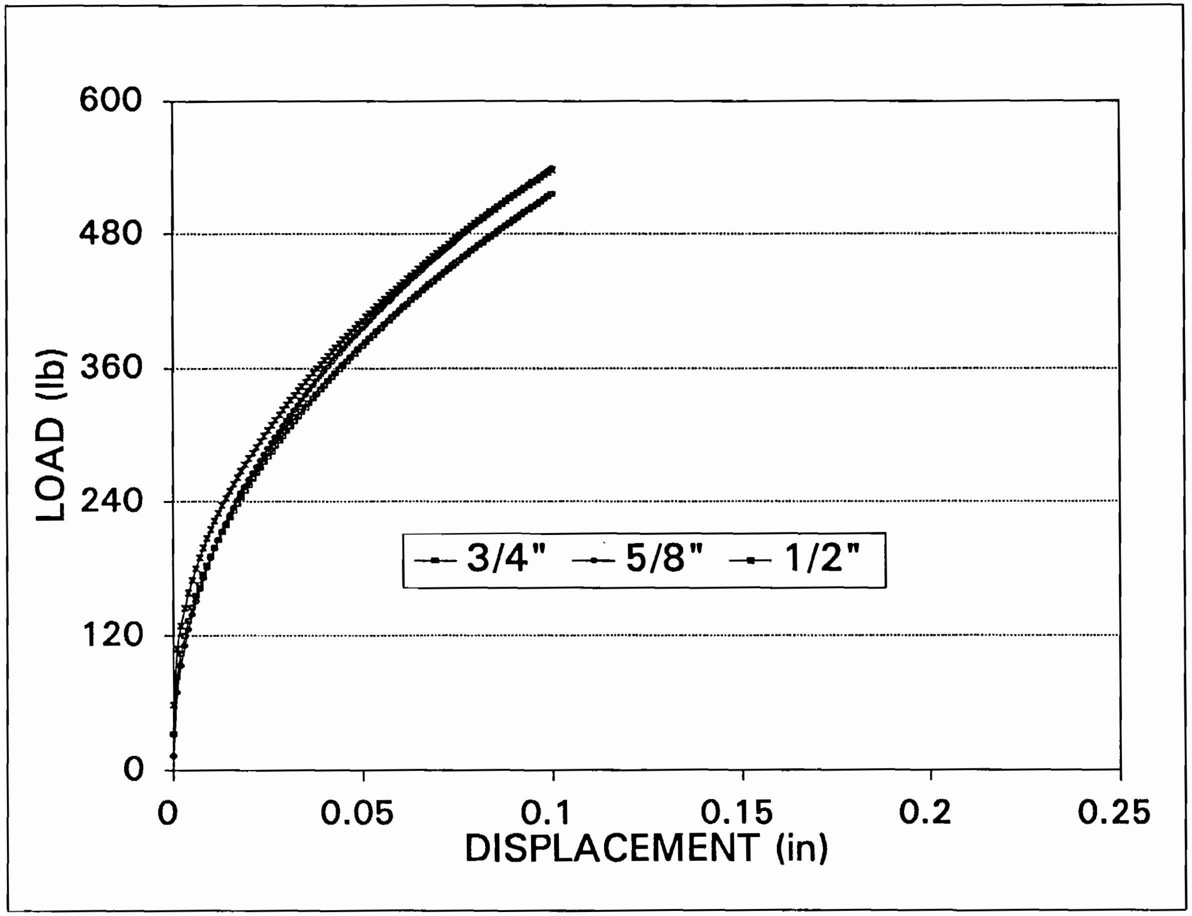


Figure 4.8 Comparison of the initial stiffness for each deckboard thickness for joint specimens fastened with nail type 3.

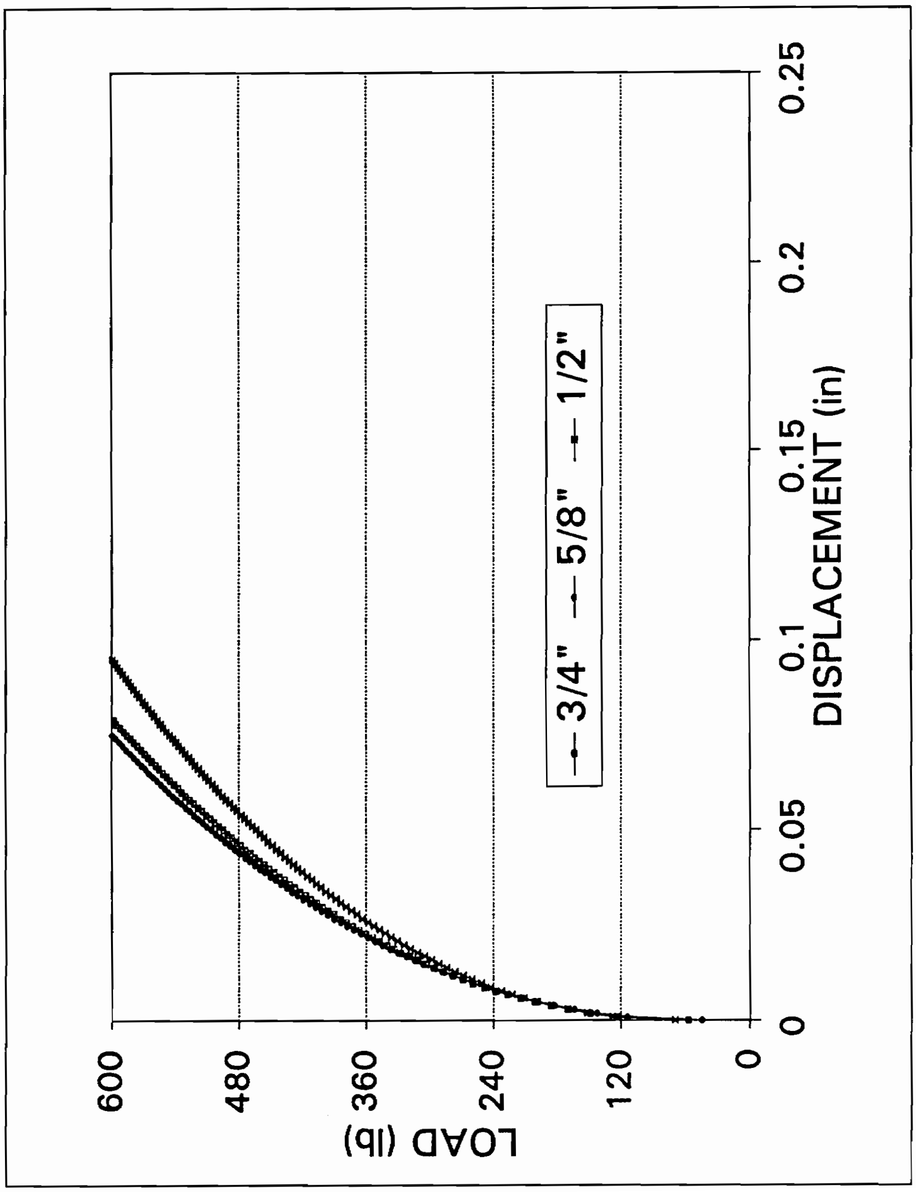


Figure 4.9 Comparison of the initial stiffness for each deckboard thickness for joint specimens fastened with nail type 4.

Table 4.7 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of moisture content and specific gravity for connections tested to determine the influence of friction.

Species: red alder (green). Nail type: 3. Nails per joint: 3. Rate of loading: 1 Hz.

Set Description		Moisture Content (%)		Specific Gravity			
		Block	Board	Bl G	Bl D	Bo G	Bo D
3/4" thick	AVG	78	142	0.39	0.43	0.38	0.42
(side member)	STDs	18	22	0.07	0.09	0.02	0.02
w/friction	COV (%)	23	16	19	20	5	4
3/4" thick	AVG	86	128	0.41	0.45	0.38	0.41
(side member)	STDs	23	20	0.05	0.06	0.02	0.02
Less friction	COV (%)	26	16	13	13	5	6
1/2" thick	AVG	103	128	0.40	0.43	0.41	0.45
(side member)	STDs	29	16	0.02	0.02	0.03	0.04
w/friction	COV (%)	28	13	6	5	7	9
1/2" thick	AVG	101	128	0.42	0.45	0.41	0.45
(side member)	STDs	30	25	0.03	0.03	0.02	0.03
Less friction	COV (%)	30	20	7	7	6	7

Note: For more details see Appendix A.

Bl = Block G = Green volume basis

Bo = Board D = Dry volume basis

Table 4.8 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of initial stiffness, yield load, and capacity for connections tested to determine the influence of friction.

Species: red alder (green). Nail type: 3. Nails per joint: 3. Rate of loading: 1 Hz.

Set		Initial Stiffness		Load at 5%		Load at Capacity		Diff*
Description		Final Curve	Initial Curve	Final Curve	Initial Curve	Final Curve	Initial Curve	%
3/4" thick	AVG	36156 psi	37952 psi	247 lb	250 lb	882 lb	1049 lb	16
w/friction	COV (%)	41	36	14	14	9	10	
3/4" Thick	AVG	22985 psi	23886 psi	202 lb	213 lb	741 lb	886 lb	16
Less friction	COV (%)	19	19	11	12	8	8	
	Diff** (%)	36	37	18	15	16	16	
1/2" thick	AVG	47932 psi	50535 psi	245 lb	252 lb	822 lb	1013 lb	19
w/friction	COV (%)	19	18	17	16	9	7	
1/2" thick	AVG	23057 psi	23643 psi	204 lb	206 lb	666 lb	831 lb	20
Less friction	COV (%)	23	18	12	13	4	4	
	Diff** (%)	52	53	17	18	19	18	

* difference = [(capacity of initial-capacity of final)/capacity of initial]*100.

(D) = Dry , (G) = Green.

Note: For more details see Appendix A.

** difference = [(friction-less friction)/friction]*100.

Two friction comparisons were made, one using thirty joint specimens with 1/2 inch thick side members, and the other using thirty specimens with 3/4 inch thick side members. For each side member thickness, fifteen specimens were tested with friction, and fifteen, without.

For connections with 1/2 inch thick side members, the T-test for the null hypothesis of equality of the variances of the capacities had a t value of 4.07, with $Pr>t=0.0129$ (probability of error type I). For connections with 3/4 inch thick side members, the t-test for the null hypothesis of equal variances had an t value of 2.11, with $Pr>t=0.1747$. Both tests had an α value of 0.05; for the first case (1/2 inch side members), the null hypothesis was rejected. For the second case (3/4 inch side members), there was insufficient evidence to reject the null hypothesis. Table 4.8 and Figures 4.10 and 4.11, however, exhibit the actual averages of the data, which showed a difference of 18, and 22 percent between reduced friction and friction test sets for the 1/2 inch and 3/4 inch thicknesses, respectively. The difference between the statistic t-test and the figures and tables is due to the fact that the confidence limits of both mean capacities fall within each other's range.

4.1.4 Effect of Moisture Content

Three different moisture conditions were tested, all of the connections used in this part of the study had a 3/4 inch deckboard thickness. The first

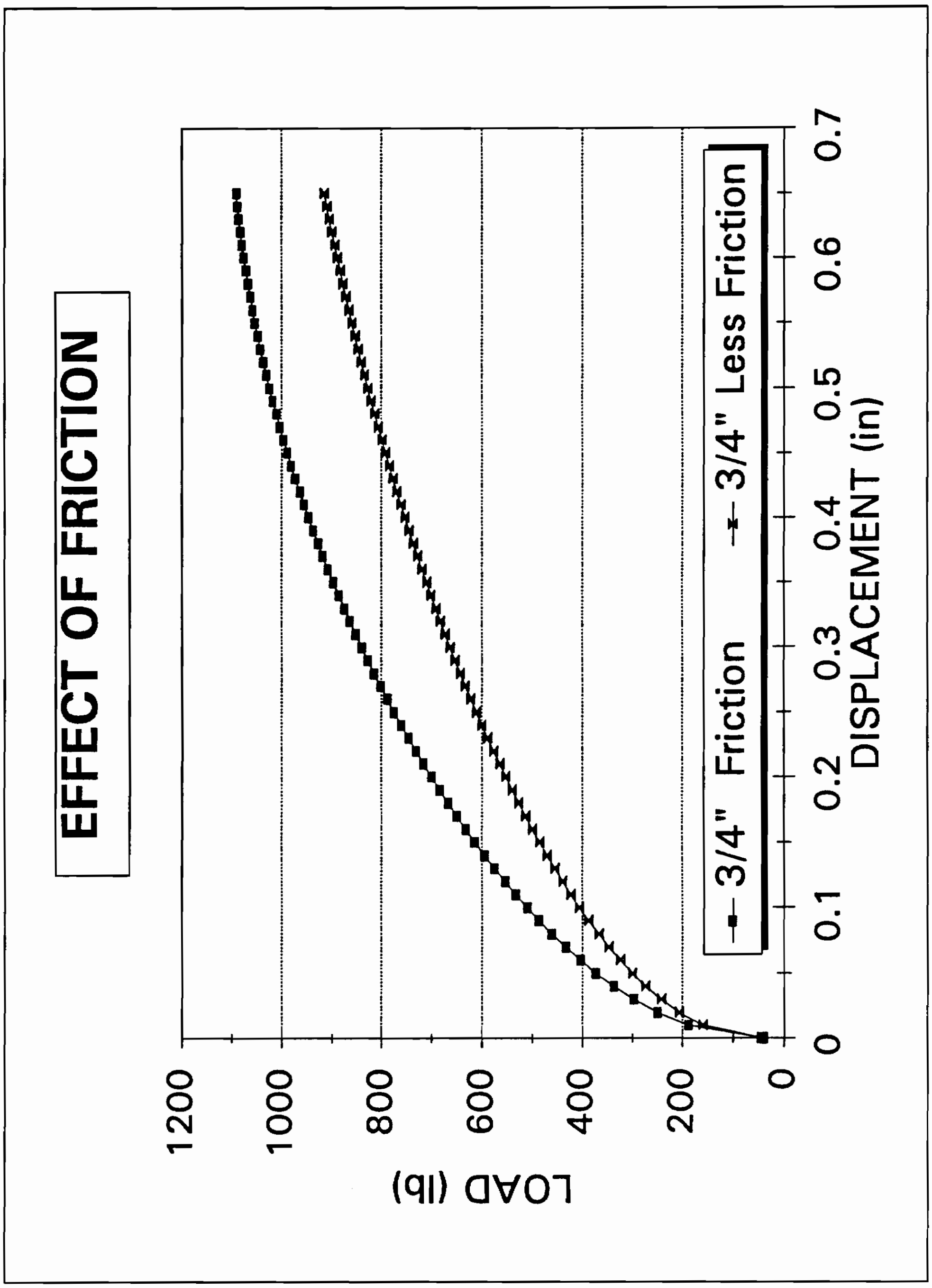


Figure 4.10 Comparison of the mean load-slip curves for specimens tested with friction and with less friction using 3/4" thick deckboards.

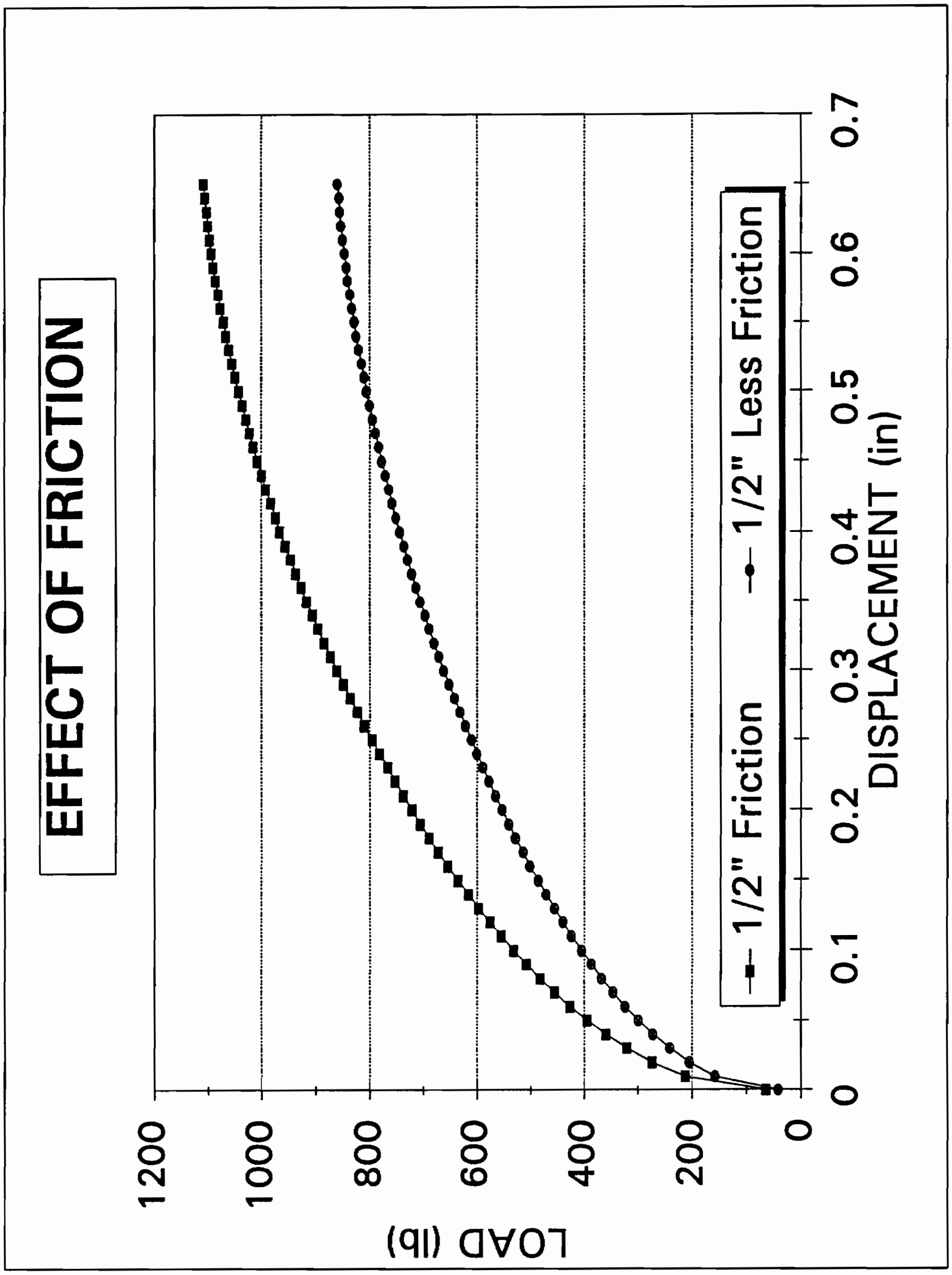


Figure 4.11 Comparison of the mean load-slip curves for specimens tested with friction and with less friction using 1/2" thick deckboards.

set of joint specimens were manufactured and tested with wood in the green state. The second set of specimens were manufactured in the green state and tested in the dry state (approximately 15 percent moisture content), and the third set of specimens were manufactured dry and tested dry. Table 4.9 presents the average values and coefficients of variation for the moisture content and specific gravity of the joint specimens at the time of testing. An ANOVA test was run to determine if a difference existed between the mean capacities of the three joint specimen moisture conditions.

H_o: The mean capacities of the three moisture conditions are equal

H_a: The mean capacities for each moisture condition was different

For the three conditions: $F=47.78$ $Pr>F=0.0001$

The null hypothesis of equality was rejected for an α value of 0.05, because the probability of error type I is equal to 0.0001, significantly below the α value. Multiple comparison testing showed that there is a significant difference between the Green/Dry condition (manufactured Green and tested Dry) and the other two conditions. However, there was no significant difference between the mean values of the Green/Green and Dry/Dry conditions. This statistical test shows that the strongest connections were found in the Green/Dry joint specimens, followed by the Green/Green and Dry/Dry respectively. Table 4.10 and Figure 4.12 show agreement with

Table 4.9 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of moistu content and specific gravity for connections tested to determine the influence of moisture content. (Board thickness: 3/4". Species: red alder (green). Nail type: 3. Nails per joint: 3).

Set Description		Moisture Content (%)		Specific Gravity			
		Block	Board	Bl G	Bl D	Bo G	Bo D
Assembled: G	AVG	78	142	0.39	0.43	0.38	0.42
and	STDs	18	22	0.07	0.09	0.02	0.02
Tested: G	COV (%)	23	16	19	20	5	4
Assembled: D	AVG	20	15	0	0.41	0	0.43
and	STDs	1	0	0	0.02	0	0.03
Tested: D	COV (%)	5	2	0	5	0	8
Assembled: G	AVG	19	15	0	0.43	0	0.44
and	STDs	2	0	0	0.03	0	0.02
Tested: D	COV (%)	8	2	0	8	0	5

Note: For more details see Appendix A.

Bl = Block G = Green volume basis

Bo = Board D = Dry volume basis

Table 4.10 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of initial stiffness, yield load, and capacity for connections tested to determine the influence of moisture content.

Board thickness: 3/4". Species: red alder (green). Nail type: 3. Nails per joint: 3. Rate of loading: 1 Hz.

Set		Initial Stiffness		Load at 5%		Load at Capacity		Diff*
Description		Final Curve	Initial Curve	Final Curve	Initial Curv	Final Curve	Initial Curv	%
Assembled: G	AVG	36156 psi	37952 psi	247 lb	250 lb	882 lb	1049 lb	16
and	COV (%)	41	36	14	14	9	10	
Tested: G	Diff** (%)	100	100	100	100	100	100	
Assembled: D	AVG	22191 psi	22476 psi	178 lb	177 lb	831 lb	996 lb	17
and	COV (%)	29	30	19	19	11	9	
Tested: D	Diff** (%)	61	59	72	71	94	95	
Assembled: G	AVG	14298 psi	14130 psi	199 lb	221 lb	1122 lb	1322 lb	15
and	COV (%)	27	23	14	25	7	7	
Tested: D	Diff** (%)	64	63	112	125	135	133	

Note: For more details see Appendix A * Difference = ([capacity of initial-capacity of final]/capacity of initial)*100

(D) = Dry , (G) = Green.

** Difference in percent using assembled green and tested green connections as a base.

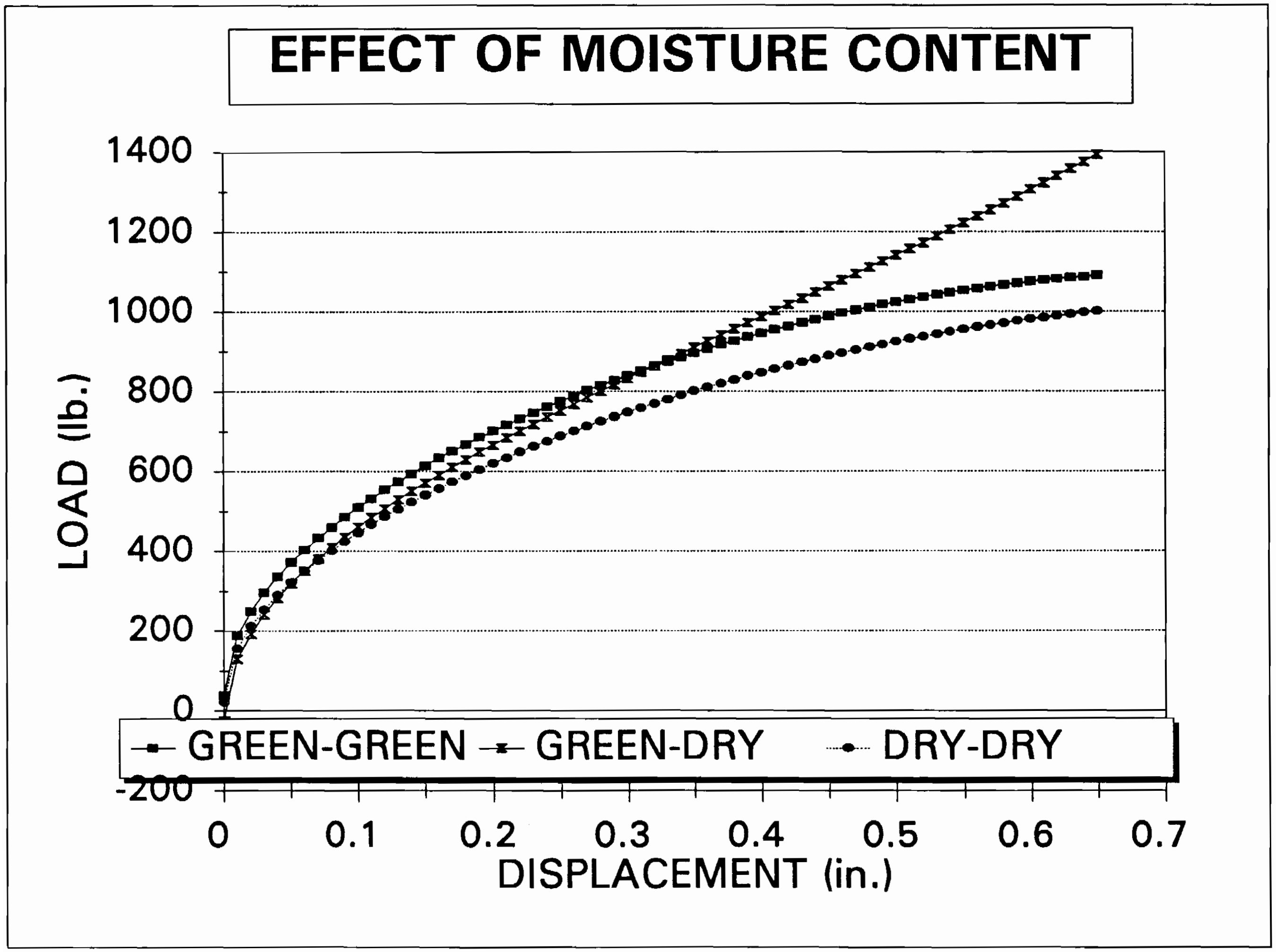


Figure 4.12 Comparison of the mean load-slip curves for specimens tested at different moisture contents and constructed with 3/4" thick deckboards.

these statistical results for the capacity of the connections. Table 4.10 also illustrates that the Green/Green joint specimens had the highest average value of initial stiffness, followed by Dry/Dry, with Green/Dry having the lowest average value. The results show that the green-dry connection curves have a transition from the weakest of the three at the beginning of the curve to the strongest at capacity. This is a consequence of the friction between members and the effect of the kind of nail used in the connection. Lack of friction decreased the strength of the joint at low deformations because of the gap created between members when seasoning of the wood, however, at high deformations the kind of nail affected the withdrawal force and the strength of the connection. This effect is observed in wood nail connections fasten with helically threaded nails when they are built with green wood and then seasoned to 30% or less moisture content (see 2.1.2 for more details). All the joint specimens were planned to size for uniformity, this fact affects the behavior of the connections. There was more friction between the two members in the green-green and green-dry connections than in the dry-dry connections due to the smoothness of the later when compared to the other two.

4.1.5 Effect of Pattern of Nails

Figure 4.13 and Table 4.11 illustrate and describe the results of the two different patterns of nails. Fifteen specimens were tested with each

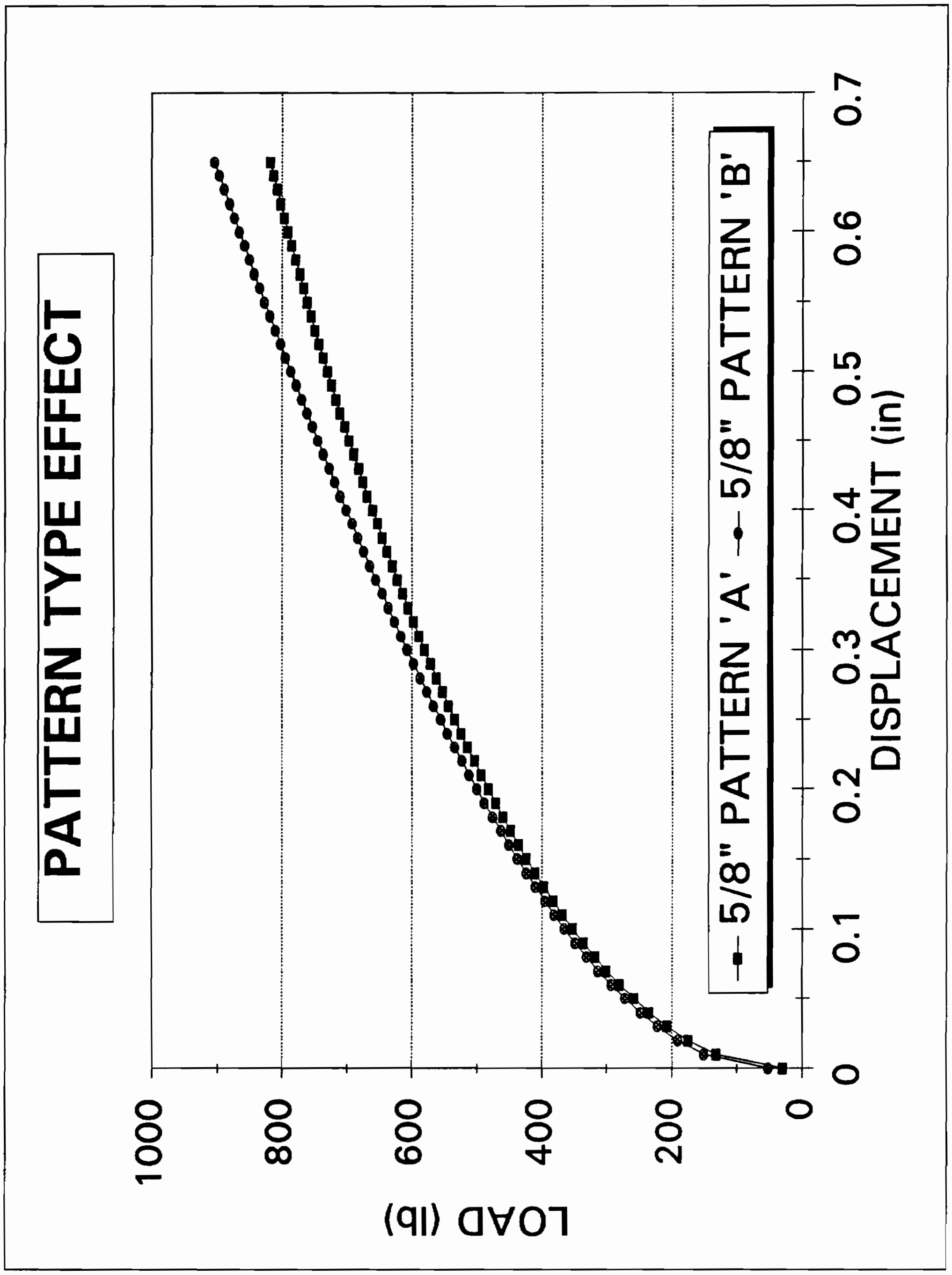


Figure 4.13 Comparison of the mean load-slip curves for specimens tested for pattern effect and constructed with 3/4" thick deckboards.

Table 4.11 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of moisture content and specific gravity for connections tested to determine the influence of pattern effect. (Board thickness: 5/8". Species: red alder (green). Nail type: 3. Nails per joint: 3).

Set Description		Moisture Content (%)		Specific Gravity			
		Block	Board	Bl G	Bl D	Bo G	Bo D
Pattern "A"	AVG	49	69	0.39	0.43	0.36	0.39
	STDs	9	14	0.04	0.04	0.02	0.01
	COV (%)	18	20	10	10	4	3
Pattern "B"	AVG	102	72	0.39	0.43	0.37	0.40
	STDs	26	18	0.03	0.04	0.02	0.01
	COV (%)	26	25	8	8	6	4

Note: For more details see Appendix A.

Bl = Block G = Green volume basis

Bo = Board D = Dry volume basis

pattern (A and B, as discussed in section 3.2), and the results show that pattern B has higher average capacity (maximum load) than pattern A. The average initial stiffness is also higher in pattern B. Table 4.12 presents the average values and coefficients of variation for the moisture content and specific gravity of the joint specimens at the time of testing. A t-test was run to determine if a difference existed between the mean values of capacity for the two nail patterns.

H_o: Mean capacities of the two nail patterns are equal

H_a: Mean capacities for each nail pattern are different

For the two conditions: $T=3.21$ $Pr>T=0.0431$

The null hypothesis of equality was not rejected due to insufficient evidence for an α value equal to 0.05. Since the P value (0.0431) is so close to the α value of 0.05, there is high probability that error type I may have occurred. This means that the mean capacities of the two patterns are not statistically different from each other, as could be appreciated in Figure 4.13 and Table 4.11. Both of them show a very small difference between pattern A and pattern B. Pattern B seems to create connections 7% stronger than pattern A, however , the difference is so small that it is believed to be caused by the normal variability of wood.

Table 4.12 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of initial stiffness, yield load, and capacity for connections tested to determine the influence of pattern effect.

Board thickness: 5/8". Species: red alder (green). Nail type: 3. Nails per joint: 3. Rate of loading: 1 Hz.

Set		Initial Stiffness		Load at 5%		Load at Capacity		Diff*
Description		Final Curve	Initial Curve	Final Curve	Initial Curve	Final Curve	Initial Curve	%
Pattern "B"	AVG	28102 psi	27813 psi	169 lb	174 lb	693 lb	859 lb	19
	STDs	4005 psi	4072 psi	31 lb	32 lb	58 lb	73 lb	
	COV (%)	14	15	19	18	8	8	
Pattern "A"	AVG	24018 psi	23495 psi	149 lb	149 lb	643 lb	791 lb	19
	STDs	6481 psi	6381 psi	28 lb	28 lb	34 lb	40 lb	
	COV (%)	27	27	18	18	5	5	
	Diff** (%	15	16	12	14	7	8	

* Difference = ([capacity of initial-capacity of final]/capacity of final)*100.

** Difference = ([stiffness "B"-stiffness "A"]/stiffness "B")*100.

4.1.6 Effect of Number of Nails

In this section, fifteen specimens were tested for 3 configurations: one, two and three nail connections. The joint specimens used nail type two and 3/4 inch thick side member. Average values and coefficients of variation for the moisture content and specific gravity of the joint specimens at the time of testing are presented in Table 4.13. An ANOVA test was run to determine if a difference in the mean capacities of strength existed for the joint specimens between the different numbers of nails.

H_o: The mean capacities of the three samples are equal

H_a: The mean capacity for each sample are different

For the three conditions: $F=813.67$ $Pr>F=0.0001$

The null hypothesis of equality was rejected for an α value of 0.05, because the probability of error type I is equal to 0.0001, significantly below the α value. Multiple comparison test results indicated that there is a significant difference between the mean capacities of one, two and three nail connections. The data collected show strength increases in increments between one and two nails, and between two and three nails, with the appearance, overall, of close to a linear relationship between number of nails and strength increase (Table 4.14). This appearance is misleading, because the average strength increase between one nail and two nail connections is almost doubled, as would be expected in a linear relationship. The average

Table 4.13 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of moisture content and specific gravity for connections tested to determine the influence of number of nails. (Board thickness: 3/4". Species: red alder (green). Nail type: 2).

Set Description		Moisture Content (%)		Specific Gravity			
		Block	Board	Bl G	Bl D	Bo G	Bo D
One nail/joint	AVG	81	135	0.37	0.40	0.40	0.44
	STDs	27	16	0.01	0.01	0.03	0.04
	COV (%)	34	12	4	4	8	9
Two nails/joint	AVG	106	130	0.35	0.38	0.39	0.44
	STDs	30	11	0.02	0.02	0.03	0.04
	COV (%)	28	9	7	6	8	9
Three nails/joint	AVG	88	118	0.42	0.46	0.39	0.43
	STDs	24	34	0.04	0.05	0.03	0.03
	COV (%)	28	29	9	10	7	7

Note: For more details see Appendix A.

Bl = Block G = Green volume basis

Bo = Board D = Dry volume basis

Table 4.14 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of initial stiffness, yield load, and capacity for connections tested to determine the influence of number of nails.

Board thickness: 3/4". Species: red alder (green). Nail type: 2. Rate of loading: 1 Hz.

Set Description		Initial Stiffness		Load at 5%		Load at Capacity		Diff*
		Final Curve	Initial Curve	Final Curve	Initial Curve	Final Curve	Initial Curve	%
One nail/joint	AVG	12073 psi	12836 psi	86 lb	89 lb	226 lb	272 lb	20
	COV (%)	29	33	14	12	10	8	
	Diff** (%)	100	100	100	100	100	100	
Two nails/joint	AVG	29266 psi	29746 psi	147 lb	154 lb	469 lb	544 lb	16
	COV (%)	31	31	36	35	35	37	
	Diff** (%)	242	232	170	173	208	200	
Three nails/joint	AVG	43933 psi	45165 psi	289 lb	297 lb	788 lb	939 lb	19
	COV (%)	21	23	18	16	5	5	
	Diff** (%)	364	352	335	333	350	345	

* Difference = ([capacity of initial-capacity of final]/capacity of final)*100.

** Difference in percent using one nail connections as a base.

strength increase between two nail and three nail connections, however, is again almost doubled, which does not fit the NDS predicted pattern of strength increase (Figure 4.14). It is believed that the reason for the variation from the linear assumption of the NDS manual is due to the nail pattern in the specimen. The three nails in the connection were driven in a staggered pattern. When the third nail was driven in between the other two but not in the same horizontal row, the load-carrying capacity of the nailed joint was improved, increasing the carrying capacity more than was expected for a single nail.

4.1.7 Effect of Specific Gravity

Three species were tested to investigate the effect of specific gravity on performance of the connections. These species were: red alder (specific gravity = 0.42), southern yellow pine (specific gravity = 0.51), and white oak (specific gravity = 0.68). Table 4.15 presents the average values and coefficients of variation for the moisture content and specific gravity of the joint specimens at the time of testing. The results of an ANOVA test were expected to determine if a significant difference existed between the means of strength of the three joint specimens with differing specific gravities. The hypothesis was:

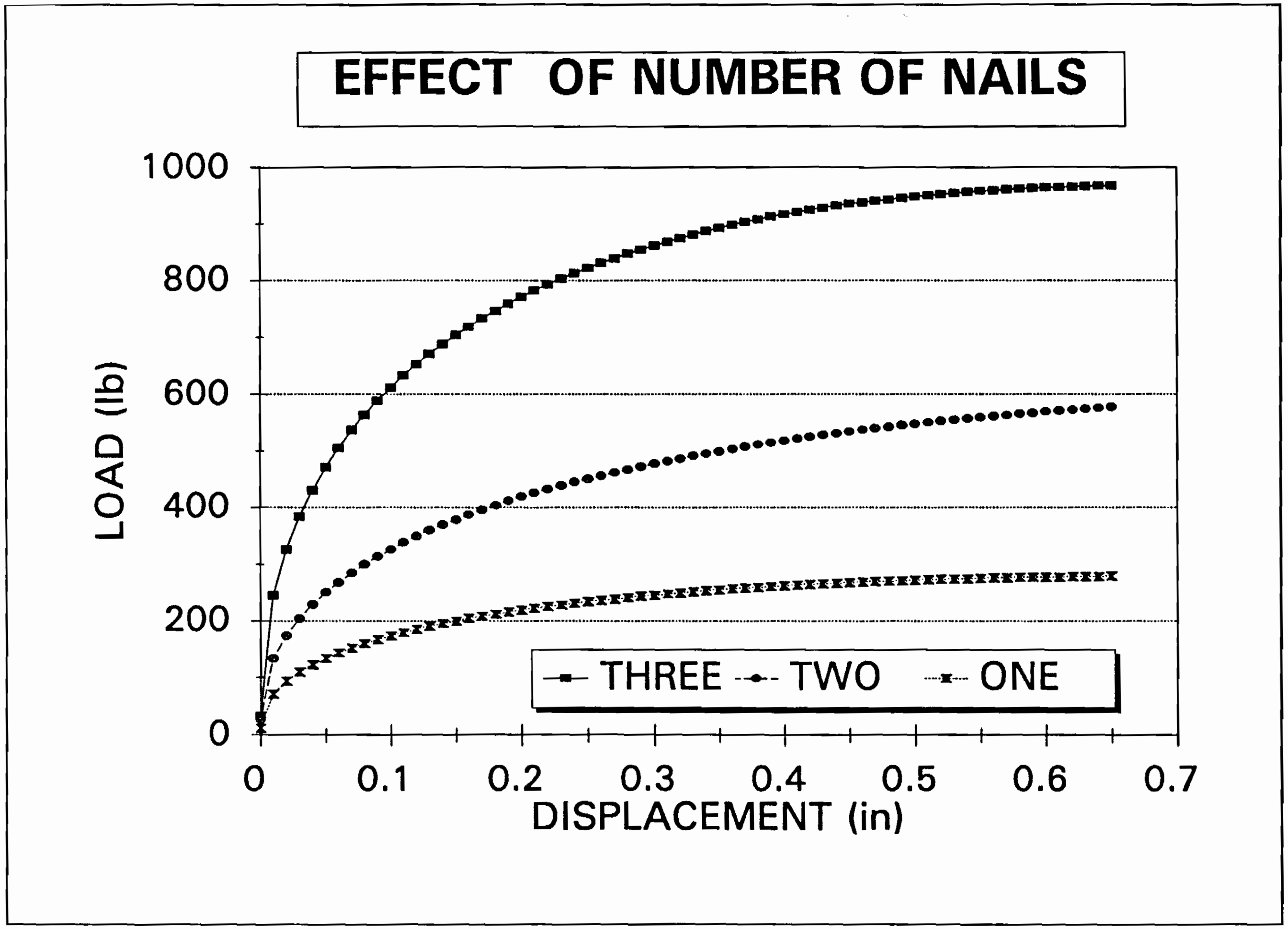


Figure 4.14 Comparison of the mean load-slip curves for specimens tested for the effect of number of nails and constructed with 3/4" thick deckboards.

Table 4.15 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of moisture content and specific gravity for connections tested to determine the influence of specific gravity. (Board thickness: 3/4". Nail type: 3. Nails per joint: 3).

Set		Moisture Content (%)		Specific Gravity			
Description		Block	Board	Bl G	Bl D	Bo G	Bo D
Red alder	AVG	78	142	0.39	0.43	0.38	0.42
	STDs	18	22	0.07	0.09	0.02	0.02
	COV (%)	23	16	19	20	5	4
S. y. pine	AVG	82	61	0.45	0.48	0.43	0.46
	STDs	40	29	0.04	0.04	0.03	0.04
	COV (%)	49	47	9	9	8	9
White oak	AVG	70	58	0.68	0.76	0.64	0.72
	STDs	5	4	0.02	0.03	0.02	0.02
	COV (%)	7	6	2	3	3	3

Note: For more details see Appendix A.

Bl = Block G = Green volume basis

Bo = Board D = Dry volume basis

H_o: The mean capacities for the three specific gravities are equal.

H_a: The mean capacity for each specific gravity is different

For the three conditions: F=402.36 Pr>F=0.0001

The null hypothesis of equality was rejected for an α value of 0.05, because the probability of error type I is equal to 0.0001, significantly below the α value. Multiple comparison testing shows that there is a significant difference between the means of the three species. This statistical test shows that the strongest connections were found in the white oak specimens, followed by the red alder and southern yellow pine, respectively. Table 4.16 and Figure 4.15 agree with these statistical results, in the strength of the connections. This table also illustrates that white oak joint specimens had the highest average value of initial stiffness, followed by red alder, with southern yellow pine having the lowest average value. The results obtained for initial stiffness values are as expected for the white oak, but the yellow pine was expected to be stronger than the red alder specimens, because of the difference in specific gravity between pine and alder (0.43 and 0.38 in green, respectively). It has been established by several studies that specific gravity of the wood is directly related to its mechanical properties (for more details in this topic see section 2.1.2). The reason why southern yellow pine samples had lower capacity values than the red alder specimens may be due the difference in anatomical structure

Table 4.16 Average (AVG), standard deviation (STDs), and coefficient of variation (COV) of initial stiffness, yield load, and capacity for connections tested to determine the influence of specific gravity.

Board thickness: 3/4". Nail type: 3. Nails per joint: 3. Rate of loading: 1 Hz.

Set Description		Initial Stiffness		Load at 5%		Load at Capacity		Diff*
		Final Curve	Initial Curve	Final Curve	Initial Curve	Final Curve	Initial Curve	%
Red alder	AVG	36156 psi	37952 psi	247 lb	250 lb	882 lb	1049 lb	16
	COV (%)	41	36	14	14	9	10	
	Diff** (%)	31	32	46	46	51	54	
S. y. pine	AVG	28895 psi	29660 psi	214 lb	221 lb	668 lb	801 lb	17
	COV (%)	21	22	19	19	8	9	
	Diff** (%)	25	25	40	41	38	41	
White oak	AVG	116867 psi	117833 psi	536 lb	542 lb	1737 lb	1947 lb	11
	COV (%)	22	22	11	12	8	8	
	Diff** (%)	100	100	100	100	100	100	

* Difference = ([capacity of initial-capacity of final]/capacity of final)*100.

** Difference in percent using white oak connections as a base.

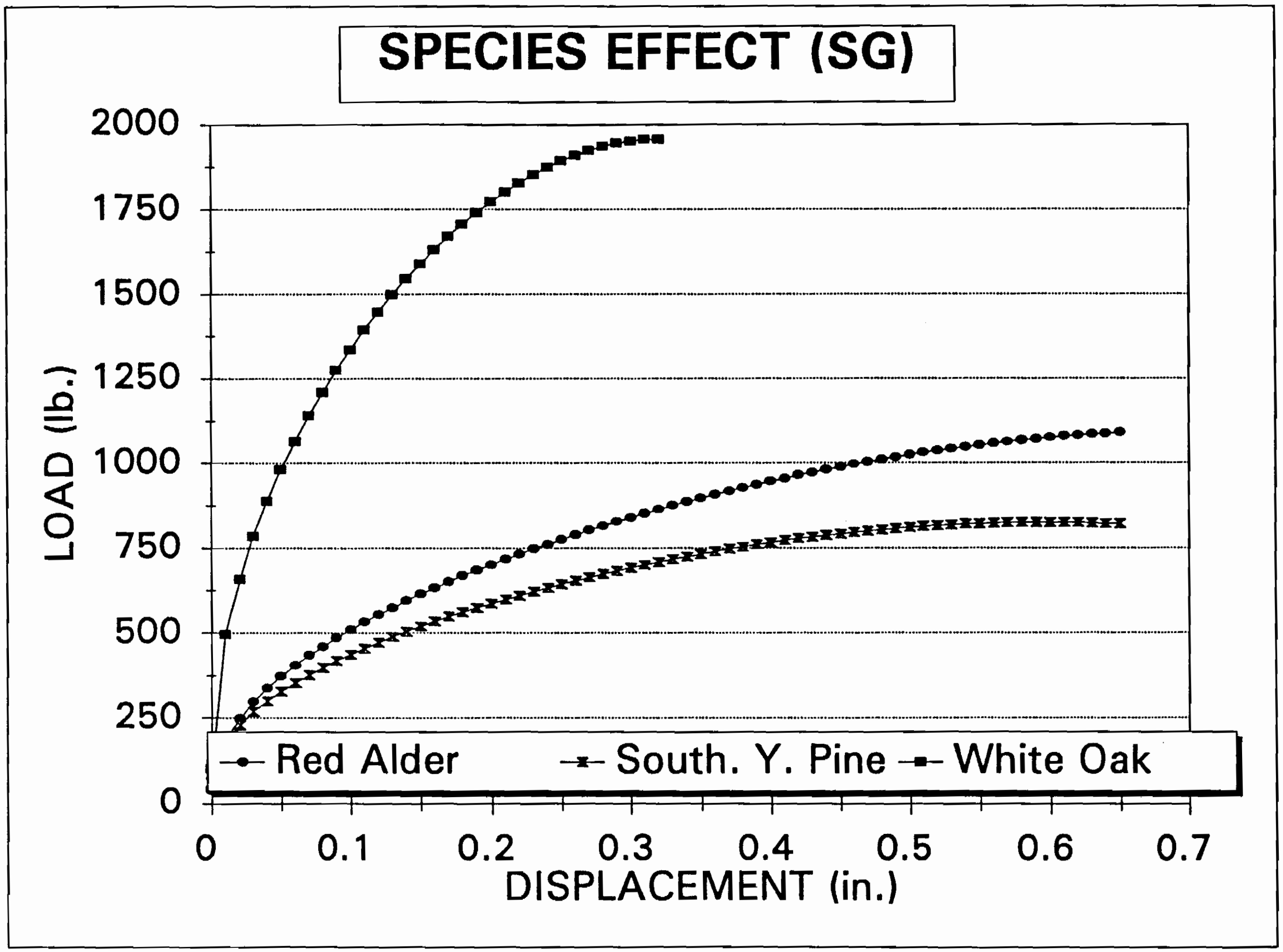


Figure 4.15 Comparison of the mean load-slip curves for specimens tested for the effect of specific gravity using 3/4" thick deckboards.

between the two species. Red alder is a diffuse porous species with very uniform anatomic configuration, southern yellow pine has an abrupt transition between the early and latewood and therefore a large difference in specific gravity between the two zones. Consequently, depending on the exact placement of the nail in either early or latewood higher or lower strength joint may result. The specific gravity of the specimen may not be related to specific gravity of the wood in the vicinity of the nail because specific gravity is measured, in this study, as an average for the specimen rather than a pointwise measurement.

4.1.8 Effect of rate of loading

The predicted curves of three different data sets of connections were compared to investigate the effect that rate and type of loading have on the performance of their load-slip curves. Average curves were derived from nail-wood connections tested at three different rates of loading 1) monotonic lateral loading, 2) cyclic lateral loading at 1/2 Hz, and 3) cyclic lateral loading at 1 Hz (Figure 4.16). It appears to be a significant increment has an effect on the initial stiffness between the two cyclic test curves, as compared to the monotonic curve. The increment in the initial stiffness of the two cyclic envelope curves is derived from the increment of the rate of loading at the time of testing. There is insignificant difference between the three curves at capacity and there is no statistical difference among the three curves at this

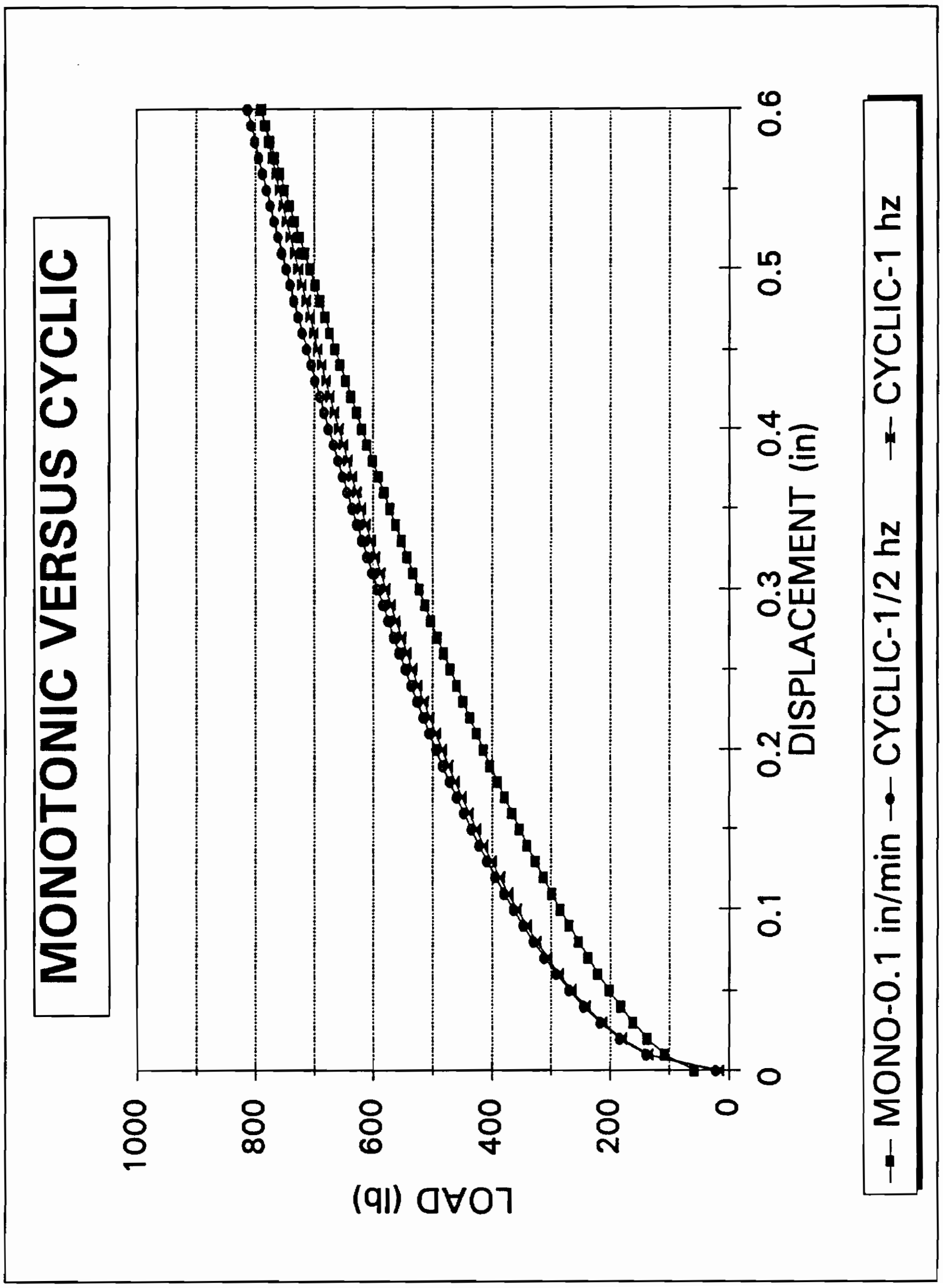


Figure 4.16 Effect of rate and type of loading in curve performance.

point. In fact, it seems that the curve derived from the monotonic lateral test is rising, and will intersect the others. When the two envelope curves are compared to the monotonic curve at the yield load, the envelope curves have higher values. However, at high deformations, before failure or capacity, the two curves seem to be affected by the previous loading history, which is reflected in a decrease at capacity (maximum load).

4.2 Yield Theory Results

4.2.1 Dowel Bearing Strength

The results obtained from the dowel bearing test of green and dry red alder are found in Table 4.17. Average values and coefficient of variation for these two conditions of red alder wood are used to determine if the dowel bearing strength was affected by moisture content. There was no standard method for defining this property. The two most commonly used methods are the Nordtest (Aune and Patton-Mallory, 1986) and the one used by Wilkinson (1991). For this research, a proposed ASTM standard (under review) was followed, similar to the one used by Wilkinson. Because of the specific gravity of red alder, the thickness of the side member, and the use of hardened threaded nails, it was assumed that the mode of failure for this type of nailed wood connection was defined by the side member thickness. Since the range of deckboard thickness tested was from 0.5 inch to 0.75 inch, and the threaded portion of the nail shank is two-thirds of the nail

Table 4.17 Experimental Dowel Bearing Strength for red alder (green) and at 15% moisture content loaded parallel to the grain.

Replication Number	Wire Diameter (inch)	Specimen Thickness (inch)		Specific Gravity		5% Offset load (lb)		Dowel Bearing Strength (psi)	
		Green	Dry	Green	Dry	Green	Dry	Green	Dry
1	0.12	0.752	0.746	0.39	0.46	243	405	2693	4524
2	0.12	0.752	0.749	0.39	0.42	207	360	2294	4005
3	0.12	0.752	0.745	0.39	0.41	190	390	2105	4362
4	0.12	0.752	0.740	0.39	0.41	201	400	2227	4505
5	0.12	0.752	0.745	0.39	0.41	214	360	2371	4027
6	0.12	0.752	0.715	0.39	0.42	217	355	2405	4137
7	0.12	0.766	0.722	0.37	0.41	218	348	2372	4017
8	0.12	0.766	0.746	0.37	0.44	216	410	2350	4580
9	0.12	0.766	0.733	0.37	0.42	222	397	2415	4513
10	0.12	0.766	0.750	0.37	0.40	184	383	2002	4255
11	0.12	0.766	0.733	0.37	0.48	206	290	2241	3296
12	0.12	0.762	0.735	0.40	0.50	217	370	2373	4195
13	0.12	0.759	0.743	0.40	0.47	263	370	2888	4150
14	0.12	0.770	0.735	0.38	0.49	237	390	2565	4422
15	0.12	0.771	0.740	0.38	0.40	270	322	2918	3626
16	0.12	0.755		0.38		205		2263	
17	0.12	0.756		0.38		207		2282	
18	0.12	0.770		0.39		267		2890	
19	0.12	0.765		0.39		240		2614	
20	0.12	0.755		0.36		250		2759	
21	0.12	0.762		0.36		265		2898	
AVG	0.12	0.760	0.738	0.38	0.44	226	370	2473	4174
STDs		0.01	0.01	0.01	0.03	26	33	276	355
COV (%)		0.9	1.3	3.1	7.9	11.5	8.9	11.2	8.5

Note: The amount of specimens tested was 21 in the green state and 15 at 15 % of moisture content.

length, the bearing effect on the nail was in the non-threaded portion of the shank. In order to determine the dowel bearing strength for this type of connection, all the tests were done using 0.120 inch wire diameter. The definition of the 5 percent offset load was not an easy task because of the nonlinearity in the initial part of the load-slip curve (for wood connections), and the lack of specific criteria to account for this nonlinearity.

Table 4.17 shows a significant difference in dowel bearing strength between the average value for green red alder and the average value for red alder at 15 percent of moisture content. The difference between the two moisture contents was approximately 69 percent. This difference is due to the increase in dowel bearing strength with decreasing moisture content.

4.2.2 Nail Bending Yield Moment

Table 4.18 shows the results of the nail yield moment test for the threaded-shank types of nails. The nail bending yield stress seems to increase with decreasing wire diameter. These results were also found by Wills, et al. (1993), who state that this difference is due to the manufacturing process required for each nail diameter. Wills, et al. described this effect as: " ...the smaller diameter wire is drawn through more forming dies and therefore experiences more strain hardening than the larger diameter nails." However, the differences among these types of nails are smaller for bending yield stress than for MIBANT angle (Ma). An

Table 4.18 Experimental Nail Yield Moment for the Four Types of Nails (15 specimens were tested for each nail type).

Replication Number	5-percent Offset load (lb)				Nail Moment (lb-in)				Nail Yield Stress (psi)			
	Nail Type				Nail Type				Nail Type			
	1	2	3	4	1	2	3	4	1	2	3	4
1	128	71	100	173	40	22	31	54	175486	97340	108507	187717
2	141	74	108	169	44	23	34	54	193309	101453	117187	186632
3	125	67	106	171	39	21	33	55	171373	91856	115017	190972
4	126	69	100	170	39	22	31	54	172744	94598	108507	187717
5	129	69	107	173	40	22	33	53	176857	94598	116102	185547
6	133	71	108	175	42	22	34	54	182341	97340	117187	186632
7	136	68	99	170	42	21	31	53	186454	93227	107422	184462
8	125	81	103	170	39	25	32	53	171373	111050	111762	184462
9	130	71	105	170	41	22	33	53	178228	97340	113932	184462
10	135	68	103	172	42	21	32	55	185083	93227	111762	189887
11	130	77	104	171	41	24	33	54	178228	105566	112847	187717
12	132	75	105	173	41	23	33	53	180970	102824	113932	184462
13	142	72	100	176	44	23	31	53	194680	98711	108507	185547
14	137	69	103	172	43	22	32	53	187825	94598	111762	183377
15	132	74	106	173	41	23	33	54	180970	101453	115017	187717
AVG	132	72	104	172	41	22	32	54	181061	98345	112630	186487
STDs	5	4	3	2	2	1	1	1	7319	5296	3260	2165
COV (%)	4	5	3	1	4	5	3	1	4	5	3	1

Nail moment = pl/4 where: p=5% offset load (lb) and l=span (in).

Nail yield stress = pl/4s where: s=section modulus=([wire diameter]^3)/6.

example to illustrate this is found in Table 3.1, where there is a description of the four nail types, when comparing nail type 4 (Ma = 18 degrees, length = 2.86 inch) against nail type 1 (Ma = 27 degrees, length = 2.25), nail type 1 has an increase of 9 degrees over nail type 4. However, these two nails have similar nail bending yield moment (181, 061 psi and 181, 902 psi respectively). These results suggest variations derived from the slight differences in manufacturing processes among nail diameters, as well as among manufacturers. Loferski and Mclain (1991) found a similar result and observed that there was a very low correlation between MIBANT angle and nail yield moment. It is important to remark that it was observed that the MIBANT test provides a better correlation to connection yield strength than the nail yield moment test.

4.2.3 Results of the NDS Yield Equation Against Experimental Data

Table 4.19 shows the results obtained from a comparison of the 5 percent offset yield values, using A) the NDS values and the four yield mode equations, selecting the smallest value (Note: in all cases mode type III_s was the predicted failure mode); B) the experimental data for the dowel bearing strength and nail yield stress parameters inserted into the NDS yield equations; C) the 5 percent yield value of the initial envelope curve measured from the nailed wood joint experimental curves; and D) the 5 percent yield value of the envelope curve of the final cycles

Table 4.19 Comparison of Methods to Obtain the 5% Offset Yield Values for Green-Red Alder Nailed Connections.

Set	Avg Deck Thickness		Nail	Yield Equation Values using:			Yield Values from Envelope Curves			
I.D.	Nominal	Actual	Type	NDS Data	Experimental Data		Initial		final (stabilized)	
				Load (lb)	Load (lb)	% Diff*	Load (lb)	% Diff*	Load (lb)	% Diff*
1	1/2"	0.520"	1	312	324	4	206	-34	203	-35
2		0.520"	2	312	251	-19	261	-16	252	-19
3		0.520"	3	359	305	-15	252	-30	245	-32
4		0.520"	4	364	383	5	283	-22	278	-24
5	5/8"	0.655"	1	334	335	0	241	-28	234	-30
6		0.655"	2	334	271	-19	255	-24	240	-28
7		0.655"	3	380	322	-15	251	-34	238	-37
8		0.655"	4	385	393	2	315	-18	291	-24
9	3/4"	0.710"	1	344	342	-1	265	-23	263	-24
10		0.710"	2	344	280	-19	297	-14	289	-16
11		0.710"	3	390	331	-15	250	-36	247	-37
12		0.710"	4	396	398	1	320	-19	310	-22

Table 4.19a Comparison of Methods to Obtain the 5% Offset Yield Values for Dry-Red Alder Nailed Connections.

Set	Avg Deck Thickness		Nail	Yield Equation Values using:			Yield Values from Envelope Curves			
I.D.	Nominal	Actual	Type	NDS Data	Experimental Data		Initial		final (stabilized)	
				Load (lb)	Load (lb)	% Diff	Load (lb)	% Diff*	Load (lb)	% Diff*
19	3/4"	0.710"	3	455	482	6	177	-61	178	-61
20	3/4"	0.710"	3	455	482	6	221	-51	199	-56

*% Diff = Difference in percent when compared to NDS.

(stabilized response), measured from the nailed wood joint experimental curves. Figure 4.17 illustrates the comparison of the four, 5 percent offset yield values. First, there is no statistical difference between the 5 percent offset load values of the initial and final (stabilized) envelope curves. Second, the NDS equation predictions show inconsistent differences when compared to the experimental values because the assumed nail yield stress in the NDS is constant for all the nails used in this study (F_{yb} = 130, 000 psi for 0.120" and 0.135" diameter but nail types 1 and 4 have an $F_{yb} \approx$ 181, 000 psi and nail types 2 and 3 below 112, 000 psi). Third, the yield equation produces liberal predictions. The estimated 5 percent offset values are greater than the experimental 5 percent offset values by an average of 26 percent for wood with moisture content over the fiber saturation point, and by approximately 58 percent for wood with a moisture content of 15 percent. The NDS estimate yield design values are liberal, because they are between 4 percent below and 14 percent above the experimental values (Table 4.19a). This result is derived from the difference in the NDS dowel bearing strength values and the experimental dowel bearing strength values.

Table 4.20 and Figure 4.18 illustrate the comparison of the two predicted allowable design values to the experimental capacity of the initial envelope curve of the tested joint specimens. The allowable design values were estimated using the procedure and data described in the NDS manual

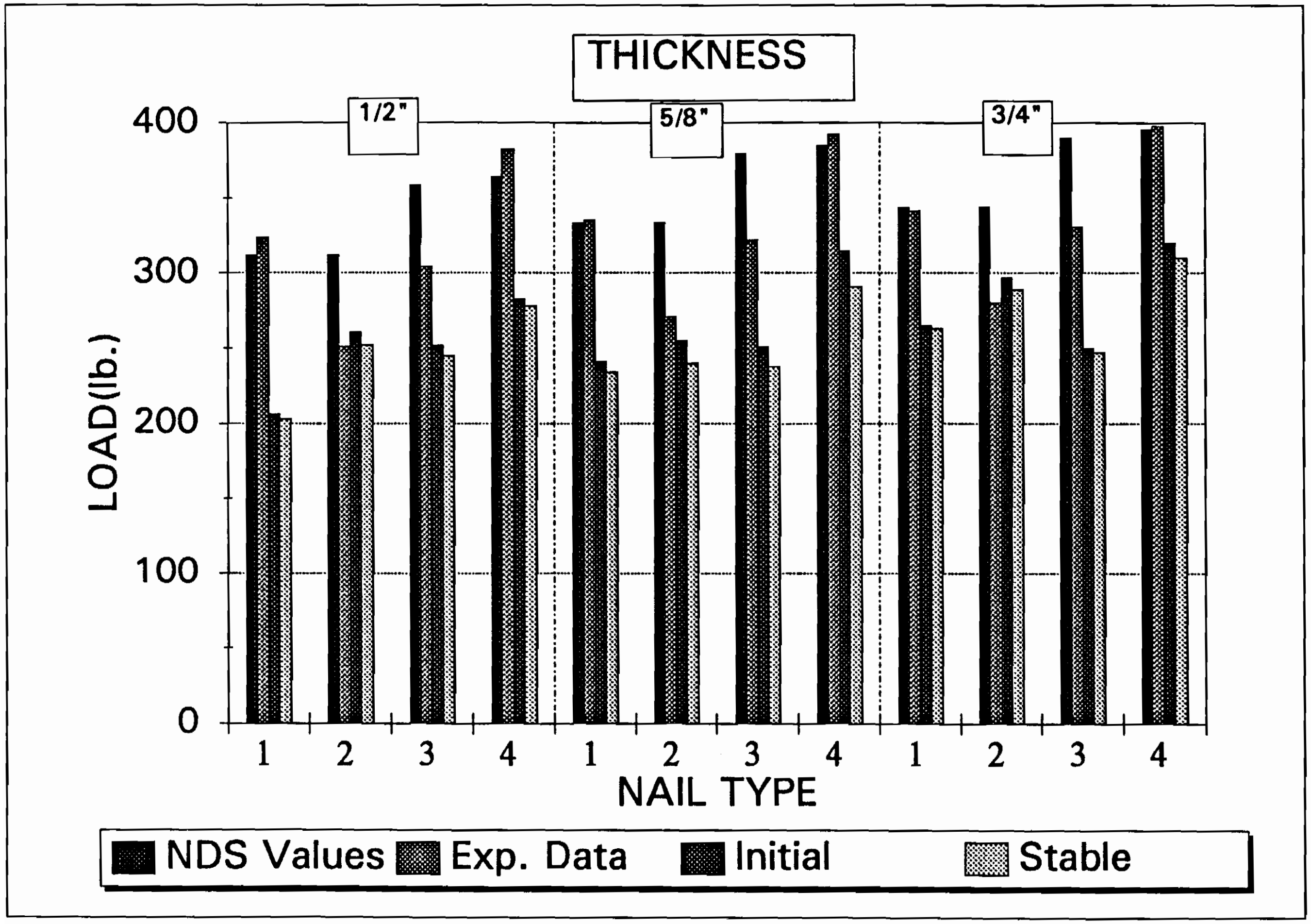


Figure 4.17 Comparison of methods to obtain the 5% offset yield values for green-red alder nailed connections (factor-of-safety not included).

Table 4.20 Comparison of Methods to Obtain the Design and Capacities Values for Green-Red Alder Nailed Connections.

Set	Avg Deck Thickness		Nail	Predicted Design Values Using:			Experimental Capacity of Envelope Curves			
I.D.	Nominal	Actual	Type	NDS Data	Experimental Data		Initial		Final (stabilized)	
				Load (lb)	Load (lb)	% Diff*	Load (lb)	F. of S.**	Load (lb)	F. of S.**
1		0.520"	1	227	235	4	942	4.15	773	3.41
2	1/2"	0.520"	2	227	183	-19	931	4.10	762	3.36
3		0.520"	3	261	222	-15	1013	3.88	822	3.15
4		0.520"	4	265	278	5	1076	4.06	869	3.28
5		0.655"	1	243	244	0	999	4.11	822	3.38
6	5/8"	0.655"	2	243	197	-19	921	3.79	768	3.16
7		0.655"	3	276	234	-15	1044	3.78	855	3.10
8		0.655"	4	280	286	2	1170	4.18	951	3.40
9		0.710"	1	250	248	-1	1033	4.13	870	3.48
10	3/4"	0.710"	2	250	204	-18	939	3.76	788	3.15
11		0.710"	3	284	240	-15	1049	3.69	882	3.11
12		0.710"	4	288	290	1	1205	4.18	1011	3.51

Table 4.20a Comparison of Methods to Obtain the Design and Capacities Values for Green-Red Alder Nailed Connections.

Set	Avg Deck Thickness		Nail	Predicted Design Values Using:			Experimental Capacity of Envelope Curves			
I.D.	Nominal	Actual	Type	NDS Data	Experimental Data		Initial		Final (stabilized)	
				Load (lb)	Load (lb)	% Diff*	Load (lb)	F. of S.**	Load (lb)	F. of S.**
19	3/4"	0.710"	3	331	350	6	996	3.01	831	2.51
28	3/4"	0.710"	3	331	350	6	1322	3.99	1122	3.39

* % Diff = Difference in percent when compared to NDS.

** F. of S. (Factor-of-safety) = initial/NDS data.

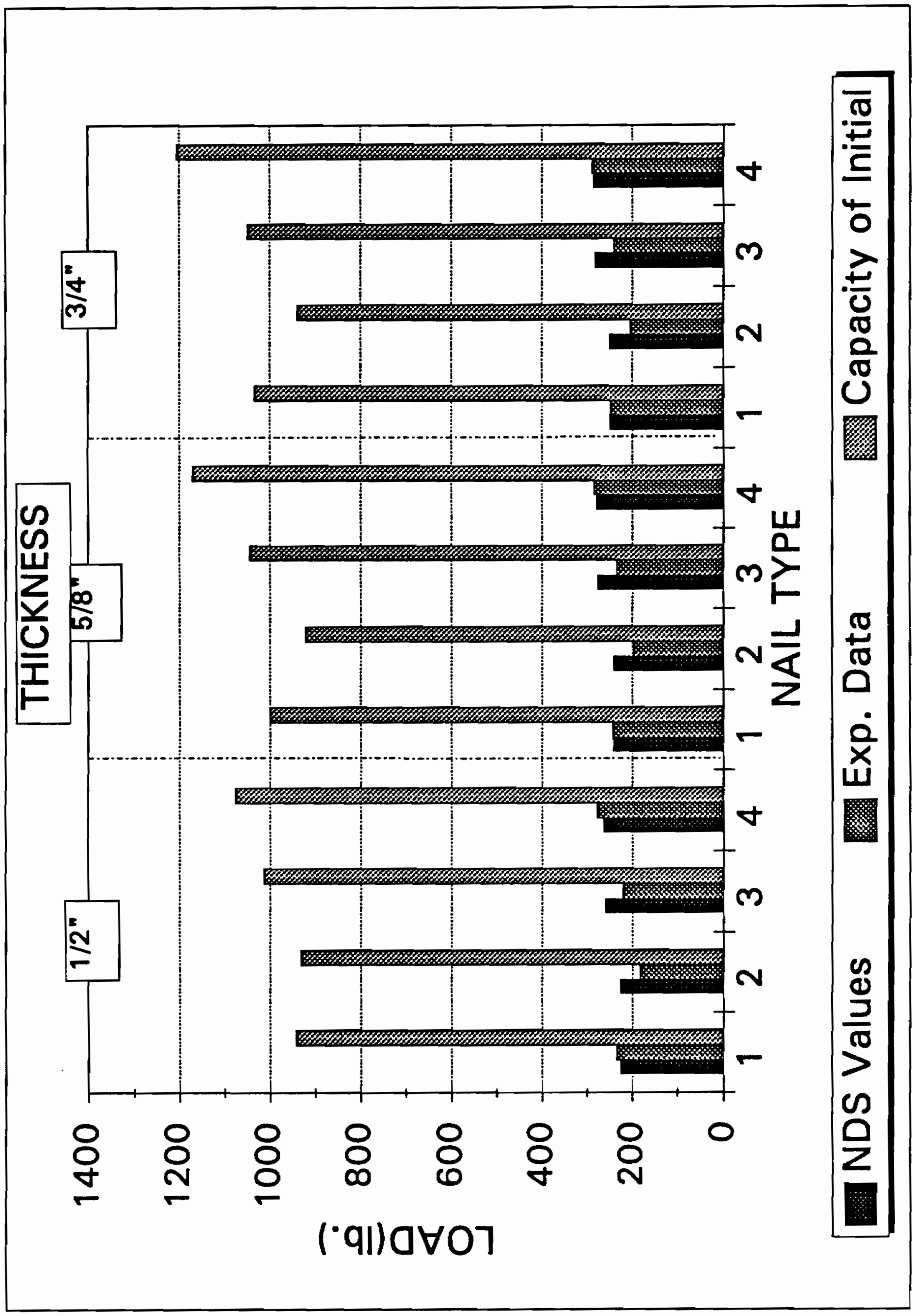


Figure 4.18 Comparison of methods to obtain the allowable design values for green-red alder nailed connections (factor-of-safety for short-term loads).

as well as experimental values for dowel bearing strength and nail yield stress. The capacity of the initial envelope curve was obtained from the lateral cyclic testing of the nailed wood connections. The predicted allowable design values for connections using wood with moisture content over the fiber saturation and helically threaded nails are conservative with a minimum factor-of-safety of 3.69 (ratio = capacity/NDS value). For connections using wood at 15% moisture content and the same kind of nails, it was found that the predicted allowable design values are also conservative with a minimum factor-of-safety of 3.01 (Table 4.20a). The average specific gravity used for estimation of the NDS yield design values were of 0.39 for green joint specimens and of 0.44 for joint specimens at 15 percent of moisture content.

4.3 Description of Mathematical Models

Mathematical models were fit to sets of 15 specimens, using a commercial statistical software (TableCurve), and the "best" model was selected. Twenty-four sets of initial envelop curves, and 24 sets of stabilized curves were used. Two different models (Equation 1123 and Equation 12) were selected from the established software, and Foschi's equation was fit as a user-defined function (Figures 4.19, 4.20, and 4.21, respectively). A description of the equation characteristics -- identification,

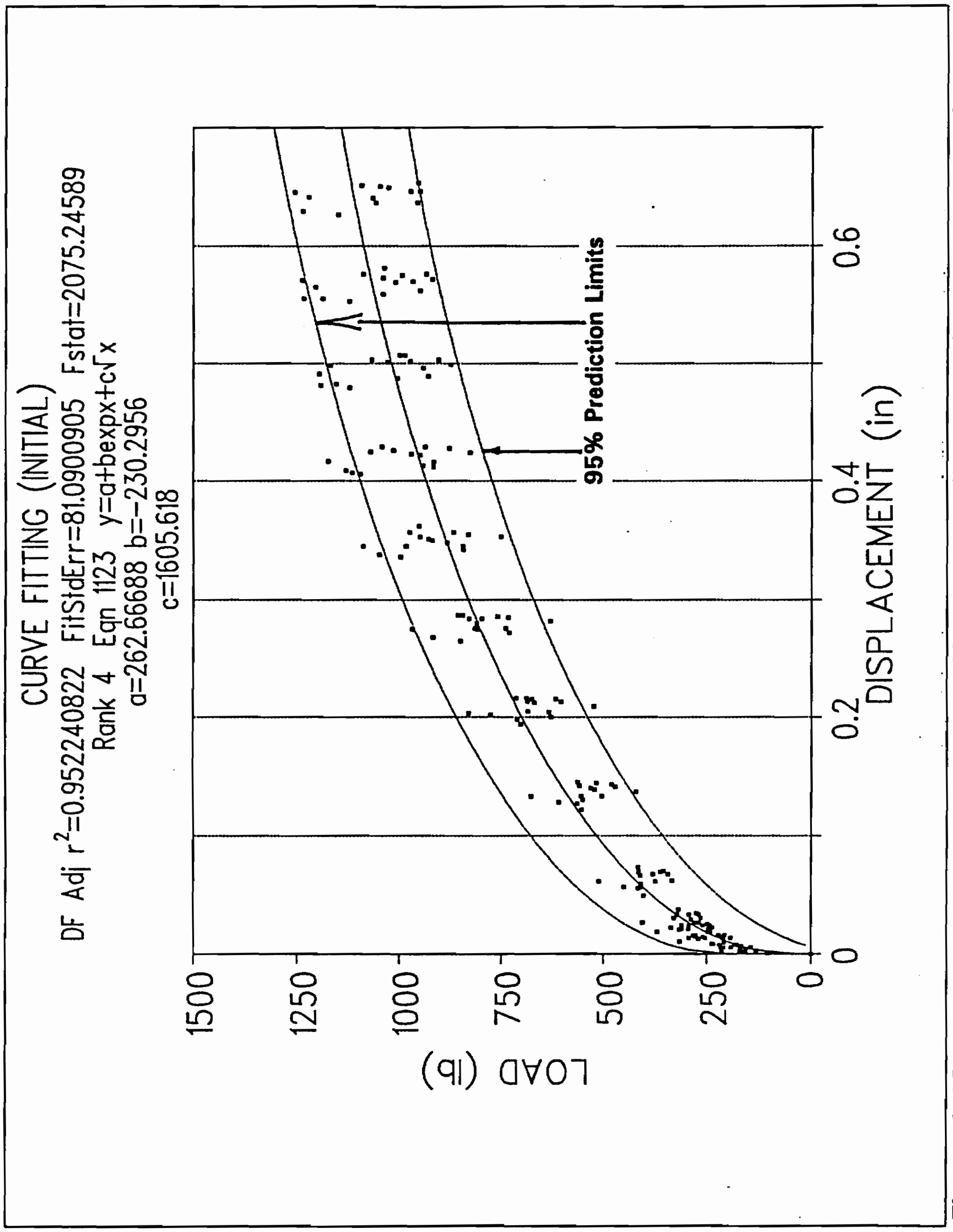


Figure 4.19 Typical curve fitting and 95% prediction limits obtained when equation 1123 (TABLECURVE) was fitted to the data set (15 specimens with 14 points each).

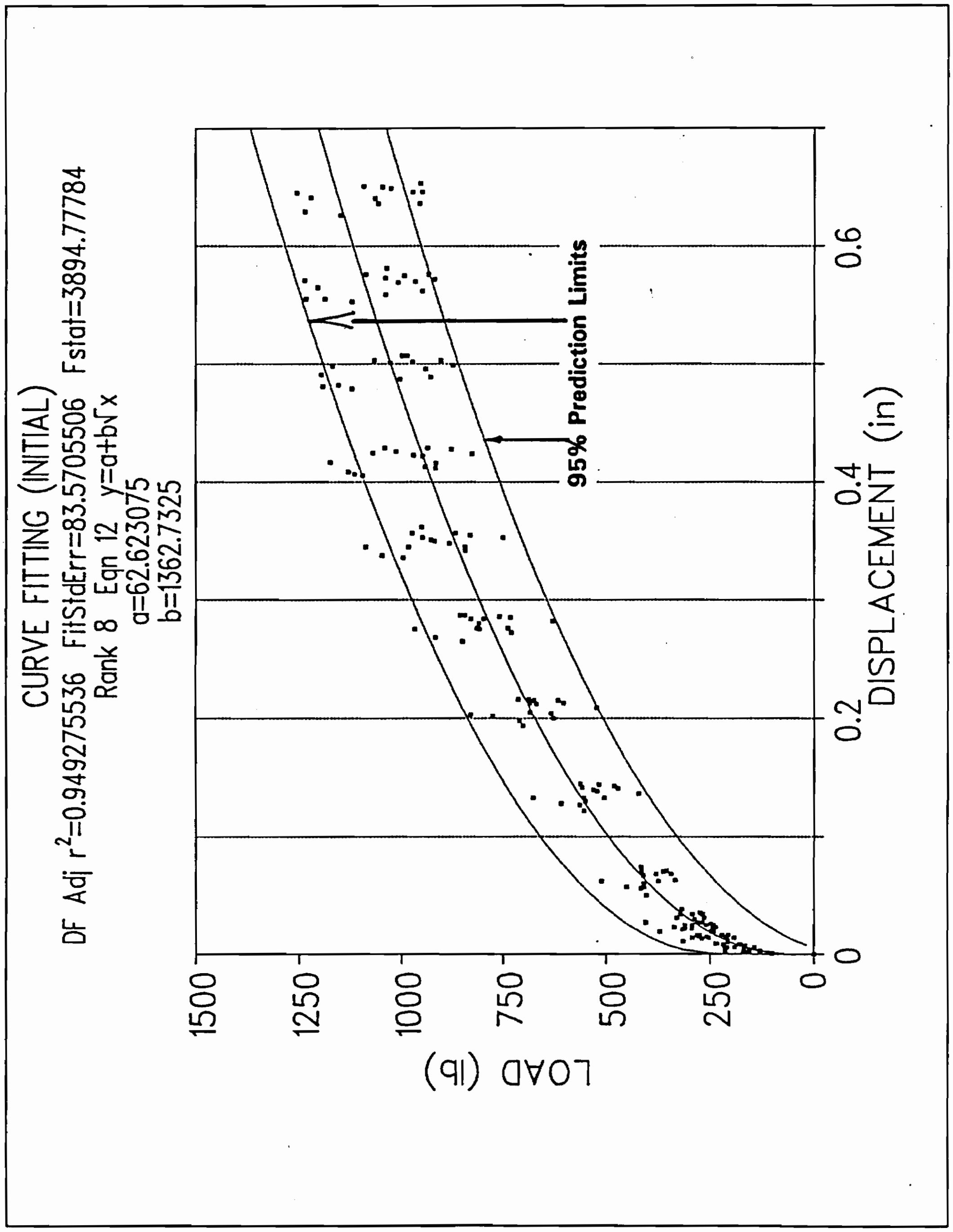


Figure 4.20 Typical curve fitting and 95% prediction limits obtained when equation 12 (TABLECURVE) was fitted to the data set (15 specimens with 14 points each).

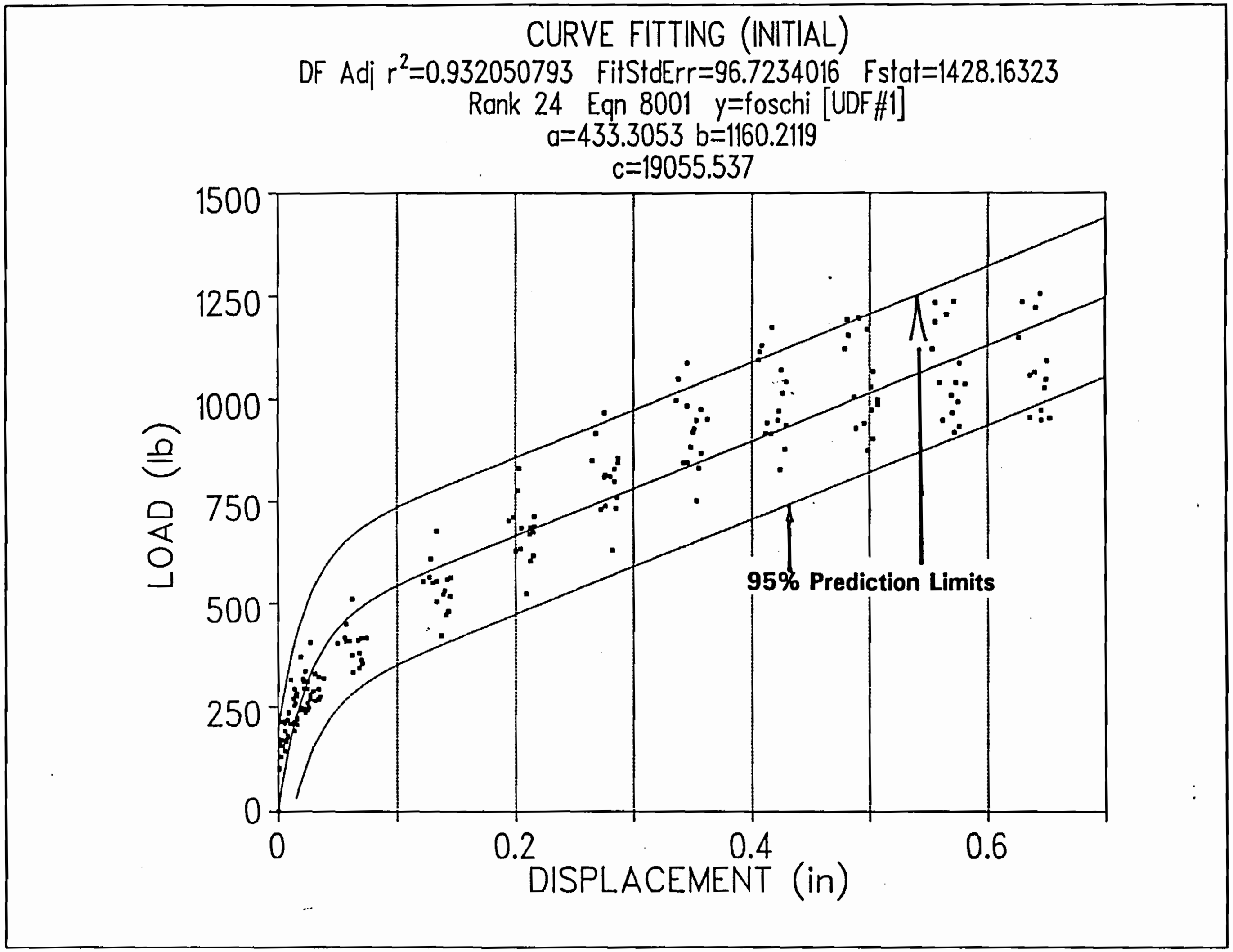


Figure 4.21 Typical curve fitting and 95% prediction limits obtained when Foschi's equation was fitted to the data set (15 specimens with 14 points each).

parameters, equation and level of fitting -- were summarized in Tables 4.21, 4.22, 4.23 and 4.24. The two equations selected are:

Equation 1123 (number used in TableCurve)

$$y = a + b\exp^{x} + c\sqrt{x} \qquad (4.1)$$

and Equation 12 (TableCurve)

$$y = a + b\sqrt{x} \qquad (4.2)$$

The criteria for selecting the best model was

1) equation with minimal number of parameters (two or three)
2) visual analysis to determine if the equation form fits well across the data
3) Higher fitting value with sort method based in Adjust R^2, and fit standard error, both of which order the equations based upon a pure least squares criteria.

4.3.1 Fitting Foschi's Model

As stated above, Foschi's model was fit to the experimental data following the same criteria. The model was fit to 24 average cyclic monotonic curves, and 24 average stabilized curves. The results of this fitting are shown in Tables 4.23 and 4.24 and Figure 4.21.

Even when there is a mathematical model for prediction, this model must have general applications in order to be useful. This is not the case

Table 4.21 Values for Parameters of Equations 1123 and 12 Fitted to the Initial Envelope Curves for Each Set of Experimental Data.

Initial Envelope Curve	EQUATION # 1123 THREE PARAMETER MODEL						EQUATION #12 TWO PARAMETER MODEL				
Set	MODEL			Adj R^2	Fit Stat.	F Value	MODEL		Adj R^2	Fit Stat.	F Value
I.D.*	A	B	C	(1)			A	B	(1)		
1	291	-270	1508	0.971	57	3517	52	1233	0.966	62	5928
2	386	-340	1603	0.967	61	2934	81	1278	0.961	67	4836
3	274	-216	1588	0.963	72	2675	78	1385	0.961	74	5053
4	524	-455	1868	0.963	72	2531	112	1452	0.955	79	4097
5	405	-365	1629	0.962	67	2677	84	1253	0.953	74	4288
6	597	-562	1755	0.959	65	2258	99	1199	0.936	80	2861
7	444	-431	1807	0.970	62	3194	64	1375	0.960	73	4676
8	701	-656	222	0.979	58	4424	108	1616	0.966	740	5261
9	611	-572	1912	0.957	75	2336	111	1314	0.937	92	3072
10	869	-823	2034	0.947	76	1698	133	1248	0.906	101	1819
11	263	-230	1606	0.952	81	2075	63	1363	0.949	84	3895
12	554	-496	2070	0.978	63	4339	111	1584	0.968	75	6021
13	144	-121	1120	0.925	77	1284	41	985	0.923	77	2511
14	81	-49	1060	0.944	66	1757	38	1007	0.944	66	3511
15	244	-227	568	0.940	22	1349	42	356	0.907	27	1684
16	411	-381	1063	0.964	32	2526	54	786	0.953	37	3879
17	149	-110	1213	0.965	56	2871	54	1094	0.964	57	5574
18	242	-212	1282	0.975	44	3999	60	1056	0.970	48	6734
19	217	-205	1470	0.962	68	2677	37	1256	0.959	70	4965
20	-385	385	1278	0.979	66	4902	-51	1685	0.973	74	7650
21	-25	77	967	0.955	62	2085	44	1044	0.955	63	4138
22	418	-374	1414	0.964	52	2717	91	1031	0.951	61	3882
23	2114	-2056	4798	0.971	115	3499	140	3583	0.962	132	5294

* See appendix A for set definition.

(1)See appendix B for definition.

Table 4.22 Values for Parameters of Equations 1123 and 12 Fitted to the Final Envelope Curves for Each Set of Experimental Data .

Final or Stabilized Envelope Curve	EQUATION #1123 THREE PARAMETER MODEL						EQUATION #12 TWO PARAMETER MODEL				
Set	MODEL			Adj R^2	Fit Stat.	F Value	MODEL		Adj R^2	Fit Stat.	F Value
I.D.*	A	B	C		(1)		A	B		(1)	
1	310	-277	1268	0.966	50	2874	65	984	0.957	56	4558
2	433	-375	1367	0.956	57	2139	96	1005	0.943	65	3236
3	188	-157	969	0.906	70	981	53	797	0.903	71	1873
4	498	-418	1552	0.954	65	1913	118	1174	0.944	71	3116
5	355	-294	1302	0.957	57	2321	96	998	0.948	63	3759
6	515	-460	1414	0.946	60	1655	107	963	0.923	71	2273
7	483	-454	1530	0.965	54	2691	86	1061	0.944	68	3289
8	680	-619	1842	0.971	56	3126	126	1253	0.947	74	3402
9	541	-484	1575	0.952	65	2053	119	1062	0.928	80	2674
10	673	-600	1608	0.934	72	1388	143	999	0.895	91	1681
11	283	-229	1341	0.950	68	1994	85	1095	0.945	71	3607
12	478	-399	1685	0.970	60	3232	124	1285	0.960	69	4790
13	193	-163	974	0.907	69	1008	54	793	0.902	71	1906
14	164	-123	946	0.913	68	1077	58	812	0.910	69	2094
15	219	-195	458	0.916	20	974	46	272	0.876	25	1259
16	429	-392	908	0.945	32	1660	62	620	0.927	37	2455
17	172	-119	1005	0.959	50	2431	71	874	0.956	51	4618
18	321	-280	1119	0.964	42	2675	79	823	0.951	49	3859
19	280	-251	1280	0.952	63	2070	60	1013	0.945	68	3590
20	-226	227	1185	0.977	59	4324	-29	1427	0.974	63	7677
21	55	-1	865	0.953	53	1682	54	864	0.953	52	3386
22	396	-339	1160	0.950	49	1899	100	809	0.931	58	2717
23	2217	-2150	4429	0.965	114	2870	157	3134	0.952	133	4120

* See appendix A for set (Table) definition.

(1)See appendix B for definition.

Table 4.23 Values for Parameters of Foschi's Equation Fitted to the Initial Envelope Curves for Each Set of Experimental Data.

Initial Envelope Curve	FOSCHI'S EQUATION THREE PARAMETER MODEL					
Set	MODEL			Adj R^2	Fit Stat.	F Value
I.D.*	A	B	C	(1)		
1	420	974	15846	0.952	74	2039
2	397	1164	32686	0.944	80	1673
3	389	1348	48318	0.947	86	1826
4	470	1335	40435	0.938	93	1464
5	457	989	20984	0.941	84	1660
6	496	838	19073	0.921	89	1138
7	545	922	13470	0.944	85	1659
8	580	1295	26778	0.954	86	1930
9	566	882	21040	0.931	96	1404
10	572	787	25569	0.910	100	947
11	433	1160	19056	0.932	97	1428
12	551	1322	32835	0.960	83	2416
13	321	806	11811	0.907	85	1019
14	283	921	15438	0.930	74	1388
15	153	261	7813	0.911	26	875
16	231	809	21997	0.943	40	1591
17	340	954	17773	0.959	61	2449
18	360	867	15514	0.962	55	2562
19	423	972	13730	0.954	75	2163
20	298	1708	13607	0.979	65	4926
21	253	1072	33580	0.951	65	1927
22	402	798	19374	0.941	67	1623
23	870	4110	109231	0.968	122	3109

* See appendix A for set definition.

(1) See appendix B for definition.

Table 4.24 Values for Parameters of Foschi's Equation Fitted to the Final Envelope Curves for Each Set of Experimental Data.

Final or Stabilized Envelope Curve	FOSCHI'S EQUATION THREE PARAMETER MODEL					
Set	MODEL			Adj R^2	Fit Stat.	F Value
I.D.*	A	B	C	(1)		
1	343	808	19386	0.942	65	1669
2	345	905	40380	0.934	70	1378
3	273	666	13122	0.884	77	776
4	378	1157	56761	0.935	77	1342
5	367	841	26249	0.937	70	1524
6	371	799	27543	0.908	78	936
7	541	715	15550	0.933	74	1371
8	504	966	27935	0.938	81	1423
9	458	770	25200	0.925	82	1277
10	465	705	32039	0.904	87	927
11	370	950	23150	0.928	82	1344
12	460	1116	40300	0.958	71	2270
13	281	644	12572	0.884	77	786
14	264	717	16542	0.897	73	899
15	127	209	9396	0.896	23	768
16	204	623	25084	0.927	37	1218
17	298	758	19821	0.957	51	2320
18	322	648	16632	0.948	50	1831
19	382	752	14925	0.942	69	1711
20	284	1400	12675	0.975	61	4097
21	236	862	33779	0.950	54	1576
22	342	625	21451	0.936	56	1452
23	824	3437	109101	0.963	116	2742

* See appendix A for set definition.

(1) See appendix B for definition.

with the first two models, equation 1123 and equation 12, because they cannot be generalized to data other than the set for which they were created. Additionally, their parameters (a, b, c) do not have any physical meaning that could relate them to the nailed wood connection properties.

Foschi's equation is more useful. Although it is only applicable to one set of data, the three parameters of the equation have a direct relationship to the characteristics of the load-slip behavior for the nailed wood connection. This equation is a three-parameter, nonlinear representation of connection performance, with the initial slope of the curve (K_o) as one of the parameters, the slope of the asymptote (K_2) and the load-intercept (P_o) as the other two. See Chapter 2, for more details on Foschi's equation.

4.3.2 Model Comparisons

Figure 4.22 illustrates the performance of the three models when they are compared to each other (where equation 1123 represents the average curve of the actual data set). In this curve, Foschi's equation seems to under estimate initial stiffness and overestimate capacity, but it has the highest slope at the asymptote. The curve from equation 12 seems to have the shortest range of linear behavior, and good prediction of the initial stiffness, however, it overestimates the capacity the most.

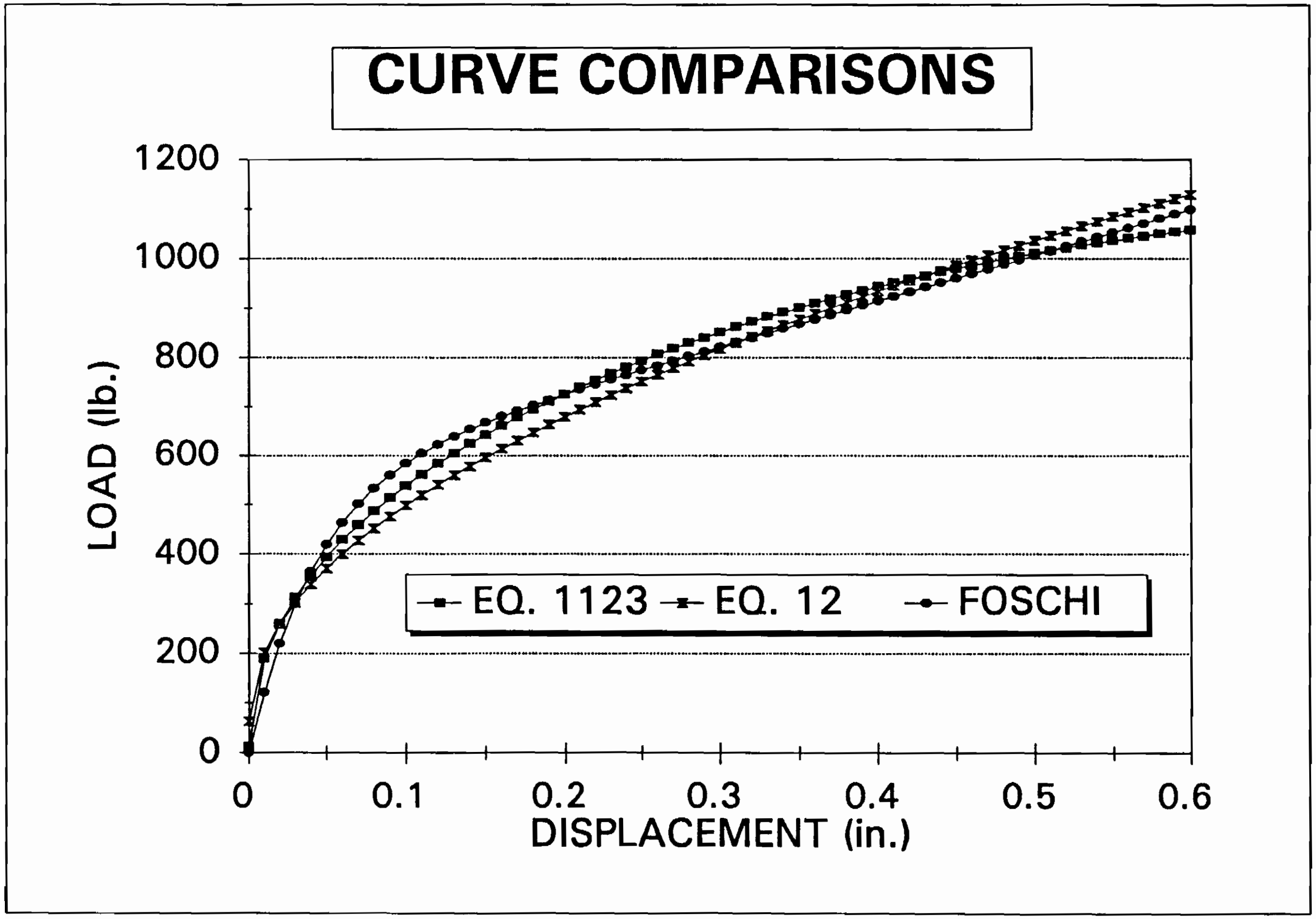


Figure 4.22 Comparison of the mean curves created with three different models for the same set (set 11, see appendix A for definition).

4.4 General Regression Model Development

The development of a statistical model for the prediction of the load-slip relationship of nailed wood connections made of green, red alder and subjected to cyclic lateral loading is the major contribution intended in this work. Red alder is a hardwood species only found in the West coast of the United States, with average green specific gravity ranging from 0.36 to 0.39 and oven dry specific gravity ranging from 0.39 to 0.49. It was selected for this study because of its availability, its growth characteristics and the scarcity of accessable softwoods on the West coast. Wood with moisture contents varying from 52 percent to 170 percent was used. Three side member thicknesses were used, 1/2 inch, 5/8 inch, and 3/4 inch, and four nail types with variable stiffness characteristics were included. A total of 180 tests were conducted and the load-slip curves were obtained and used to analyze and create the statistical model. The initial model was of the form:

$$Y = \beta_o + \beta_1(D) + \beta_2\,(th) + \beta_3\,(MC) + \beta_4\,(SG) + \beta_5\,(N1) + \beta_6\,(N2) + \beta_7\,(N3) + \beta_8\,(thN1) + \beta_9\,(thN2) + \beta_{10}\,(thN3) + \beta_{11}\,(th)^2 + \epsilon$$

where: Y = load; D = Displacement; th = deckboard thickness;

MC = members average moisture content; β_i = Coefficients;

SG = members average specific gravity; N1 = Nail type 1;

N2 = Nail type 2; N3 = Nail type 3; N4 = Nail type 4.

A spreadsheet was developed and analyzed using the *Analysis of Covariance* in SAS. The analysis of covariance was used to account for the quantitative variables in the data; nail type was a typical quantitative variable. This procedure combines features of the analysis of variance and regression, making use of a general linear model (Lyman, R. Ott, 1994). To develop this analysis for the qualitative variables (the four nail types), three "dummy" variables must be used, where:

N1 = 1 if set 1 was used, N1 = 0 otherwise

N2 = 1 if set 2 was used, N2 = 0 otherwise

N3 = 1 if set 3 was used, N3 = 0 otherwise

The expected value for observations on set 4 (joint specimens using nail type 4) is found by substituting N1 = 0, N2 = 0, N3 = 0.

After several trials and model adjustments, a large dispersion between the data and the predicted values, was observed at the beginning of the curve. This suggested deletion of those initial points causing the dispersion, which led to smaller differences between the predicted values and the data. The model obtained is of the form:

$$Y = \beta_o + \beta_1(D) + \beta_2(th) + \beta_3(MC) + \beta_4(SG) + \beta_5(N3) + \beta_6(thN1) + \beta_7(th)^2 + \epsilon$$

therefore

$$Y = -364.97 + 1525.10(D) + 6.25(MC) + 198.49(SG) + 267.22(th) - 53.79(N3) - 0.54(MCN1) - 0.02(MC)^2 \quad (4.3)$$

was selected as the "best" model with ADJ $R^2=0.848$. Table 4.25 presents the three next "best" models in descending order of prediction as measured by ADJ R^2 (adjusted R^2) and MSE (mean square error).

Table 4.25 List of Models in Descending Order of Prediction as Measured by Adjusted r^2 (adj r^2) and Mean Squared Error (MSE).

Adjusted r^2	MSE	Variables in the model
0.848	17255.96	D TH SG N3 THN1
0.845	17622.94	D MC SG N3 THD1
0.845	17618.71	D TH MC SG N3 THN1

4.4.1 Model Accuracy

The prediction accuracy of the statistical model for three different typical connections, selected at random from the main statistical block design (4x3), is illustrated in Figures 4.23, 4.24, and 4.25. Sets HXAAF3, HXBBF1, and HXCCF4, were chosen for the test of accuracy. The first set represents the joint specimens using 3/4 inch thick side members and type 3

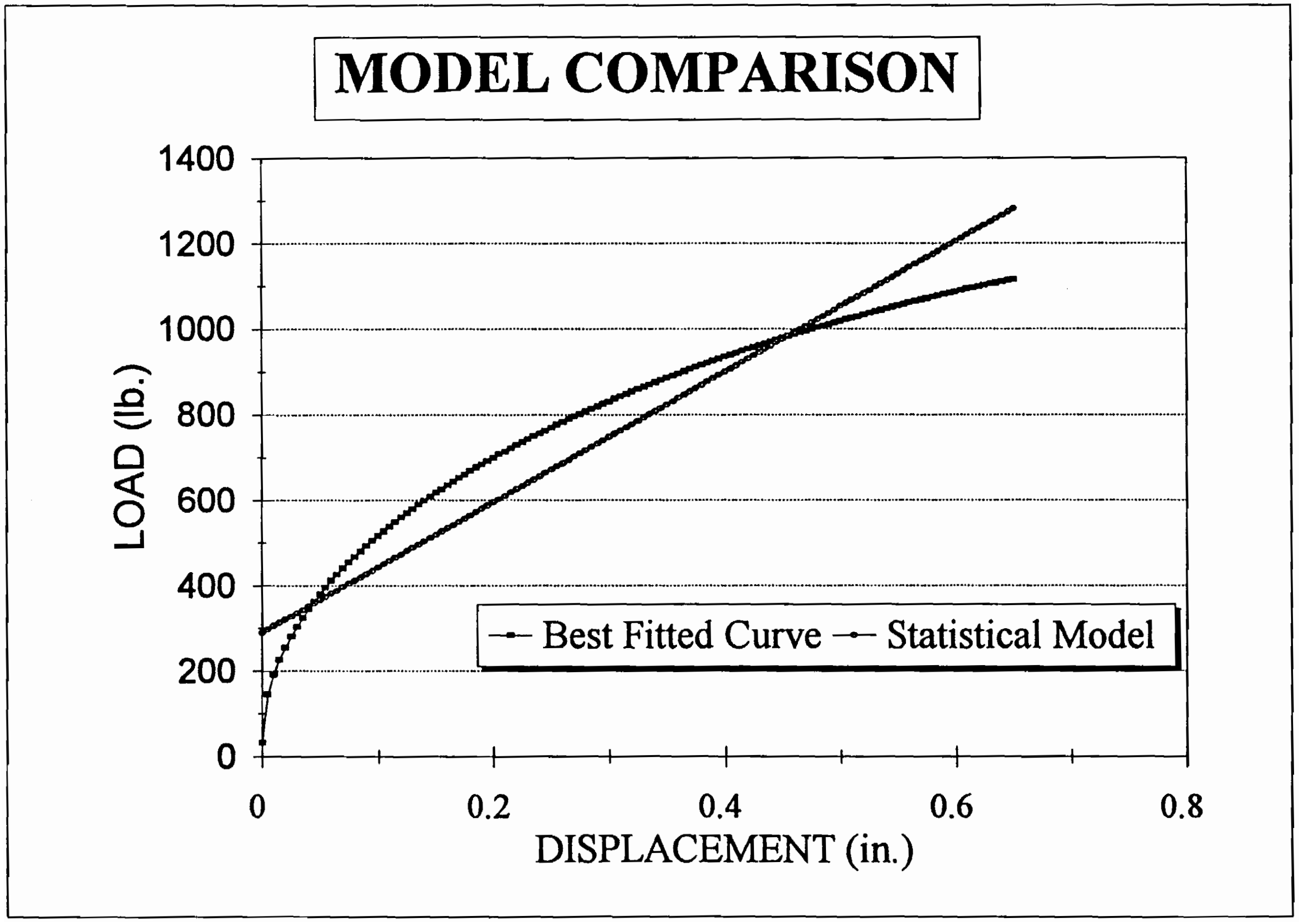


Figure 4.23 Comparison of the statistical model to the average best fitted curve for the set of 3/4" thick red alder connections fastened with nail type 3.

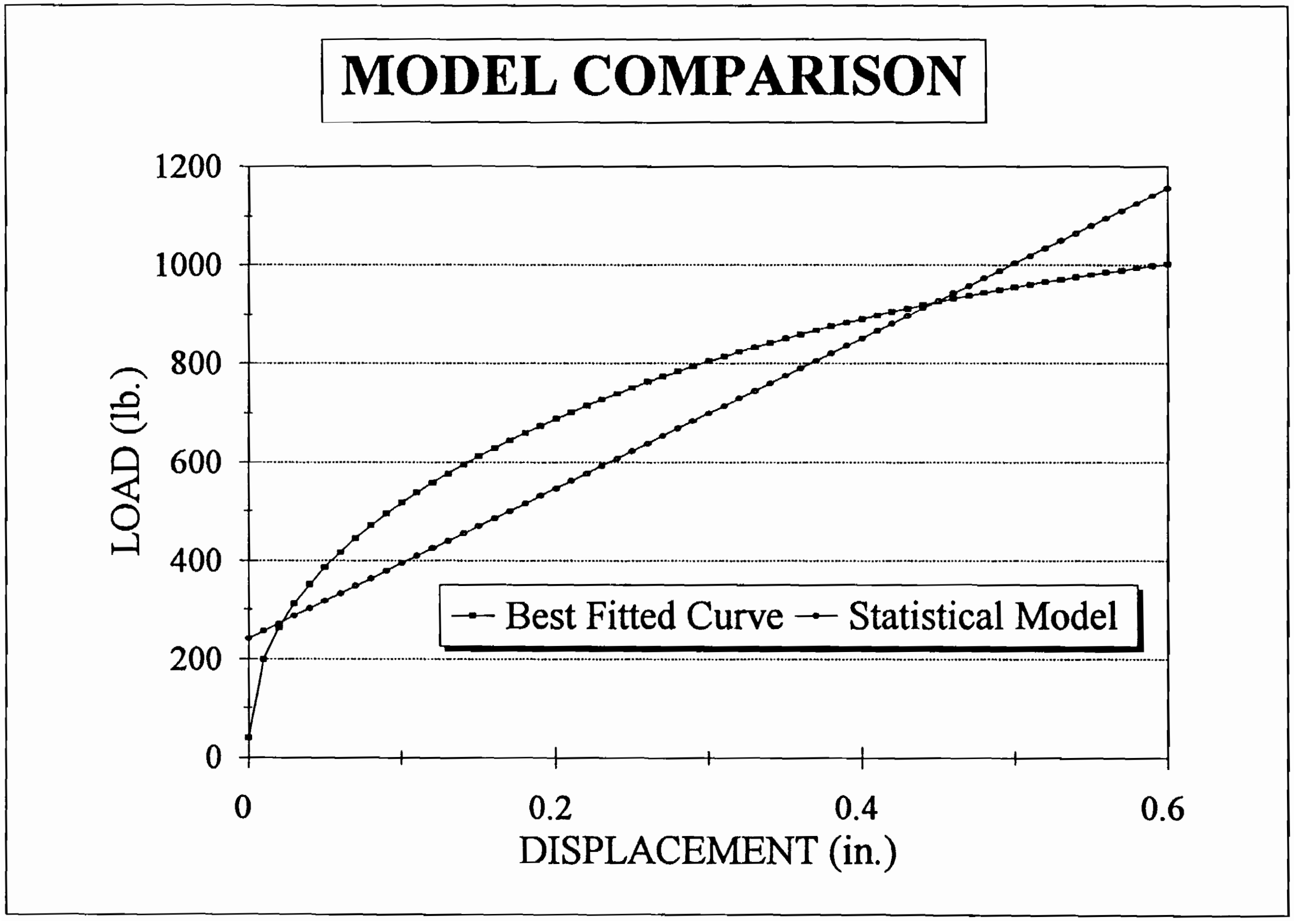


Figure 4.24 Comparison of the statistical model to the average best fitted curve for the set of 5/8" thick red alder connections fastened with nail type 1.

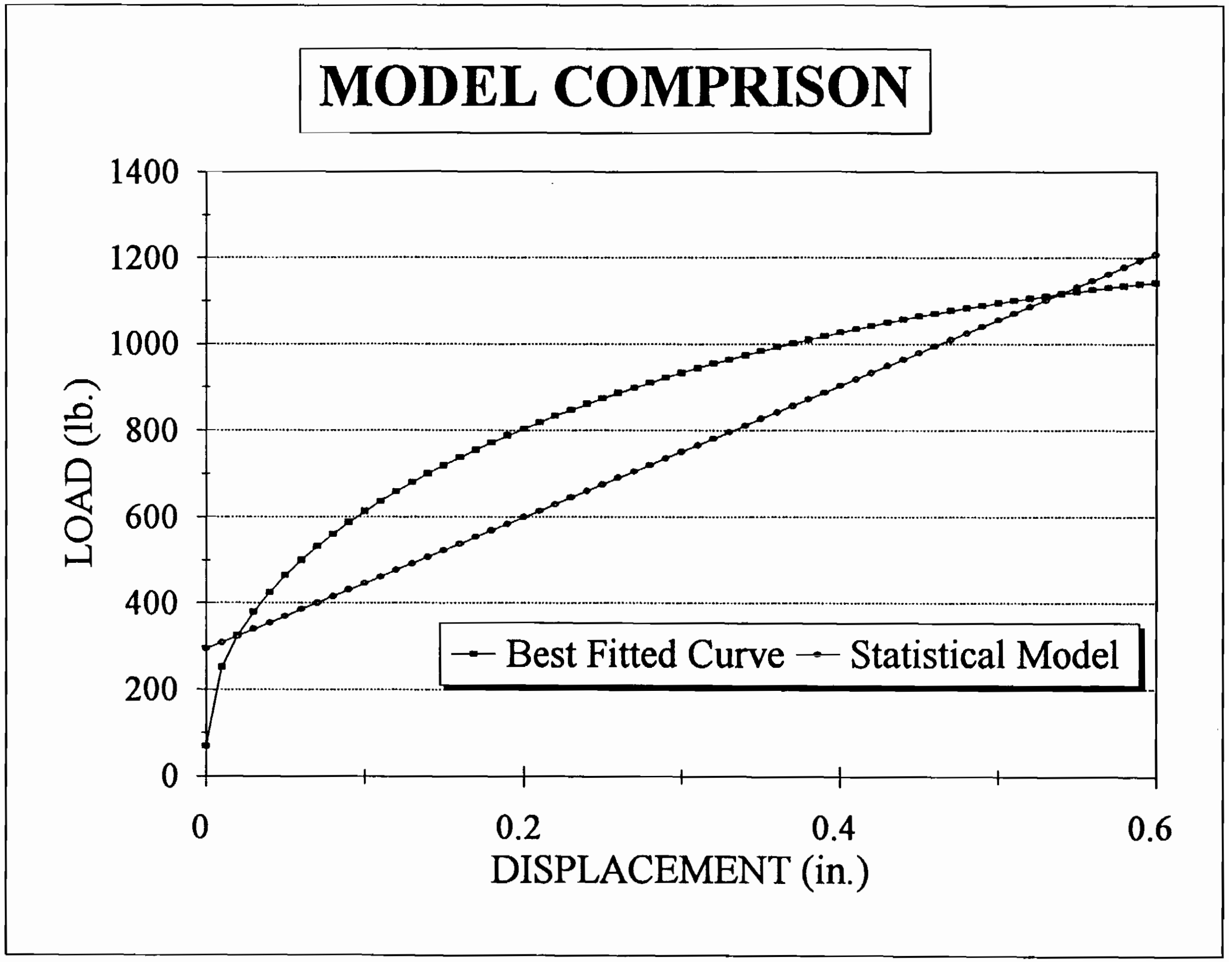


Figure 4.25 Comparison of the statistical model to the average best fitted curve for the set of 1/2" thick red alder connections fastened with nail type 4.

nails, the second set represents the joint specimens that use 5/8 inch thick side members and type 1 nails, and the last set, the 1/2 inch thick side members and type 4 nails. The general linear model produced a straight line when plotted against the generated average curve of the data, which does not predict the load-slip behavior of the nailed wood connection. The lack of fit of this model suggests readjustment to linearize the data. This transformation (or re-expression of the variables) can be done on either the dependent variable, the independent variable, or both variables, to eliminate the curvature in the data. For more details in this technique see Ott (1994) and Neter and Wasserman (1974).

After transforming the data the "most appropriate" model was found. This transformation requires relatively simple methods of estimation and involves different parameters than the first model presented. The final model is of the form:

$$Y' = \beta_0 + \beta_1 (D') + \beta_2 (SG) + \beta_3 (th) + \beta_4 (N1) + \beta_5 (N3) + \beta_6 (thN2) + \beta_7 (thN3) + \beta_8 (thth) + \epsilon$$

therefore

$$Y' = 0.416\ (D') + 0.129\ (SG) + 2.790\ (th) - 0.098\ (N1) + 0.038\ (N3) - 0.140\ (thN2) - 0.197\ (thN3) - 1.982\ (thth) \qquad (4.4)$$

where, Y' = LOG_{10} (Y), and D' = LOG_{10} (D). This was selected as the "most appropriate model with ADJ R^2 = 0.946 and MSE = 0.006. This model required the re-expression of the dependent variable as well as the re-expression of independent variable, displacement (D). Table 4.26 presents the four next "best" models in descending order of prediction as measured by ADJ R^2 (adjusted R^2) and MSE (mean square error).

Table 4.26 List of Models in Descending Order of Prediction as Measured by Adjusted r^2 (adj r^2) and Mean Squared Error (MSE).

Adjusted r^2	MSE	Variables in the model
0.945	0.006	D' SG th N1 thN2 thN3
0.945	0.006	D' th N1 N3 thN2 thN3
0.945	0.006	D' th N1 thN2 thN3 thth
0.945	0.006	D' SG th N1 N3 thN2 thth

The prediction accuracy of the model was tested using the same mean curves from sets HXAAF3, HXBBF1, and HXCCF4 which were already used for the prediction accuracy of the first model. Figures 4.26, 4.27, and 4.28 show that the label of prediction of the model has improved

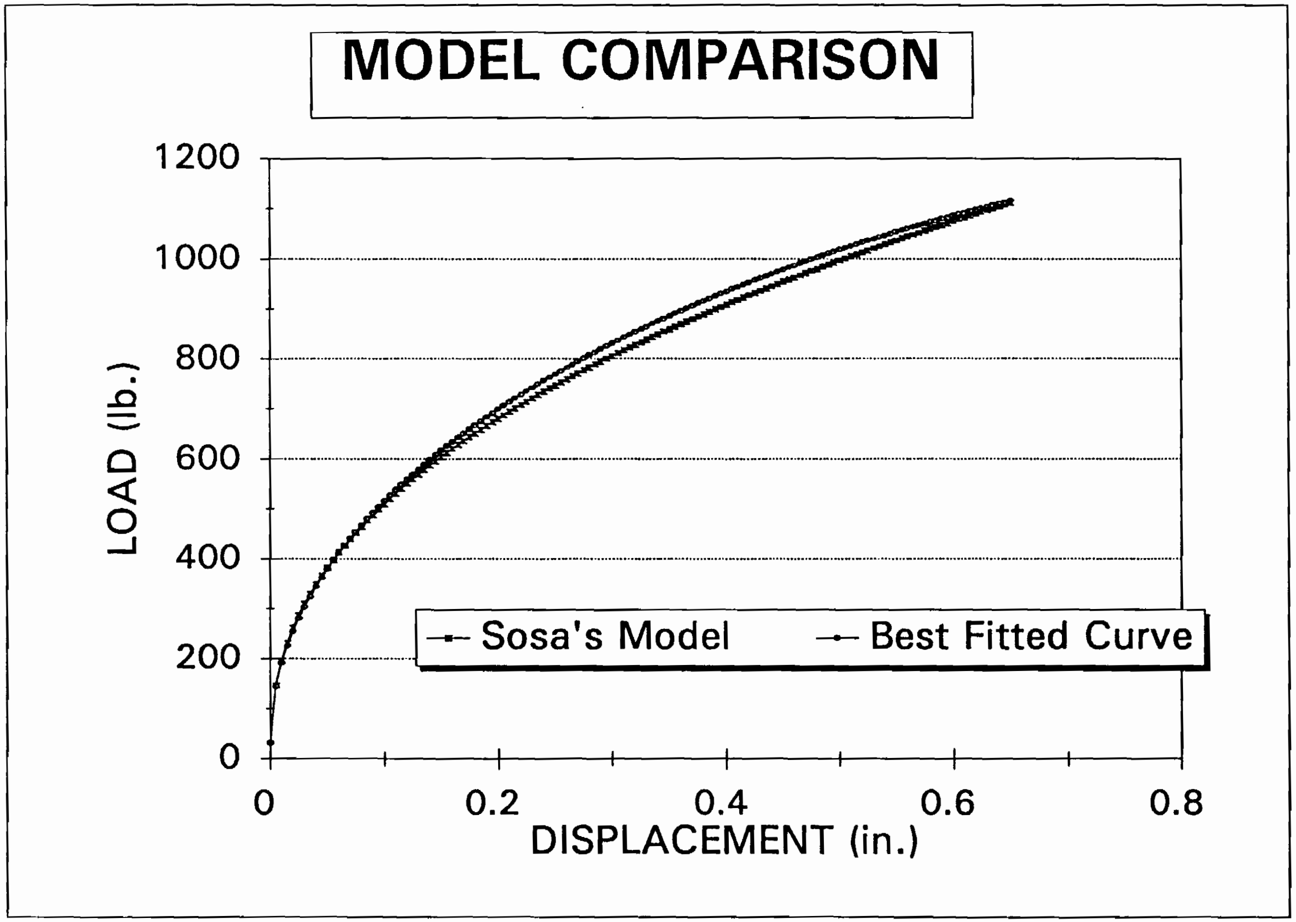


Figure 4.26 Comparison of the statistical model to the average best fitted curve for the set of 3/4" thick red alder connections fastened with nail type 3.

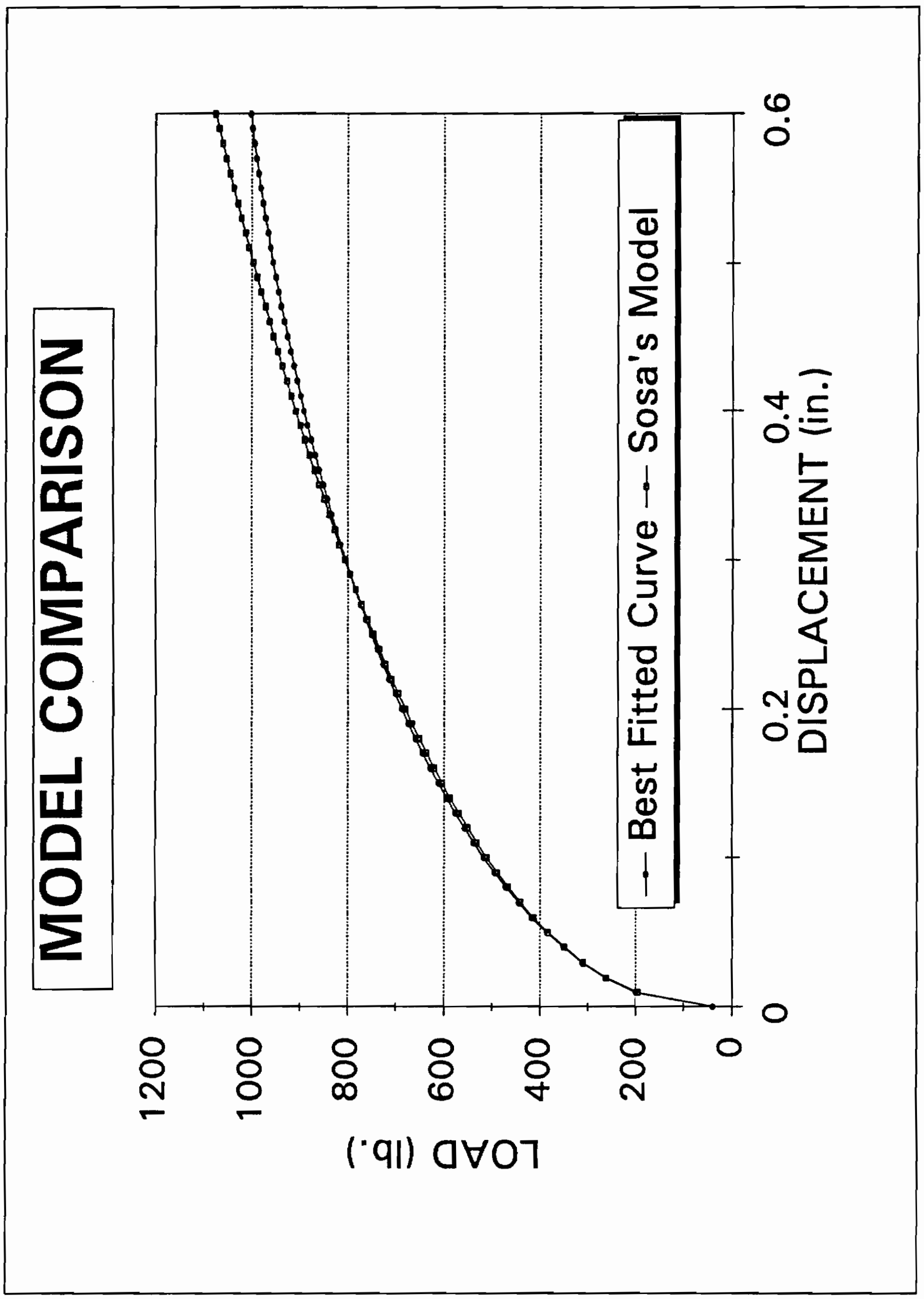


Figure 4.27 Comparison of the statistical model to the average best fitted curve for the set of 5/8" thick red alder connections fastened with nail type 1.

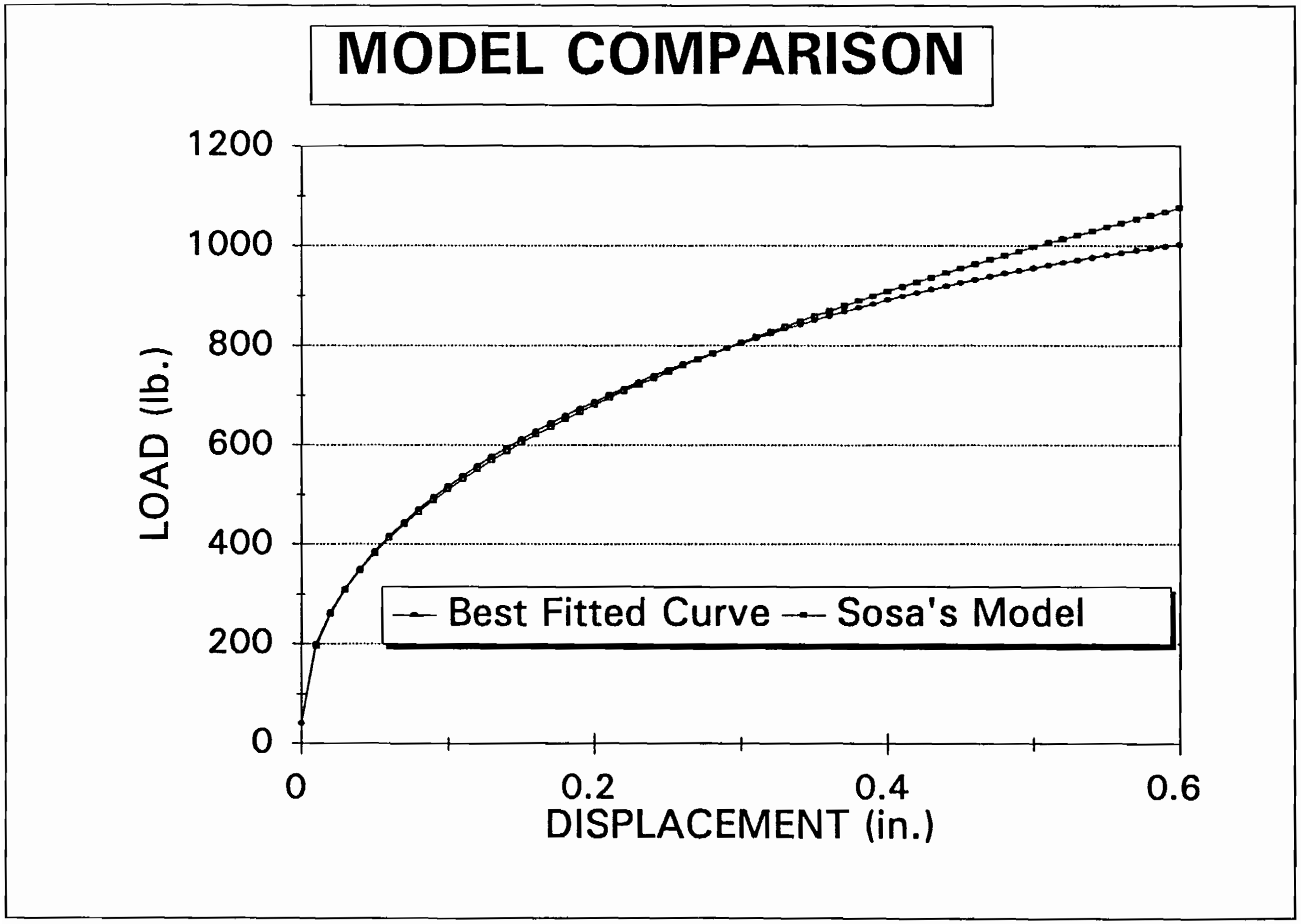


Figure 4.28 Comparison of the statistical model to the average best fitted curve for the set of 1/2" thick red alder connections fastened with nail type 4.

dramatically, this model is able to yield reasonably accurate predictions for the load in the load-slip relationship against the experimental curves for these three mean sets.

Although the author's prediction equation seems to be accurate for prediction, its applicability is restricted to the range of the variables involved:
1) wood with a moisture content over saturation point (more than 30 percent), 2) red alder or species with similar green specific gravity (0.36 to 0.40),
3) joint specimens with similar joint geometry

a.-two member joints with dissimilar thickness

b.-joints fasten with three helically threaded nails

c.-all the other characteristics of the butted block pallet connection

4) nails with similar characteristics as the four types of nails used in this research.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results of the cyclic lateral testing discussed in the previous chapter show that, in general, thickness of the deckboard, nail stiffness, and nail length define the mode of failure of butted block pallet connections made of red alder. The analysis of the results of the main statistical block design support the following conclusions

1) The nail type used in the manufacture of the connection significantly influences the performance of nailed wood connections. Stiffer nails (smaller MIBANT angles) produce stiffer and stronger joints. The mode of ultimate failure of lateral loaded nailed wood connections is related to the length of the nail when the thickness or specific gravity of the wood made the joint fail in withdrawal at large deformations. It is concluded that in general, nail type 4 produces the strongest connections, followed by nails 3 and 1, with the weakest being nail type 2.

2) In two-member nailed connections, the thickness of the side and main members influence the behavior of the connection. When there is a significant difference in thickness between the side and the main member, and they have similar specific gravities, the mode of failure is defined by the

side member thickness or by the fastener stiffness. Thicker deckboards produce stronger and stiffer connections. The joint specimens fabricated with 3/4 inch side members made the strongest connections, followed by 5/8 inch and 1/2 inch thick side members.

3) The method of defining the initial stiffness influences the results of the load at 5% offset of the fastener diameter. Because it is based on visual judgement by the individual doing the measurement, this method is subjective, and not accurate enough to be used to compare results.

4) Nail pattern appears to influence the joint strength and stiffness. Three-nail connections in pattern "B" seem to be 8.6 percent stronger than joints nailed in pattern "A".

5) Joint strength seems to increase when the block pallets are manufactured green and used dry. Joints manufactured and tested green seem to have lower strength but the highest stiffness. Joints manufactured and tested dry seem to have the lowest strength. Evidence seems to indicate that the green-dry joint connections were 26 percent stronger than the green-green connections and 33 percent stronger than the dry-dry connections.

6) Friction appears to increase the strength of the block pallet connection by approximately 20 percent.

7) There is no significant difference between the envelope curves for the initial and final cycles at the 5 percent offset yield load, either value can be used for design purposes of the connection.

8) Experimental data of laterally loaded butted joints of the block pallet, can be modeled by Foschi's equation with an Adj r^2 that varies from 0.88 to 0.98. The load-slip behavior of laterally loaded butted joints of a block pallet type, can be modeled by Foschi's equation only if the three variables of the equation are known from previous testing.

9) The estimated NDS allowable design values are conservative for green and dry (wood at 15% moisture content) red alder nailed connections subjected to lateral loading with a minimum factor-of-safety of 3.69 and 3.01, respectively, when compare to the capacity of the connection. The defined NDS values for the dowel bearing strength of red alder are below the experimental values, and the NDS values for the nail yield moment of threaded-shank nails with small diameters are lower than those actually measured.

10) The statistical model developed for predicting the strength and stiffness of a red alder block pallet connection is:

$$Y' = 0.416\ (D') + 0.129\ (SG) + 2.790\ (th) - 0.098\ (N1) + 0.038\ (N3) - 0.140\ (thN2) - 0.197\ (thN3) - 1.982\ (thth)$$

where, $Y' = LOG_{10}$ (Load), and $D' = LOG_{10}$ (D). This was selected as the "most appropriate" model with ADJ R^2 = 0.946 and MSE = 0.006.

Where:

Y = load, D = Displacement, th = deckboard thickness, MC = members average moisture content, SG = members average specific gravity, N1 = Nail type 1, N2 = Nail type 2, N3 = Nail type 3, and N4 = Nail type 4.

5.2 Recommendations

*Research should be expanded with a wider range of specific gravity species.

*More joint specimens with one, two, and four nails should be tested to develop a more general prediction model.

*A prediction model that incorporates other pallet materials (plastic or composite) should be develop.

*The Yield theory requires more accurate values for nail yield moment of threaded-shank nails and dowel bearing strength of red alder for estimation of design values, additional research on these topics is suggested.

*The prediction model developed in this research may be improved by studying other variables including species with higher and lower specific gravity, more types of nails, others connection geometries.

*A more general model can be developed by a mechanical analog approach, using springs to model the connection actions.

LITERATURE CITED

American Forest & Paper Association (formerly National Forest Products Association). 1993. "1991 National Design Specification for Wood Construction." Washington, D.C.

American Forest & Paper Association (formerly National Forest Products Association). 1993. "Commentary on the 1991 National Design Specification for Wood Construction." *Part II, Design Values for Structural Members*. Washington, D.C.

American Society for Testing and Materials (ASTM). 1992-a. "Standard Methods for Evaluating Dowel Bearing Strength of Wood and Wood-base Products." Section D 07.05.02 Draft 6.

American Society for Testing and Materials (ASTM). 1992-b. "Standard Methods for Evaluating Dowel Bearing Strength of Wood and Wood-base Products." Section D 07.05.02 Draft 7.

American Society for Testing and Materials (ASTM). 1993. ASTM standard D2395-83 "Standard Test Methods for Specific Gravity of Wood and Wood Based Materials," Annual Book of ASTM standards, Section 4. Construction. Volume 04.09 Wood, pp. 379-386.

American Society for Testing and Materials (ASTM). 1993. ASTM standard D1761 "Standard Test Methods for Mechanical Fasteners in Wood," Annual Book of ASTM standards, section 4. Construction. Volume 04.09 Wood, pp. 300-311.

Aune, P., and Patton-Mallory, M. 1986. "Lateral Load-Bearing Capacity of Nailed Joints Based on the Yield Theory." Theoretical Development. Research Paper, FPL 469. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory.

Aune, P., and Patton-Mallory, M. 1986. "Lateral Load-Bearing Capacity of Nailed Joints Based on the Yield Theory." Experimental Verification. Research Paper, FPL 470. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory.

Borland International, Inc. 1993. "Quattro Pro," Version 5.0, Scotts Valley, CA.

Bush, R.; Hansen, E. and Punches, J. 1993. "Wood Use in the U.S. Pallet and Container Industry: 1993." Center for Forest Products Marketing, Department of Wood Science and Forest Products, VPI & SU, Blacksburg, VA.

Colclough, R.G. 1987. "The Development and Verification of Analysis Models for Block-type Wooden Pallets." M.S. Thesis, VPI & SU. Blacksburg, VA.

Cristoforo, J.C.; Reddy, V.S.; Punches, J.W. and Bush, R.J. 1992. "Status of the Pallet and Container Industry." PhD Dissertation, VPI & SU, Blacksburg, VA.

Dolan, J.D. 1993. "Standard Test Method for Dynamic Properties of Connections Assembled with Mechanical Fasteners." Proposed ASTM standard.

Dolan, J.D., Gutshall, S.T. and Mclain, T.E. 1994. "Monotonic and Cyclic Tests to Determine Short-term Duration-of-load Performance of Nail and Bolt Connections: Volume I: summary report." Timber Engineering Report TE-1994-001, VPI & SU, Blacksburg, VA.

Ehlbeck, J. 1979. Nailed Joints in Wood Structures, VPI & SU Wood Research and Wood Construction Laboratory, Bulletin No. 166. Blacksburg, VA.

Ellingwood, B., Rosowsky, D. 1991. " Duration of Load Effects in LRFD for Wood Construction." Journal of Structural Engineering 117(2): 584-599.

Erki, M.A. 1991. "Modelling the Load-Slip Behavior of Timber Joints with Mechanical Fasteners." Department of Civil Engineering, Royal Military College of Canada, Kingston, Ontario, Canada.

Foschi, R.O. 1974. Load-slip Characteristics of Nails. Wood Science, 7(1): 69-76.

Foschi, R.O. and Bonac, T. 1977. Load-slip Characteristics for Connections with Common Nails. Forest Products Journal, 35(9): 118-123.

Girhammar, U.A., and Andersson, H. 1988. "Effect of Loading Rate on Nailed Lumber Joint Capacity." Journal of Structural Engineering 114(11), 2439-2456.

Gutshall, S.T. 1994. "Monotonic and Cyclic Short-Term Performance of Nailed and Bolted Timber Connections." Master Thesis, VPI & SU, Department of Forest Products and Wood Science, Blacksburg, VA.

Hunt, R.D., and Bryant, A.H., 1990. "Laterally Loaded Nail Joints in Wood." Journal of Structural Engineering, 116(1): 111-124.

Jandel Scientific. 1992. "SigmaPlot for DOS," registered trademark of Jandel Corporation. San Rafael, CA.

Jandel Scientific. 1991. "TableCurve, Version 3.0," registered trademark of Jandel Corporation. San Rafael, CA.

Jenkins, J.L., Polensek, A, Bastendorff, K.M. 1979. "Stiffness of Nailed Wall Joints Under Short and Long Term Lateral Loads." Forest Products Research Society. Wood Science 11(3): 145-154.

Kalkert, R.E., and Dolan, J.D. 1994. "Characterizing the Response of Nailed Connections Subjected to Monotonic and Cyclic Loading." Timber Engineering Report TE-1994-006, VPI & SU, Blacksburg, VA.

Liu J.Y., and Soltis, L.A., 1984. "Lateral Resistance of Nailed Joints - a Test Method." Forest Products Journal, Vol. 34 (1): pp 55-60.

Loferski, J.R., 1985. "A Reliability Based Design Procedure for Wood Pallets." PhD Dissertation, VPI & SU, Blacksburg, VA.

Loferski, J.R., and Gamalath, S. 1990. "Predicting Rotational Stiffness of Nail Joints." VPI&SU, William H. Sardo Jr. Pallet and Container Laboratory, Bulletin No. 13. Blacksburg, VA.

Loferski, J.R., and McLain, T.E. "Static and Impact Flexural Properties of Common Wire Nails". Journal of Testing and Evaluation, ASTM, vol. 19(4):297-304. July, 1991.

McLain, T.E. 1975. "Curvilinear Load Slip Relations in Laterally-Loaded Nailed Joints." PhD Dissertation, Colorado State University, Department of Forest and Wood Sciences, Fort Collins, CO.

McLain,T.E., and Carroll, J.D. 1990. "Combined Load Capacity of Threaded Fastener-Wood Connections." Journal of Structural Engineering, Vol. 116 (9): pp 2419-2432.

McLain, T.E. 1991. "Engineered Wood Connections and the 1991 National Design Specification." Wood Design Focus, 2(2): 7-10.

McLain,T.E., and White, M.S. 1992. "Optimizing the Performance of Red Alder Mechanical Connections and Pallets." Proposal No. 92-2058-05. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory.

McLain, T.E. 1993. "Connection Design in the United States: Bolted Connections. Proceedings of the International Workshop on Wood Connectors," sponsored by the Wood Products Center, the Forest Products Society, and the USDA Forest Products Laboratory, Madison, WI, pp. 122-127.

National Wooden Pallet & Container Association. 1993. Estimated Production Report (New Pallets). Arlington, VA.

National Wooden Pallet & Container Association. 1994. "Uniform Voluntary Standard for Wood Pallets." Arlington, VA.

Neter, J., and Wasserman, W.. 1974. "Applied Linear Statistical Models." Richard D. Irwin, Inc. Georgetown, Ontario.

Ott, L. 1994. "An Introduction to Statistical Methods and Data Analysis." Fourth Edition. PWS-KENT Publishing Company.

Patton-Mallory, M. 1989. "Yield Theory of Bolted Connections Compared with Current U.S. Design Criteria." Proceedings of the second Pacific Timber Engineering Conference, vol 1: pp 323-329.

Pellicane, P.J., Stone, J.L., and Vanderbilt, M.D. 1990. "Generalized Model for Lateral Load Slip of Nailed Joints." Journal of Materials in Civil Engineering, 3 (1): pp 60-77.

Pellicane, P.J. 1991-a. "Mechanical Behavior of Nailed Joints with Various Side Member Materials." ASTM Journal of Testing and Evaluation, 19 (2): pp 97-106.

Pellicane, P.J. 1991-b . "Application of the European Yield Model to Nailed Joints in Southern Hardwoods." ASTM Journal of Testing and Evaluation, Vol. 19 (5): pp 385-393.

Pellicane, P.J., And SáRibeiro, R.A., 1992. "Load-Slip Behavior of Nailed Joints in Seven Amazonian Hardwoods." ASTM Journal of Testing and Evaluation, Vol. 20 (1): pp 51-58.

Polensek, A. 1982. "Creep Prediction for Nailed Joints Under Constant and Increasing Loading". Forest Products Research Society. Wood Science 15(2), 183-192.

Polensek, A., and Sangsik J. 1989. "Predicting Creep of Nailed Lumber-to-Plywood Joints." Journal of Engineering Mechanics, 115(10), 2182-2198.

Powell, D.S.; Faulkner, J.L.; Darr, D.R.; Zhu, Z.; and MacCleery, D.W. 1993. "Forest Resources of the United States, 1992." General Technical Report RM-234. Fort Collins, Colorado. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experimental Station.

Samarasinghe, S. 1987. "Predicting Rotation Modulus for Block Pallet Joints." M.S. Thesis, VPI & SU, Blacksburg, VA.

SáRibeiro, R.A. 1990. "Improved Model of the Load-Slip Behavior of Nailed Wood Connections." PhD Dissertation. Colorado State University, Department of Forest and Wood Sciences, Fort Collins, CO.

SáRibeiro, R.A., and Pellicane, P.J. 1992. "Modeling Load-Slip Behavior of Nailed Joints." Journal of Materials in Civil Engineering, 4(4): pp. 385-398.

SAS Institute, Inc. "SAS User's Guide: Basics, Version 5 Edition." Cary, NC: SAS Institute, Inc., 1985. pp. 219-242.

SAS Institute Inc. "SAS/STAT Users Guide, Release 6.03 Edition." Cary, N.C.: SAS Institute Inc., 1988. pp. 941-947

Soltis, L.A., and Mtenga, P.V.A. 1985. "Strength of Nailed Wood Joints Subjected to Dynamic Load." Forest Products Journal 35 (11/12), 14-18.

Stern, E.G. 1964. "Moisture Content of Lumber Influences Nail-Holding Power." VPI & SU, Wood Research and Wood Construction Laboratory, Bulletin No. 51. Blacksburg,VA.

Stern, E.G. 1993. Draft No. 3. "Standard Test Method for Determining Bending Yield Moment of Nails." Proposed ASTM standard.

Wilkinson, T.L. 1971. "Theoretical Lateral Resistance of Wood Nailed Joints," Journal of the Structural Division, A.S.C.E., Vol. 97(5): pp. 1381-1398.

Wilkinson, T.L. 1972 -a. "Effect of Deformed Shanks, Prebored Lead Holes, and Grain Orientation on the Elastic Bearing Constant for Laterally Loaded Nail Joints." USDA, Forest Service Research Paper FPL 192., Madison, WI.

Wilkinson, T.L. 1972 -b. "Analysis of Nailed Joints with Dissimilar Members," Journal of the Structural Division, A.S.C.E., Vol 98(9): pp 2005-2013.

Wilkinson, T.L. 1974 -a. "Elastic Bearing Constants for Sheathing Materials." USDA, Forest Service, Forest Products Laboratory, Research Paper FPL 224, Madison, WI.

Wilkinson, T.L. 1974 -b. "Elastic Bearing Constants of Wood: Effect of Moisture Content Conditions." USDA, Forest Service, Forest Products Laboratory, Research Paper FPL 235, Madison, WI.

Wilkinson, T.L. 1991. "Dowel Bearing Strength." USDA, Forest Service, Forest Products Laboratory, Research Paper FPL-RP-505, Madison, WI.

Wills, B.L., Bender, D.A.and Winistorfer, S.G. 1993. "Contemporary Issues Facing Nail Fasteners." Paper 93-4545. Paper presented at The 1993 International Winter Meeting of the American Society of Agricultural Engineers; Chicago. St. Joseph, MI: American Society of Agricultural Engineers; 1993. 19p.

Zahn, J.J., 1992. Reliability of Bolted Wood Connections. Journal of Structural Engineering, 118 (12): pp 3362-3376.

APPENDIX A:

Tables for Data Acquisition with Specimen Identification Code.

The Tables contain the average values and coefficient of variation for moisture content, specific gravity, initial stiffness, load at 5% and load at capacity for each specimen by set.

Table 1 Average values and coefficient of variation for set HXCCF1 (C= 1/2" thick red alder deckboard. F1 = Nail type 1. HX = Rate of loading, 1Hz. Pattern "A").
Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	64	124	0.42	0.46	0.43	0.49	42500	54000	232	232	772	945
2	57	141	0.37	0.40	0.41	0.45	46667	46667	277	286	762	918
3	60	169	0.40	0.43	0.38	0.41	19500	20000	243	243	750	908
4	53	165	0.40	0.44	0.38	0.42	19571	20429	166	176	761	950
5	40	159	0.47	0.51	0.38	0.42	28500	29250	146	146	703	862
6	48	165	0.35	0.37	0.38	0.42	29000	30500	177	177	756	926
7	48	164	0.41	0.44	0.37	0.41	28000	29000	204	204	773	937
8	43	157	0.52	0.57	0.40	0.41	31000	31000	198	198	696	865
9	42	159	0.53	0.58	0.36	0.39	44667	45667	187	187	794	974
10	41	157	0.50	0.56	0.36	0.39	19000	19833	164	164	791	950
11	59	161	0.39	0.42	0.38	0.42	34000	34000	187	187	714	900
12	51	155	0.40	0.44	0.38	0.42	40000	40000	206	215	781	958
13	54	129	0.39	0.43	0.40	0.44	40250	40250	217	217	869	1026
14	49	133	0.39	0.42	0.39	0.43	60250	60250	291	306	818	1011
15	55	155	0.37	0.41	0.37	0.41	20833	21833	157	157	856	1006
AVG	51	153	0.42	0.46	0.38	0.42	33583	34845	203	206	773	942
STDs	7	14	0.06	0.07	0.02	0.02	12027	12671	43	45	50	49
COV (%)	14	9	13	14	5	6	36	36	21	22	6	5

Table 2 Average values and coefficient of variation for set HXCCF2 (C=1/2" thick red alder deckboard. F2=Nail type 2. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	64	141	0.38	0.41	0.41	0.45	36375	47750	280	293	765	904
2	110	163	0.42	0.46	0.37	0.41	25833	31500	261	278	757	945
3	99	163	0.42	0.45	0.36	0.40	22833	24000	179	196	774	950
4	71	149	0.38	0.41	0.37	0.41	32600	34000	200	207	750	886
5	107	135	0.41	0.45	0.40	0.44	47750	49250	251	251	838	1021
6	74	141	0.42	0.45	0.40	0.44	45600	45600	266	266	763	929
7	89	133	0.40	0.43	0.37	0.41	32571	40000	265	288	701	874
8	112	133	0.38	0.41	0.43	0.48	36600	37800	221	238	777	936
9	59	141	0.42	0.46	0.45	0.48	47500	47500	339	339	803	943
10	67	136	0.43	0.47	0.42	0.46	39000	39000	269	289	791	973
11	92	172	0.39	0.43	0.36	0.40	47000	47000	248	262	695	847
12	98	132	0.42	0.46	0.39	0.42	45600	45600	274	274	731	908
13	104	135	0.45	0.48	0.42	0.47	50000	52000	222	222	814	998
14	164	169	0.41	0.45	0.38	0.42	50500	50500	262	262	689	882
15	76	167	0.42	0.45	0.37	0.40	32167	33000	236	252	781	969
AVG	92	147	0.41	0.44	0.39	0.43	39462	41633	252	261	762	931
STDs	27	15	0.02	0.02	0.03	0.03	8970	8224	38	36	43	48
COV (%)	29	10	5	5	7	7	23	20	15	14	6	5

Table 3 Average values and coefficient of variation for set HXCCF3 (C= 1/2" thick red alder deckboard. F3 = Nail type 3. HX = Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	64	117	0.39	0.43	0.45	0.50	47333	47333	260	260	932	1126
2	145	116	0.38	0.43	0.42	0.48	53000	53000	278	290	870	1051
3	103	115	0.38	0.42	0.43	0.49	45250	45250	221	236	923	1106
4	89	119	0.39	0.43	0.44	0.50	51000	51000	203	213	816	989
5	106	112	0.38	0.42	0.44	0.49	60000	60333	235	241	752	946
6	144	125	0.38	0.42	0.41	0.46	61333	64333	251	257	811	1012
7	80	122	0.39	0.43	0.41	0.46	45400	45400	250	252	875	1072
8	89	120	0.45	0.49	0.42	0.48	51800	66750	293	315	957	1147
9	63	144	0.43	0.46	0.40	0.44	39800	39800	236	237	789	982
10	145	170	0.37	0.41	0.37	0.41	43000	44000	192	197	774	979
11	105	135	0.39	0.42	0.39	0.42	62250	62750	293	300	774	971
12	94	155	0.40	0.44	0.37	0.40	47000	47500	214	224	759	971
13	131	122	0.41	0.43	0.37	0.39	41571	48833	335	331	816	988
14	69	128	0.44	0.47	0.38	0.41	29250	40000	213	223	764	947
15	122	124	0.39	0.42	0.38	0.41	41000	41750	195	201	714	905
AVG	103	128	0.40	0.43	0.41	0.45	47932	50535	245	252	822	1013
STDs	29	16	0.02	0.02	0.03	0.04	8957	8974	41	41	73	72
COV (%)	28	13	6	5	7	9	19	18	17	16	9	7

Table 4 Average values and coefficient of variation for set HXCCF4 (C=1/2" thick red alder deckboard. F4=Nail type 4. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	64	103	0.37	0.40	0.43	0.48	53000	53000	335	335	906	1111
2	56	118	0.34	0.37	0.46	0.52	72375	72375	271	271	967	1174
3	62	107	0.35	0.38	0.42	0.46	76000	76000	328	328	942	1164
4	109	120	0.39	0.41	0.39	0.43	73333	73333	293	293	910	1114
5	124	133	0.36	0.39	0.39	0.43	88333	88333	392	392	932	1153
6	111	157	0.38	0.41	0.40	0.45	50000	50000	257	257	766	954
7	123	159	0.38	0.41	0.36	0.39	78000	78000	249	249	861	1061
8	93	132	0.40	0.44	0.38	0.42	65333	66667	256	271	817	1030
9	67	134	0.38	0.42	0.39	0.43	86500	90000	238	238	882	1093
10	52	129	0.36	0.40	0.40	0.44	47000	47000	254	254	766	954
11	63	146	0.37	0.40	0.42	0.46	62000	62000	260	260	869	1070
12	96	115	0.39	0.43	0.39	0.43	67333	67333	279	299	889	1111
13	118	149	0.38	0.41	0.40	0.43	60667	60667	228	248	824	1031
14	110	119	0.38	0.42	0.38	0.42	89077	89077	263	263	810	1031
15	57	108	0.34	0.37	0.40	0.45	65000	67000	261	281	890	1093
AVG	87	129	0.37	0.40	0.40	0.44	68930	69386	278	283	869	1076
STDs	28	18	0.02	0.02	0.02	0.03	13349	13647	43	41	61	68
COV (%)	32	14	5	5	6	7	19	20	16	15	7	6

Table 5 Average values and coefficient of variation for set HXBBF1 (B=5/8" thick red alder deckboard. F1=Nail type 1. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	113	191	0.34	0.37	0.37	0.40	23000	24000	170	170	766	908
2	174	151	0.39	0.43	0.42	0.47	47000	49250	270	288	866	1064
3	114	176	0.35	0.38	0.38	0.42	36000	36000	236	247	784	932
4	131	145	0.38	0.41	0.39	0.43	82500	84000	235	235	813	1034
5	115	154	0.46	0.50	0.38	0.42	48000	48000	276	298	841	1045
6	132	123	0.39	0.42	0.41	0.46	35600	36000	215	215	841	1033
7	136	152	0.39	0.42	0.43	0.49	40000	42200	238	252	902	1078
8	118	136	0.33	0.36	0.38	0.42	30333	31500	233	243	769	921
9	135	170	0.34	0.38	0.38	0.42	41143	41143	212	212	753	913
10	130	187	0.35	0.39	0.37	0.41	29286	30714	230	248	751	910
11	133	134	0.34	0.38	0.41	0.46	41250	33400	224	224	756	900
12	82	183	0.43	0.46	0.39	0.43	22375	31000	221	207	756	954
13	87	168	0.39	0.43	0.37	0.41	32667	32667	250	250	918	1105
14	111	153	0.39	0.43	0.37	0.41	32000	33400	200	200	794	962
15	116	126	0.38	0.41	0.47	0.52	57000	59250	293	319	1017	1219
AVG	122	157	0.38	0.41	0.39	0.44	39877	40835	234	241	822	999
STDs	22	22	0.04	0.04	0.03	0.03	15052	14929	31	39	77	93
COV (%)	18	14	10	9	7	8	38	37	13	16	9	9

Table 6 Average values and coefficient of variation for set HXBBF2 (B=5/8" thick red alder deckboard. F2=Nail type 2. HX=Rate of loading, 1Hz. Pattern "A").
Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	156	144	0.39	0.41	0.45	0.49	39200	39600	236	250	763	898
2	163	160	0.38	0.41	0.41	0.45	31000	38200	250	250	741	883
3	96	178	0.39	0.42	0.38	0.41	20625	25000	200	218	725	872
4	106	166	0.39	0.41	0.38	0.41	37667	39667	250	272	763	926
5	67	183	0.41	0.43	0.39	0.43	42000	43200	259	272	851	997
6	97	167	0.41	0.44	0.38	0.42	36600	31000	248	248	791	949
7	89	198	0.39	0.42	0.36	0.40	28000	29286	235	257	794	947
8	93	174	0.40	0.43	0.40	0.46	27429	25500	215	230	683	824
9	72	173	0.40	0.44	0.39	0.43	50200	42667	297	318	880	1027
10	95	150	0.39	0.43	0.39	0.44	27714	29143	224	246	772	923
11	59	169	0.41	0.43	0.39	0.44	23375	24500	218	234	750	912
12	65	191	0.40	0.43	0.38	0.42	31333	32000	240	240	733	910
13	107	172	0.42	0.45	0.37	0.41	25866	26857	218	238	763	916
14	82	164	0.41	0.45	0.37	0.41	36000	36000	233	253	730	877
15	61	155	0.40	0.42	0.36	0.39	43636	43636	277	292	777	956
AVG	94	170	0.40	0.43	0.39	0.43	33376	33750	240	255	768	921
STDs	31	15	0.01	0.01	0.02	0.03	8270	7021	25	25	49	50
COV (%)	33	9	3	3	6	6	25	21	10	10	6	5

Table 7 Average values and coefficient of variation for set HXBBF3 (B=5/8" thick red alder deckboard. F3=Nail type 3. HX=Rate of loading, 1Hz. Pattern "A").
Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	81	178	0.41	0.44	0.38	0.43	32833	34167	234	240	880	1069
2	107	172	0.39	0.43	0.39	0.43	26429	32167	227	239	919	1102
3	121	164	0.39	0.42	0.38	0.42	79500	83500	235	245	761	940
4	159	152	0.35	0.42	0.39	0.43	47250	49000	228	246	832	1027
5	183	176	0.37	0.41	0.39	0.44	33667	41600	253	268	819	983
6	117	153	0.39	0.43	0.37	0.41	24571	25429	221	235	832	1006
7	124	139	0.38	0.42	0.43	0.48	21125	25286	221	232	911	1093
8	124	162	0.37	0.41	0.36	0.40	21875	23625	239	255	924	1111
9	118	185	0.41	0.43	0.37	0.41	35000	46000	247	269	835	1045
10	116	164	0.38	0.41	0.37	0.40	25000	26143	215	228	813	1001
11	118	139	0.39	0.42	0.43	0.48	19200	20571	284	284	858	1074
12	127	145	0.38	0.42	0.42	0.48	41000	53750	255	269	860	1032
13	140	122	0.37	0.41	0.39	0.43	36286	35286	279	293	955	1160
14	141	168	0.37	0.40	0.38	0.42	19000	22429	207	220	795	991
15	135	128	0.38	0.42	0.38	0.41	25286	22750	226	238	835	1023
AVG	127	156	0.38	0.42	0.39	0.43	32535	36114	238	251	855	1044
STDs	23	19	0.02	0.01	0.02	0.03	15423	16828	22	21	53	58
COV (%)	18	12	4	2	6	6	47	47	9	9	6	6

Table 8 Average values and coefficient of variation for set HXBBF4 (B=5/8" thick red alder deckboard. F4=Nail type 4. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	114	160	0.40	0.43	0.41	0.45	36667	38500	287	315	1012	1224
2	71	156	0.38	0.42	0.40	0.44	47000	49500	326	345	990	1226
3	80	184	0.42	0.45	0.39	0.44	29857	30714	259	283	938	1135
4	92	160	0.39	0.43	0.39	0.43	36000	36000	271	299	964	1194
5	126	152	0.37	0.40	0.44	0.50	35714	44167	303	323	990	1228
6	64	146	0.40	0.43	0.40	0.44	32714	32714	263	287	1047	1250
7	74	179	0.37	0.40	0.40	0.44	32147	34000	291	319	1103	1250
8	69	169	0.43	0.47	0.36	0.41	62609	62609	279	311	947	1161
9	69	173	0.38	0.41	0.38	0.42	26750	32714	277	294	868	1085
10	70	142	0.38	0.41	0.40	0.44	37833	39667	290	309	912	1139
11	161	140	0.38	0.42	0.43	0.48	60000	60000	349	374	932	1150
12	55	152	0.41	0.44	0.35	0.39	60750	80667	259	279	871	1093
13	54	151	0.39	0.41	0.38	0.43	30000	31714	266	290	868	1084
14	79	170	0.42	0.46	0.38	0.42	38000	38000	289	310	908	1136
15	60	160	0.40	0.43	0.39	0.44	35750	43286	354	382	915	1197
AVG	83	160	0.39	0.43	0.39	0.44	40119	43617	291	315	951	1170
STDs	30	13	0.02	0.02	0.02	0.03	11820	14159	30	31	68	58
COV (%)	36	8	5	5	6	6	29	32	10	10	7	5

Table 9 Average values and coefficient of variation for set HXAAF1 (A=3/4" thick red alder deckboard. F1=Nail type 1. HX=Rate of loading, 1Hz. Pattern "A").
Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	130	96	0.34	0.36	0.35	0.41	42400	42800	267	267	827	966
2	54	143	0.41	0.43	0.39	0.43	43800	45400	280	280	918	1079
3	60	158	0.40	0.42	0.39	0.44	40000	42000	251	251	913	1098
4	68	169	0.38	0.41	0.36	0.39	37833	46400	287	309	918	1111
5	54	165	0.43	0.47	0.37	0.40	82500	83000	245	245	904	1101
6	59	138	0.39	0.42	0.37	0.40	60333	61000	289	289	974	1165
7	68	130	0.40	0.43	0.38	0.41	58000	61500	254	254	885	1052
8	155	94	0.39	0.43	0.37	0.40	32200	33400	257	257	844	1003
9	162	146	0.33	0.36	0.41	0.45	81000	81000	266	266	914	1072
10	82	128	0.38	0.41	0.47	0.53	40500	41833	311	311	952	1111
11	94	174	0.36	0.40	0.39	0.43	36667	36667	286	286	838	986
12	95	123	0.34	0.37	0.35	0.38	26500	26500	184	184	835	980
13	150	168	0.34	0.37	0.35	0.39	27714	33667	224	239	748	888
14	181	169	0.32	0.34	0.35	0.38	34667	34833	257	257	749	896
15	109	127	0.37	0.40	0.38	0.42	32857	34000	285	285	834	991
AVG	101	142	0.37	0.40	0.38	0.42	45131	46933	263	265	870	1033
STDs	44	26	0.03	0.04	0.03	0.04	17606	17191	31	31	67	82
COV (%)	43	18	9	9	8	9	39	37	12	12	8	8

Table 10 Average values and coefficient of variation for set HXAAF2 (A=3/4" thick red alder deckboard. F2=Nail type 2. HX=Rate of loading, 1Hz. Pattern "A").
Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	93	91	0.38	0.41	0.37	0.40	34000	35667	240	254	790	920
2	103	49	0.38	0.41	0.40	0.44	31000	32000	259	276	738	837
3	70	160	0.39	0.42	0.37	0.41	37833	39000	270	287	788	933
4	59	143	0.39	0.42	0.36	0.40	43600	43600	276	299	750	875
5	55	84	0.41	0.45	0.39	0.43	48500	58500	263	263	742	873
6	113	124	0.38	0.41	0.38	0.42	43667	53200	319	319	827	965
7	69	130	0.39	0.42	0.38	0.42	54000	57000	272	272	717	891
8	84	149	0.45	0.49	0.37	0.41	42800	43000	297	297	839	1005
9	147	95	0.45	0.49	0.39	0.43	52625	52625	457	457	800	980
10	80	86	0.48	0.53	0.37	0.40	26000	27625	267	278	790	944
11	87	164	0.45	0.50	0.40	0.44	46500	46500	299	299	826	1018
12	117	142	0.46	0.50	0.38	0.42	46800	34429	257	257	783	965
13	87	137	0.44	0.49	0.40	0.44	62667	64333	284	284	821	971
14	83	88	0.49	0.56	0.48	0.53	46000	47000	273	293	809	955
15	70	123	0.42	0.45	0.40	0.44	43000	43000	295	321	807	957
AVG	88	118	0.42	0.46	0.39	0.43	43933	45165	289	297	788	939
STDs	24	34	0.04	0.05	0.03	0.03	9238	10512	51	49	37	51
COV (%)	28	29	9	10	7	7	21	23	18	16	5	5

Table 11 Average values and coefficient of variation for set HXAAF3 (A=3/4" thick red alder deckboard. F3=Nail type 3. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	94	159	0.34	0.38	0.38	0.42	19500	23571	203	214	873	1027
2	128	148	0.35	0.38	0.39	0.43	21286	35833	265	265	865	1031
3	69	160	0.51	0.57	0.38	0.42	28250	28250	284	310	995	1203
4	71	126	0.34	0.38	0.37	0.42	49565	49565	250	250	772	908
5	81	157	0.35	0.38	0.35	0.40	29600	29600	214	214	790	921
6	64	154	0.36	0.39	0.38	0.43	26143	32000	262	262	894	1063
7	86	108	0.35	0.38	0.39	0.42	42400	42400	278	278	859	1032
8	82	137	0.48	0.53	0.37	0.41	70667	70667	310	310	1005	1188
9	80	158	0.33	0.37	0.37	0.41	46000	46000	220	220	770	908
10	52	163	0.46	0.51	0.37	0.41	56667	56667	246	246	927	1140
11	68	145	0.55	0.63	0.38	0.42	30833	31833	247	247	1026	1240
12	65	136	0.39	0.44	0.37	0.41	21750	22000	203	210	860	1002
13	89	83	0.36	0.39	0.44	0.48	44600	44600	287	287	917	1103
14	66	157	0.34	0.37	0.39	0.43	21875	22500	229	229	879	1035
15	82	145	0.33	0.36	0.38	0.41	33200	33800	202	202	805	938
AVG	78	142	0.39	0.43	0.38	0.42	36156	37952	247	250	882	1049
STDs	18	22	0.07	0.09	0.02	0.02	15004	13739	34	35	81	108
COV (%)	23	16	19	20	5	4	41	36	14	14	9	10

Table 12 Average values and coefficient of variation for set HXAAF4 (A=3/4" thick red alder deckboard. F4=Nail type 4. HX=Rate of loading, 1Hz. Pattern "A").
Test to determine the influence of thickness and nail type.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	48	129	0.38	0.41	0.37	0.41	39500	44000	258	281	954	1182
2	49	135	0.42	0.46	0.36	0.40	43500	43500	305	308	919	1150
3	107	116	0.38	0.41	0.42	0.48	40428	40428	345	364	1056	1250
4	77	127	0.33	0.36	0.39	0.42	43000	43000	297	305	915	1071
5	54	142	0.37	0.40	0.36	0.40	40429	41429	341	350	1051	1242
6	50	126	0.38	0.41	0.39	0.43	50750	50750	345	345	980	1172
7	163	139	0.38	0.41	0.37	0.41	50750	57750	305	305	1086	1250
8	73	116	0.35	0.38	0.45	0.50	38286	38286	271	323	933	1095
9	63	101	0.37	0.41	0.42	0.47	33000	33000	283	283	1026	1234
10	66	123	0.37	0.41	0.41	0.46	50000	50000	279	291	1008	1244
11	59	134	0.36	0.39	0.37	0.42	61000	61000	328	328	1051	1225
12	48	111	0.38	0.41	0.40	0.43	51000	51000	300	300	1037	1222
13	64	89	0.36	0.39	0.45	0.49	33429	40000	313	314	1074	1245
14	85	122	0.37	0.40	0.42	0.48	43166	51000	360	366	1032	1238
15	61	126	0.42	0.46	0.41	0.47	55714	55714	320	333	1049	1250
AVG	71	122	0.37	0.41	0.40	0.44	44930	46724	310	320	1011	1205
STDs	30	14	0.02	0.03	0.03	0.04	8029	7900	30	27	57	58
COV (%)	42	12	6	6	7	8	18	17	10	9	6	5

Table 13 Average values and coefficient of variation for set CYHEF1 (HE=5/8" thick red alder deckboard. F1=Nail type 1. CY=Rate of loading, 1/2Hz. Pattern "A"). Test to determine the influence of rate of loading.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	64	76	0.39	0.42	0.37	0.40	41667	42333	207	215	720	861
2	63	62	0.36	0.39	0.36	0.40	10375	12286	122	132	647	785
3	64	80	0.36	0.39	0.35	0.40	37600	38400	252	253	712	848
4	54	87	0.39	0.42	0.34	0.37	14429	16143	125	136	728	884
5	50	60	0.40	0.44	0.40	0.44	15429	19500	127	141	662	792
6	51	104	0.42	0.44	0.35	0.37	12875	14250	136	147	676	814
7	71	72	0.36	0.39	0.35	0.39	10889	11556	123	134	691	837
8	53	71	0.37	0.39	0.34	0.37	29000	29833	209	220	629	756
9	42	83	0.39	0.42	0.33	0.38	17333	18666	129	142	643	810
10	48	59	0.41	0.43	0.36	0.39	47800	47800	294	311	748	912
11	78	75	0.38	0.39	0.31	0.36	23375	24125	108	118	662	811
12	56	80	0.37	0.39	0.35	0.37	27778	37778	174	177	729	869
13	53	96	0.36	0.40	0.36	0.39	17309	21143	122	130	703	829
14	56	55	0.41	0.42	0.35	0.37	28500	28500	139	134	676	816
15	52	51	0.42	0.46	0.36	0.38	32000	32000	153	157	691	821
AVG	57	74	0.39	0.41	0.35	0.39	24424	26288	161.333	170	688	830
STDs	9	15	0.02	0.02	0.02	0.02	11712	11481	55	56	35	40
COV (%)	16	20	6	6	6	5	48	44	34	33	5	5

Table 14 Average values and coefficient of variation for set CYHEF3 (HE=5/8" thick red alder deckboard F3=Nail type 3. CY=Rate of loading, 1/2Hz. Pattern "A").
Test to determine the influence of rate of loading.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-O	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	64	41	0.37	0.41	0.38	0.42	20333	21222	221	221	755	953
2	50	54	0.42	0.45	0.37	0.41	41429	41429	300	300	749	924
3	41	74	0.37	0.41	0.37	0.42	22800	19500	143	143	701	899
4	63	47	0.41	0.45	0.35	0.39	33333	34333	172	172	888	1021
5	73	84	0.38	0.41	0.37	0.41	27600	27400	195	195	718	882
6	41	68	0.37	0.41	0.39	0.42	22600	28750	149	149	640	786
7	51	67	0.43	0.49	0.36	0.40	17500	18667	149	149	690	839
8	55	88	0.40	0.44	0.36	0.40	13000	13714	110	121	711	907
9	47	63	0.37	0.41	0.33	0.39	15429	13250	130	130	652	788
10	67	63	0.40	0.44	0.35	0.41	24833	29800	175	175	701	832
11	47	50	0.33	0.38	0.34	0.37	24000	26667	196	196	720	869
12	50	80	0.36	0.40	0.35	0.39	17286	20500	141	141	654	800
13	72	46	0.42	0.46	0.38	0.42	17143	21000	138	152	674	839
14	61	51	0.43	0.47	0.36	0.39	12250	15333	110	122	697	857
15	73	53	0.41	0.45	0.36	0.39	25000	25000	180	180	717	822
AVG	57	62	0.39	0.43	0.36	0.40	22302	23771	167.267	170	711	868
STDs	11	15	0.03	0.03	0.02	0.02	7774	7837	49	46	59	65
COV (%)	20	24	8	7	4	4	35	33	29	27	8	8

Table 15 Average values and coefficient of variation for set HXASF2 (A=3/4" thick red alder deckboard, S=one nail joints. F2=Nail type 2. HX=Rate of loading, 1Hz.). Test to determine the influence of number of nails.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	76	154	0.37	0.40	0.38	0.42	9143	23000	78	86	200	255
2	66	139	0.36	0.40	0.36	0.39	9286	7250	69	73	178	233
3	66	144	0.36	0.40	0.41	0.45	12333	13667	86	94	223	259
4	75	133	0.36	0.40	0.41	0.45	8571	8250	75	84	214	258
5	59	130	0.36	0.39	0.42	0.48	9857	8875	106	84	248	296
6	75	93	0.36	0.40	0.48	0.55	22000	18750	104	116	249	289
7	71	146	0.38	0.42	0.37	0.42	10429	10714	91	92	251	310
8	71	150	0.38	0.42	0.37	0.42	12800	13600	66	71	220	268
9	62	151	0.37	0.41	0.37	0.41	14600	12833	84	89	216	264
10	62	122	0.37	0.41	0.42	0.47	11667	12000	93	94	250	299
11	153	130	0.38	0.42	0.38	0.42	11429	11429	95	95	242	291
12	117	136	0.39	0.42	0.38	0.42	12167	13500	86	94	227	264
13	97	127	0.34	0.37	0.39	0.43	12667	13000	86	89	214	251
AVG	81	135	0.37	0.40	0.40	0.44	12073	12836	86	89	226	272
STDs	27	16	0.01	0.01	0.03	0.04	3448	4234	12	11	22	23
COV (%)	34	12	4	4	8	9	29	33	14	12	10	8

Table 16 Average values and coefficient of variation for set HXADF2 (A=3/4" thick red alder deckboard, D=two nails joints. F2=Nail type 2. HX=Rate of loading, 1Hz.). Test to determine the influence of number of nails.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	97	128	0.34	0.37	0.37	0.40	34000	34000	157	161	393	479
2	106	121	0.34	0.37	0.44	0.49	35750	35750	168	181	477	399
3	106	130	0.34	0.37	0.42	0.47	26000	27000	114	121	441	520
4	107	121	0.34	0.37	0.45	0.50	39333	39333	147	160	460	537
5	107	133	0.34	0.37	0.42	0.48	28750	23800	144	154	375	407
6	63	128	0.38	0.41	0.35	0.38	24600	25400	128	136	358	444
7	63	128	0.38	0.41	0.37	0.42	19500	21250	100	112	418	507
8	125	143	0.34	0.37	0.39	0.44	25000	27600	153	158	414	498
9	125	121	0.34	0.37	0.37	0.41	27500	27500	111	111	437	499
10	99	120	0.34	0.38	0.37	0.41	25750	33500	116	116	429	529
11	102	125	0.34	0.38	0.37	0.41	19800	20800	121	132	418	495
12	102	151	0.34	0.38	0.37	0.41	21375	18625	164	175	520	604
13	162	157	0.34	0.38	0.38	0.42	27250	27250	129	139	406	501
14	162	122	0.34	0.38	0.41	0.46	28667	28667	127	127	433	496
15	61	126	0.42	0.46	0.41	0.47	55714	55714	320	333	1049	1250
AVG	106	130	0.35	0.38	0.39	0.44	29266	29746	147	154	469	544
STDs	30	11	0.02	0.02	0.03	0.04	9194	9216	52	54	165	202
COV (%)	28	9	7	6	8	9	31	31	36	35	35	37

Table 17 Average values and coefficient of variation for set HXANF3 (A=3/4" thick red alder deckboard, N=less friction. F3=Nail type 3. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of friction.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	85	90	0.47	0.51	0.37	0.39	18750	19500	213	218	703	854
2	54	165	0.43	0.47	0.37	0.41	25200	26000	194	201	789	945
3	58	141	0.49	0.53	0.39	0.43	25286	29833	230	244	816	977
4	81	136	0.48	0.53	0.40	0.43	20000	23571	208	211	813	952
5	139	114	0.35	0.38	0.36	0.39	16857	17571	162	205	626	737
6	102	111	0.37	0.40	0.34	0.36	25833	27333	199	212	679	805
7	103	160	0.44	0.48	0.36	0.39	22571	22571	218	263	750	913
8	81	129	0.46	0.51	0.38	0.41	29750	29750	194	197	777	933
9	110	135	0.35	0.38	0.41	0.44	18500	19000	208	225	705	838
10	68	118	0.36	0.38	0.40	0.44	20714	21429	207	207	761	894
11	103	123	0.34	0.37	0.36	0.39	18667	18833	186	190	672	797
12	88	111	0.43	0.46	0.40	0.44	26500	26500	210	220	802	947
13	86	131	0.43	0.47	0.39	0.43	22400	22400	246	249	821	992
14	68	111	0.42	0.46	0.36	0.39	22000	22000	184	191	679	834
15	69	151	0.36	0.39	0.37	0.40	31750	32000	171	158	725	866
AVG	86	128	0.41	0.45	0.38	0.41	22985	23886	202	213	741	886
STDs	23	20	0.05	0.06	0.02	0.02	4335	4480	22	26	62	74
COV (%)	26	16	13	13	5	6	19	19	11	12	8	8

Table 18 Average values and coefficient of variation for set HXCNF3 (C=1/2" thick red alder deckboard, N=less friction. F3=Nail type 3. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of friction.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	127	126	0.40	0.44	0.38	0.42	27000	27800	195	201	658	824
2	58	133	0.45	0.49	0.39	0.43	17375	18500	199	211	626	788
3	70	103	0.43	0.47	0.40	0.44	25333	25333	190	200	687	852
4	61	120	0.45	0.48	0.40	0.45	31000	31000	268	277	703	866
5	82	108	0.43	0.47	0.43	0.48	23667	24333	192	170	671	816
6	90	109	0.41	0.45	0.40	0.45	22000	22714	205	210	670	838
7	96	110	0.41	0.44	0.40	0.44	28800	27200	210	196	703	872
8	93	133	0.41	0.44	0.42	0.47	28500	24857	224	230	700	890
9	102	175	0.41	0.45	0.38	0.42	24667	25000	212	220	655	839
10	100	140	0.47	0.51	0.42	0.45	23286	24429	213	219	703	877
11	164	177	0.37	0.40	0.38	0.41	15125	17714	166	169	623	799
12	117	103	0.39	0.42	0.42	0.47	17625	20571	196	188	662	829
13	89	110	0.43	0.46	0.47	0.52	13333	15625	165	170	627	770
14	142	163	0.36	0.39	0.38	0.41	22143	22571	211	220	659	812
15	131	115	0.41	0.45	0.41	0.46	26000	27000	210	211	645	795
AVG	101	128	0.42	0.45	0.41	0.45	23057	23643	204	206	666	831
STDs	30	25	0.03	0.03	0.02	0.03	5205	4140	24	28	29	35
COV (%)	30	20	7	7	6	7	23	18	12	13	4	4

Table 19 Average values and coefficient of variation for set HXRAF3 (A=3/4" thick red alder deckboard, D=dry-dry joints. F3=Nail type 3. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of moisture content.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	20	15	0	0.44	0	0.36	13714	12286	126	126	755	926
2	20	14	0	0.40	0	0.41	16250	16250	215	223	781	941
3	19	15	0	0.40	0	0.42	19857	19857	143	143	851	1011
4	19	14	0	0.38	0	0.39	24200	24200	180	180	643	800
5	20	15	0	0.38	0	0.41	22143	22143	198	231	836	990
6	22	15	0	0.45	0	0.41	22857	22857	203	193	893	1059
7	21	15	0	0.39	0	0.42	15286	17833	187	193	792	983
8	19	15	0	0.44	0	0.48	24750	24750	161	157	794	965
9	21	15	0	0.42	0	0.45	22250	22250	170	162	808	949
10	20	15	0	0.40	0	0.39	13714	13714	145	153	835	989
11	19	15	0	0.42	0	0.47	28000	29000	199	182	915	1100
12	20	15	0	0.39	0	0.47	39750	39750	159	149	935	1093
13	20	15	0	0.43	0	0.46	25000	25000	252	240	1029	1184
14	20	16	0	0.42	0	0.42	24091	26250	144	151	882	1053
15	18	15	0	0.40	0	0.42	21000	21000	190	176	709	895
AVG	20	15	0	0.41	0	0.43	22191	22476	178	177	831	996
STDs	1	0	0	0.02	0	0.03	6536	6655	33	34	95	94
COV (%)	5	2	ERR	5	ERR	8	29	30	19	19	11	9

Table 20 Average values and coefficient of variation for set HXRGF3 (R=3/4" thick red alder deckboard, G=green-dry joints. F3=Nail type 3. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of moisture content.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	20	15	0	0.40	0	0.42	19273	19273	229	229	1114	1300
2	17	15	0	0.41	0	0.44	14000	13000	187	187	1121	1320
3	16	15	0	0.40	0	0.49	13000	12000	158	201	1133	1389
4	18	16	0	0.39	0	0.41	9500	11500	242	310	940	1088
5	19	15	0	0.47	0	0.48	13500	11714	162	162	1247	1438
6	17	15	0	0.39	0	0.45	12250	14704	200	200	1195	1392
7	18	16	0	0.41	0	0.46	20500	20750	199	199	1219	1396
8	18	15	0	0.42	0	0.46	9333	10167	172	206	1118	1303
9	19	16	0	0.44	0	0.44	11800	12000	223	249	1109	1327
10	18	16	0	0.41	0	0.43	14000	15000	236	236	1125	1365
11	20	16	0	0.43	0	0.42	15500	13000	213	238	1198	1411
12	21	16	0	0.42	0	0.46	13722	13722	168	168	1023	1205
13	21	16	0	0.43	0	0.45	10875	11875	228	370	1168	1365
14	18	15	0	0.50	0	0.43	22543	19500	178	178	1089	1309
15	20	15	0	0.48	0	0.43	14667	13750	187	187	1034	1227
AVG	19	15	0	0.43	0	0.44	14298	14130	199	221	1122	1322
STDs	2	0	0	0.03	0	0.02	3831	3226	28	56	80	92
COV (%)	8	2	ERR	8	ERR	5	27	23	14	25	7	7

Table 21 Average values and coefficient of variation for set HXHBF3 (H=5/8" thick red alder deckboard, B=Pattern "B". F3=Nail type 3. HX=Rate of loading, 1Hz.). Test to determine the influence of pattern.

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	70	59	0.39	0.43	0.39	0.42	23000	25000	128	130	679	828
2	134	97	0.38	0.42	0.38	0.42	21833	22167	150	152	656	803
3	145	59	0.38	0.42	0.37	0.41	25714	22875	160	171	747	935
4	94	84	0.41	0.45	0.35	0.39	31250	31750	145	149	683	852
5	74	89	0.37	0.41	0.39	0.42	29600	30400	155	162	761	930
6	89	63	0.33	0.36	0.34	0.38	33000	25250	148	158	601	744
7	126	92	0.40	0.44	0.40	0.41	25571	26143	167	173	768	965
8	97	50	0.38	0.41	0.35	0.39	31000	31500	157	163	603	767
9	106	94	0.39	0.43	0.37	0.40	25000	25250	209	217	745	927
10	79	60	0.42	0.46	0.35	0.39	34500	35667	231	234	706	880
11	133	58	0.38	0.41	0.35	0.39	29750	30000	162	165	649	792
12	77	58	0.47	0.51	0.34	0.39	27000	27750	211	218	719	880
AVG	102	72	0.39	0.43	0.37	0.40	28102	27813	169	174	693	859
STDs	26	18	0.03	0.04	0.02	0.01	4005	4072	31	32	58	73
COV (%)	26	25	8	8	6	4	14	15	19	18	8	8

Table 22 Average values and coefficient of variation for set HXPAF3 (A=3/4" thick oak deckboard, P=southern y. pine. F3=Nail type 3. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of specific gravity (species).

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	64	89	0.51	0.56	0.43	0.47	28833	30833	208	222	647	805
2	53	43	0.53	0.49	0.42	0.55	30800	30800	310	310	707	863
3	35	48	0.50	0.54	0.49	0.51	31286	31286	269	277	747	898
4	147	34	0.40	0.45	0.43	0.45	23700	24900	232	253	647	777
5	32	38	0.49	0.53	0.40	0.43	24500	25750	204	195	620	782
6	50	38	0.45	0.48	0.46	0.49	44500	44500	215	229	639	779
7	45	44	0.45	0.49	0.46	0.48	27500	27500	197	212	751	883
8	88	89	0.45	0.48	0.46	0.50	34200	34200	205	220	726	893
9	124	89	0.41	0.43	0.44	0.47	20333	19429	161	165	687	845
10	101	36	0.41	0.44	0.44	0.46	30833	30833	231	225	632	778
11	114	120	0.44	0.46	0.39	0.42	28200	30000	172	181	600	768
12	139	103	0.40	0.43	0.40	0.42	31000	31000	181	190	590	766
13	32	45	0.48	0.52	0.38	0.40	31714	38667	260	272	738	590
14	97	44	0.42	0.45	0.41	0.44	27400	25333	181	166	659	804
15	111	49	0.43	0.46	0.38	0.40	18625	19875	183	192	630	789
AVG	82	61	0.45	0.48	0.43	0.46	28895	29660	214	221	668	801
STDs	40	29	0.04	0.04	0.03	0.04	6135	6505	41	42	54	75
COV (%)	49	47	9	9	8	9	21	22	19	19	8	9

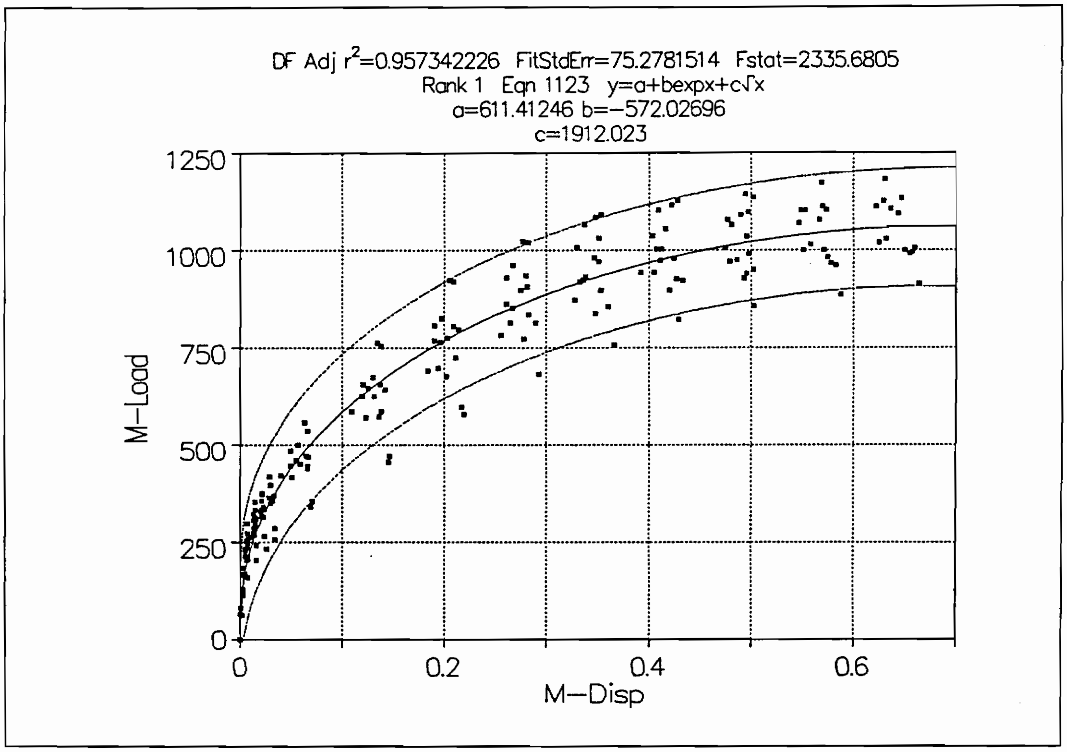
Table 23 Average values and coefficient of variation for set HXOAF3 (A=3/4" oak deckboard, O=white oak. F3=Nail type 3. HX=Rate of loading, 1Hz. Pattern "A"). Test to determine the influence of specific gravity (species).

Specimen	Moisture Content (%)		Specific Gravity				Initial Stiffness (psi)		Load at 5% (lb)		Load at Capacity (lb)	
Number	Block	Board	Block-G	Block-OD	Board-G	Board-OD	Ki-stab.	Ki-initial	stable	initial	Stable	Initial
1	65	66	0.67	0.73	0.66	0.74	120250	120250	579	579	1905	2117
2	65	65	0.68	0.75	0.67	0.75	145500	145500	510	553	1768	1971
3	74	53	0.68	0.74	0.61	0.72	112250	112500	600	600	1855	2142
4	70	55	0.71	0.80	0.65	0.73	103500	103500	647	691	1810	2040
5	79	56	0.68	0.75	0.64	0.72	117250	117250	486	486	2053	2282
6	77	58	0.68	0.75	0.63	0.72	120667	120667	594	594	1675	1885
7	71	58	0.70	0.78	0.62	0.69	131000	131000	549	549	1757	1934
8	74	56	0.71	0.79	0.62	0.70	78000	79000	455	455	1574	1773
9	65	58	0.67	0.77	0.63	0.71	98000	100000	566	566	1643	1847
10	66	60	0.66	0.72	0.65	0.74	136333	136333	523	523	1698	1904
11	73	56	0.68	0.77	0.66	0.74	74250	77000	569	569	1680	1906
12	72	59	0.70	0.80	0.63	0.71	159000	159000	489	489	1698	1846
13	67	57	0.66	0.74	0.64	0.72	156000	160500	441	441	1766	2011
14	67	57	0.67	0.74	0.65	0.72	88000	88000	500	500	1663	1871
15	66	62	0.67	0.75	0.62	0.69	113000	117000	539	539	1507	1681
AVG	70.0	58.4	0.68	0.76	0.64	0.72	116867	117833	536	542	1737	1947
STDs	5	4	0.02	0.03	0.02	0.02	25998	25951	57	64	135	153
COV (%)	7	6	2	3	3	3	22	22	11	12	8	8

APPENDIX B:

Typical Data Collected from the TableCurve™ Program for Each Set of Nailed Joint Specimens.

Each page shows a half page figure, with the 95% prediction limits and the curve fitting for the model chosen, the mathematical model and its rank, the model parameter values, and the statistics Sort Criteria of the fitted equation.



Sep 7,1994 12:15 PM

208 Active X-Y Points

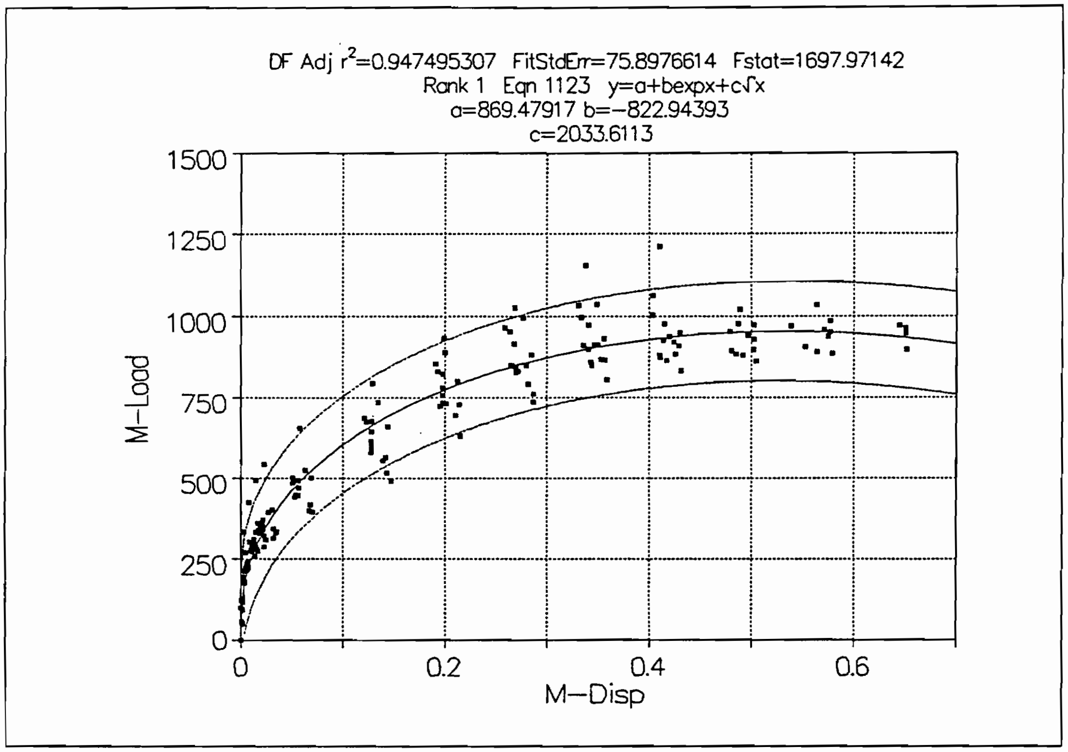
X: M-Disp	Mean: 0.2238221154	SD: 0.2189414633
Y: M-Load	Mean: 622.80288462	SD: 365.36900094

File Source: MXAAF1A.PRN

Rank 1 Eqn 1123 y=a+bexpx+cSQRTx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9579604545	0.9573422259	75.278151442	2335.6804992

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	611.4124611	50.53105741	12.09973613	511.778098	711.0468242
b	-572.026965	56.78196396	-10.0740962	-683.986522	-460.067407
c	1912.023038	62.44294874	30.62031945	1788.901462	2035.144614



Sep 7,1994 12:24 PM

188 Active X-Y Points

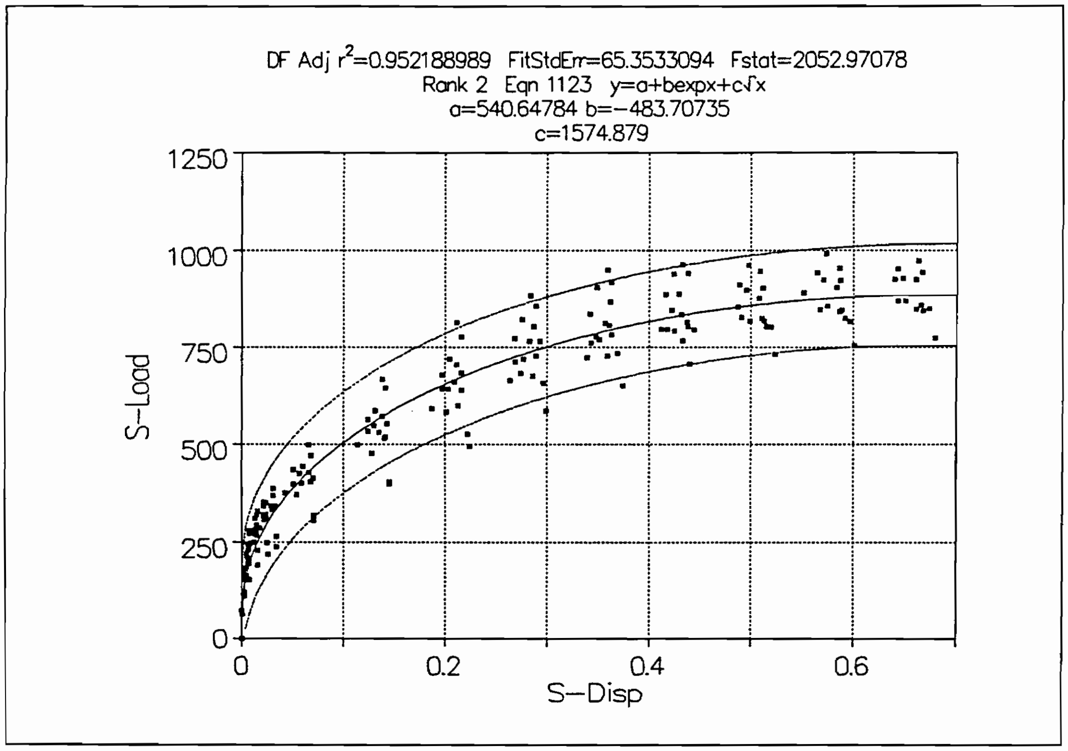
X: M-Disp	Mean: 0.186	SD: 0.1941956398
Y: M-Load	Mean: 569.30851064	SD: 332.12860812

File Source: MXAAF2A.PRN

Rank 1 Eqn 1123 y=a+bexpx+cSQRTx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9483376283	0.947495307	75.897661424	1697.9714186

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	869.4791697	61.43881503	14.15195214	748.259117	990.6992223
b	-822.94393	67.84733556	-12.1293478	-956.808126	-689.079734
c	2033.611337	68.35350821	29.75138205	1898.748452	2168.474223



Sep 8,1994 9:33 AM

206 Active X-Y Points

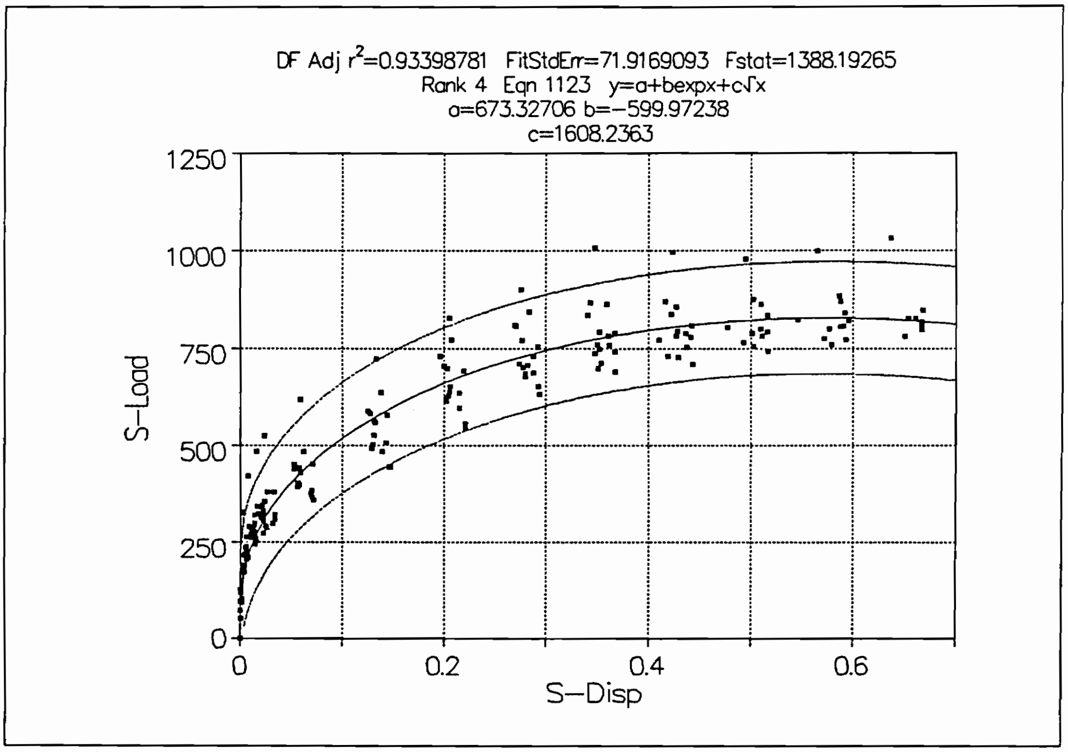
X: S-Disp	Mean: 0.2267087379	SD: 0.2233011149
Y: S-Load	Mean: 534.21359223	SD: 299.62355733

File Source: SXAAF1A.PRN

Rank 2 Eqn 1123 y=a+bexpx+cSQRTx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9528886626	0.9521889892	65.353309369	2052.9707814

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	540.6478403	42.44869378	12.73650123	456.9448814	624.3507992
b	-483.707349	47.80135691	-10.1191134	-577.96502	-389.449678
c	1574.878993	53.4099239	29.48663616	1469.562003	1680.195983



Sep 8,1994 9:37 AM

196 Active X-Y Points

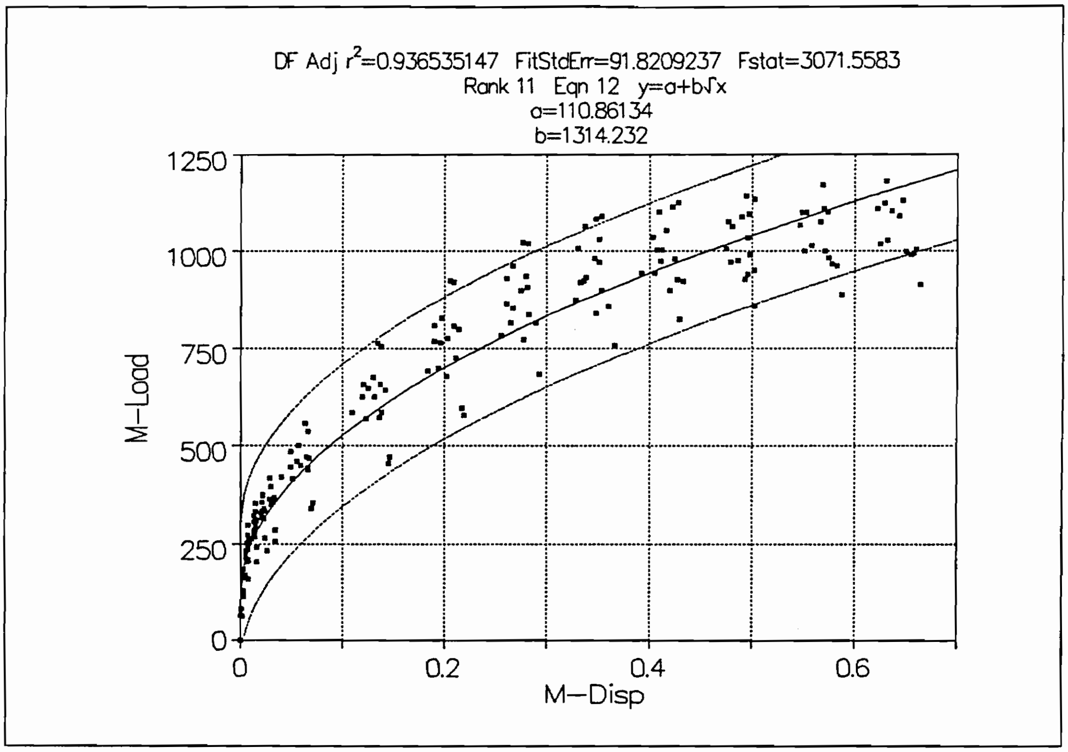
X: S-Disp	Mean: 0.2078061224	SD: 0.2121040702
Y: S-Load	Mean: 513.5	SD: 280.63832916

File Source: SXAAF2A.PRN

Rank 4 Eqn 1123 y=a+bexpx+cSQRTx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9350033826	0.9339878104	71.916909309	1388.1926477

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	673.3270557	50.3790528	13.36521864	573.9553756	772.6987358
b	-599.972382	56.13062205	-10.6888604	-710.688918	-489.255846
c	1608.236306	60.19456995	26.71729871	1489.503714	1726.968899



Sep 7,1994 12:18 PM

208 Active X-Y Points

X: M-Disp Mean: 0.2238221154 SD: 0.2189414633

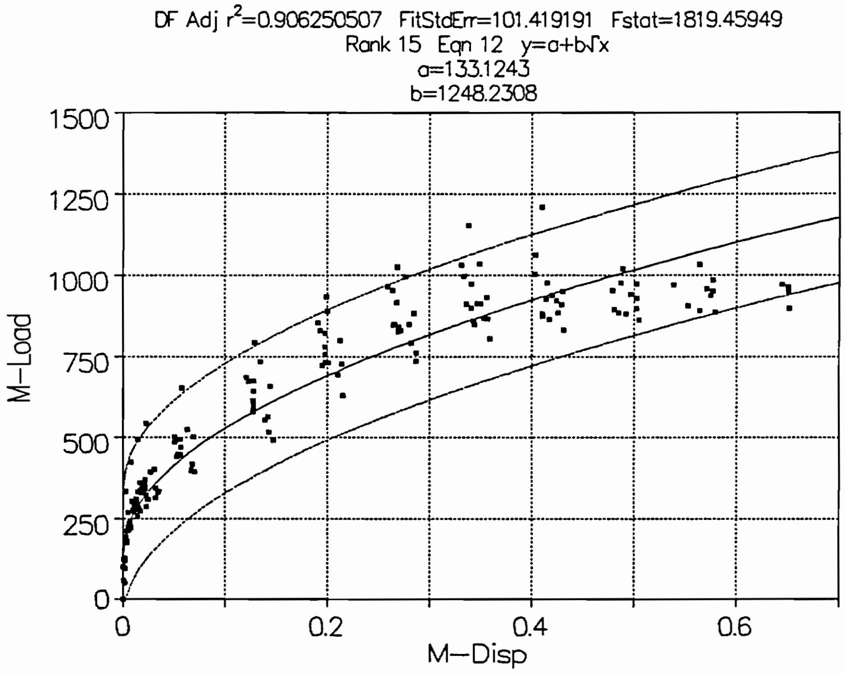
Y: M-Load Mean: 622.80288462 SD: 365.36900094

File Source: MXAAF1A.PRN

Rank 11 Eqn 12 y=a+bSQRTx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9371483339	0.9365351469	91.820923742	3071.5583013

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	110.8613375	11.21874177	9.881797779	88.74148466	132.9811903
b	1314.231992	23.71333592	55.42164109	1267.476705	1360.98728



Sep 7,1994 12:26 PM

188 Active X-Y Points

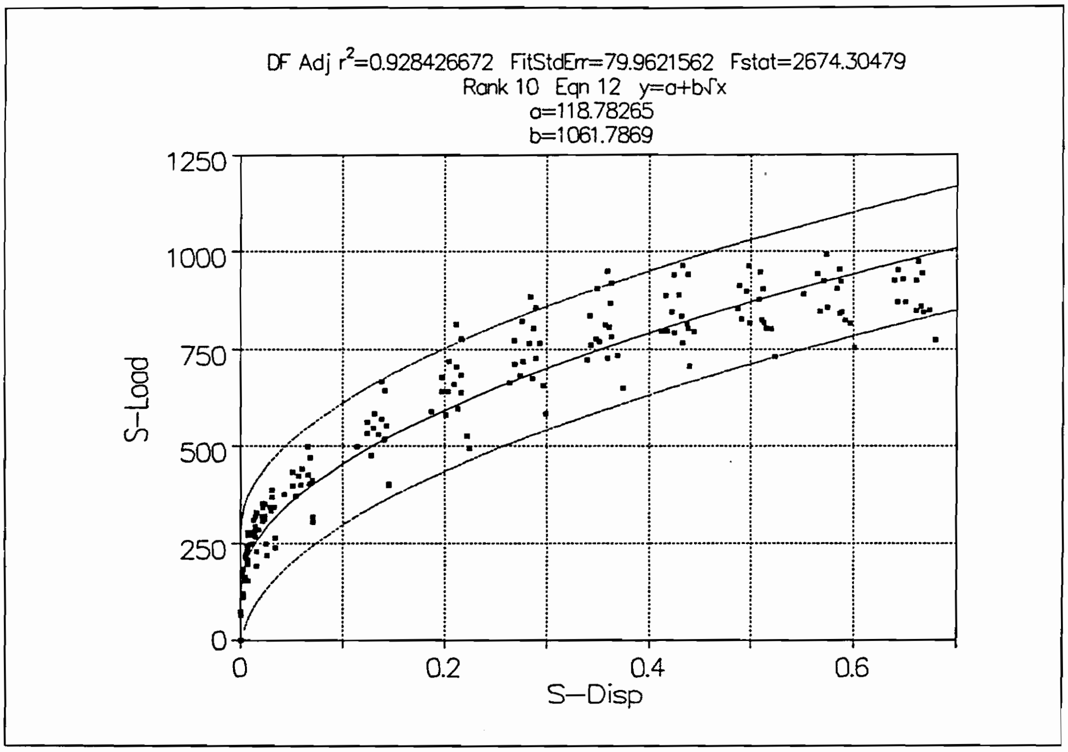
X: M-Disp	Mean: 0.186	SD: 0.1941956398
Y: M-Load	Mean: 569.30851064	SD: 332.12860812

File Source: MXAAF2A.PRN

Rank 15 Eqn 12 y=a+bSQRTx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9072531752	0.9062505068	101.41919097	1819.4594904

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	133.1243034	12.6206047	10.54817155	108.2244729	158.0241339
b	1248.230779	29.26332643	42.65512267	1190.495679	1305.965878



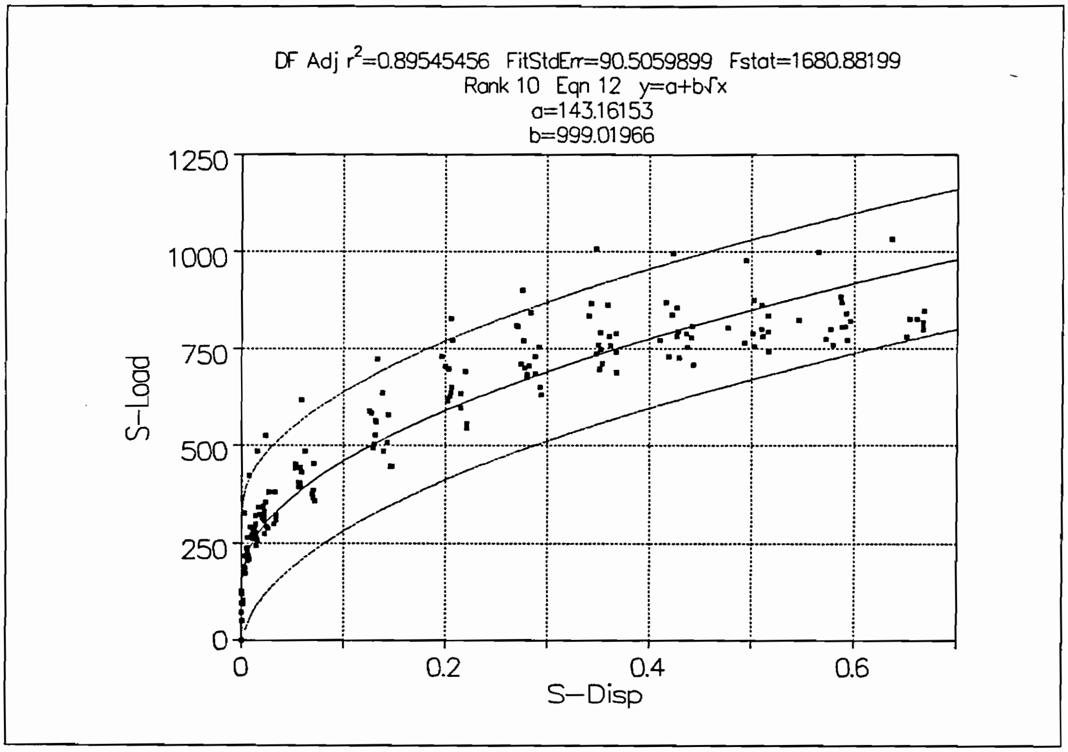
Sep 8,1994 9:35 AM

206 Active X-Y Points
X: S-Disp   Mean: 0.2267087379   SD: 0.2233011149
Y: S-Load   Mean: 534.21359223   SD: 299.62355733
File Source: SXAAF1A.PRN

Rank 10 Eqn 12 y=a+bSQRTx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9291249485	0.9284266721	79.962156213	2674.3047863

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	118.7826458	9.776109039	12.15029879	99.506083	138.0592087
b	1061.786888	20.53203081	51.71368084	1021.301765	1102.272012



Sep 8,1994 9:39 AM

196 Active X-Y Points

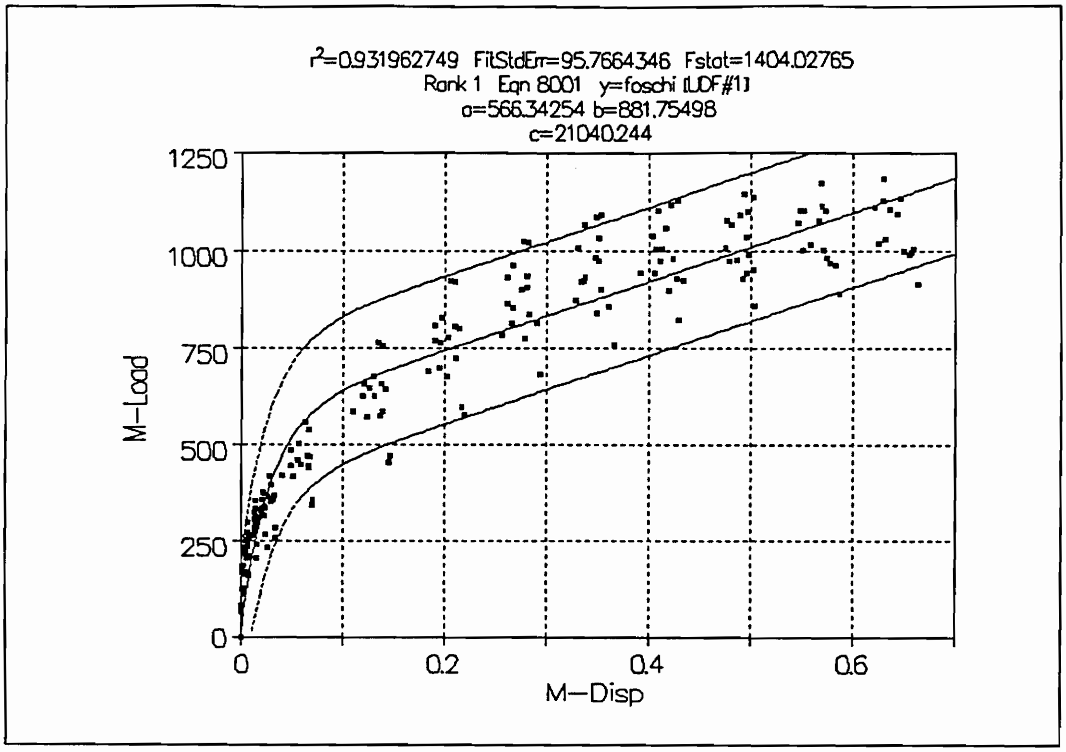
X: S-Disp	Mean: 0.2078061224	SD: 0.2121040702
Y: S-Load	Mean: 513.5	SD: 280.63832916

File Source: SXAAF2A.PRN

Rank 10 Eqn 12 y=a+bSQRTx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.896526821	0.8954545601	90.505989905	1680.8819922

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	143.1615263	11.10796731	12.88818397	121.2519988	165.0710538
b	999.0196624	24.36718854	40.99856086	950.9574407	1047.081884



Jul 5,1994 11:32 AM

208 Active X-Y Points

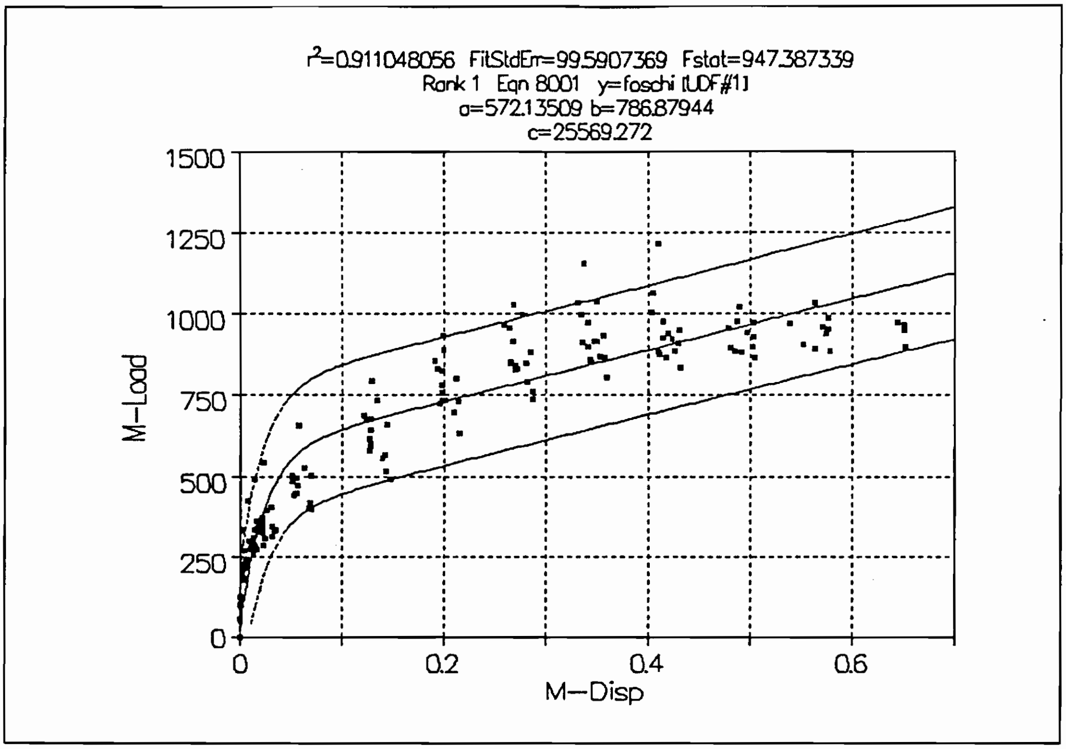
X: M-Disp	Mean: 0.2238221154	SD: 0.2189414633
Y: M-Load	Mean: 622.80288462	SD: 365.36900094

File Source: MXAAF1A.PRN

Rank 1 Eqn 8001 y=foschi [UDF#1]

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.931962749	0.9309622012	95.76643461	1404.0276515

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	566.3425396	21.7963591	25.98335515	523.3656761	609.3194031
b	881.7549793	52.69367284	16.73360257	777.8564899	985.6534687
c	21040.24446	1568.499201	13.41425259	17947.56391	24132.92502



Jul 5,1994 11:36 AM

188 Active X-Y Points

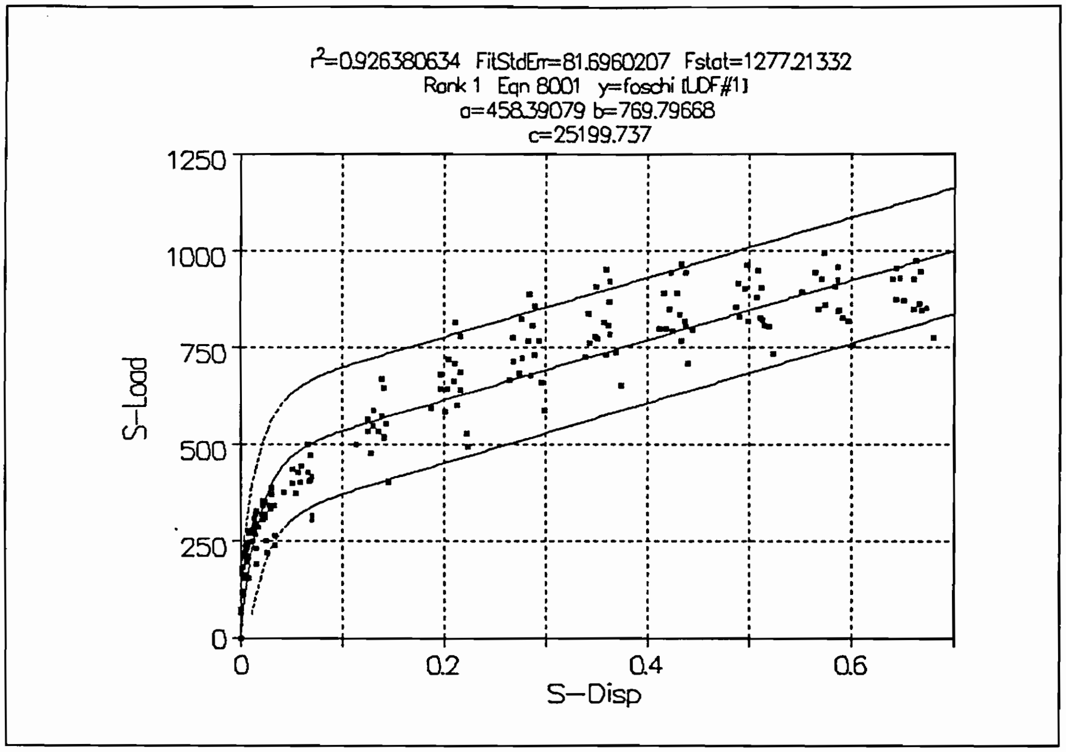
X: M-Disp	Mean: 0.186	SD: 0.1941956398
Y: M-Load	Mean: 569.30851064	SD: 332.12860812

File Source: MXAAF2A.PRN

Rank 1 Eqn 8001 y=foschi [UDF#1]

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9110480563	0.9095977529	99.590736864	947.38733867

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	572.1350876	22.94294187	24.93730275	526.8681888	617.4019864
b	786.8794438	63.15968271	12.45857183	662.2640836	911.4948039
c	25569.2718	2009.725992	12.72276514	21604.04085	29534.50274



Jul 5,1994 11:34 AM

206 Active X-Y Points

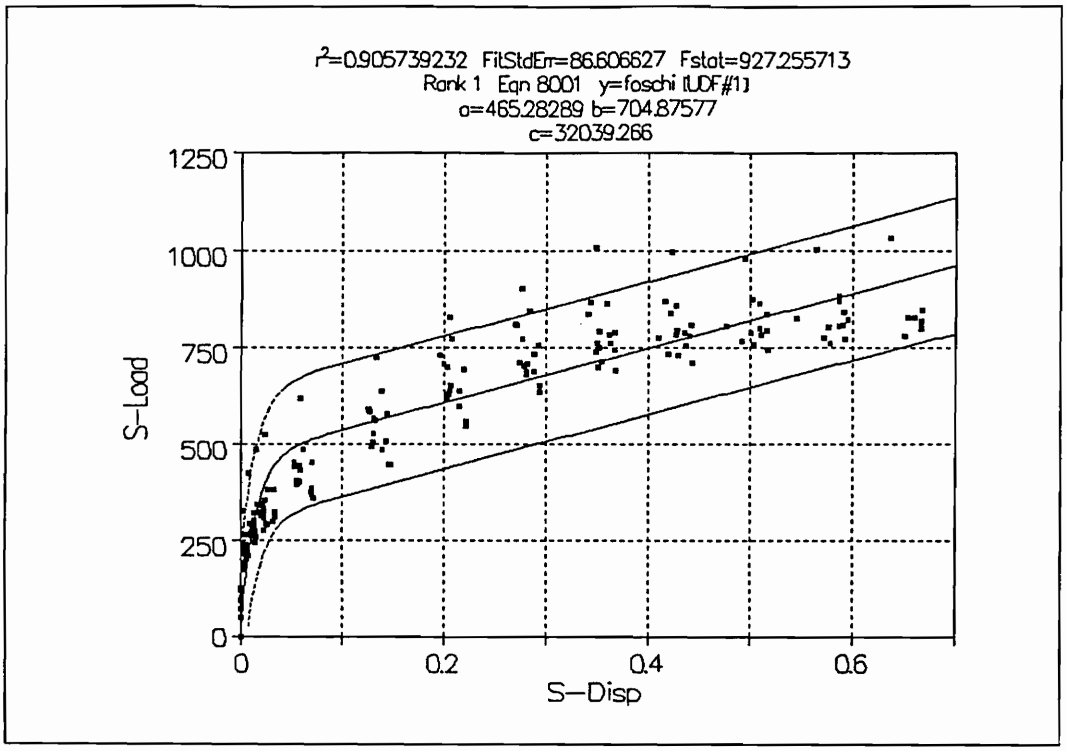
X: S-Disp	Mean: 0.2267087379	SD: 0.2233011149
Y: S-Load	Mean: 534.21359223	SD: 299.62355733

File Source: SXAAF1A.PRN

Rank 1 Eqn 8001 y=foschi [UDF#1]

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9263806343	0.9252872774	81.696020694	1277.2133187

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	458.3907939	16.39876154	27.95276904	426.054702	490.7268858
b	769.7966835	40.16397175	19.16634859	690.5988808	848.9944862
c	25199.73742	2018.683147	12.48325546	21219.17318	29180.30166



Jul 5,1994 11:37 AM

196 Active X-Y Points
X: S-Disp Mean: 0.2078061224 SD: 0.2121040702
Y: S-Load Mean: 513.5 SD: 280.63832916
File Source: SXAAF2A.PRN

Rank 1 Eqn 8001 y=foschi [UDF#1]

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9057392317	0.9042664072	86.606626989	927.25571285

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	465.2828904	16.76716271	27.74964962	432.2099953	498.3557855
b	704.87577	44.03958879	16.00550299	618.0085567	791.7429834
c	32039.26572	2793.811993	11.46793908	26528.52711	37550.00434

SORT CRITERIA

There are four options that can be used to sort the fitted equations. These four statistics are also described in Appendix E.

Coef of det r^2

Coefficient of determination, r^2,

$$r^2 = 1-(SSE/SSM)$$

where, SSE = Sum of Squares due to error and SSM = Sum of Squares about mean.

Dof adjusted r^2

This is a coefficient of determination that has been adjusted for degrees of freedom. The standard r^2 sort criteria, but will better represent a true least squares sort criteria. As with the unadjusted r^2, the closer the value to 1.0, the better will be this statistical measure of the fit. It is recommended that either this method or the fit standard error be used for approximating functions.

fit std Error

This sort criterion is the actual least squares error of fit. It is known as the Fit Standard Error or Root MSE. The closer this value is to zero, the better the least-squares fit will be. The disadvantage of this criteria is that the values will not be normalized and as such cannot be used to compare the fit of dissimilar data sets. The Fit Standard Error will be directly related to the number of data points and is sensitive to any shift in the X-Y data. If only a single data set is under consideration, the **fit std Error** option is the fastest of all sort options, and again is wholeheartedly recommended for approximating functions.

F-statistic

The F-statistic is a measure of the extent to which the given equation represents the data. If an additional parameter makes a statistically significant contribution to a model, the F-statistic increases. Otherwise, a decrease occurs. The higher the F-statistic, the more efficiently a given equation models the data.

NOTE: This material was taken from TableCurve (Curve Fitting Software)™, User's Manual.

For this study the statistic **Adj r^2** was used as sort criteria.

VITA

(December, 1994)

The author was born in Uruapan, Michoacan, Mexico, on June 18, 1956. He receive a Bachelor degree in Wood Technology from Universidad Michoacana de San Nicolas de Hidalgo in June, 1977. His undergraduate education was conducted in the Escuela de Ingenieros en Technologia de la Madera. Upon receiving his undergraduate degree, the author has been working for a number of companies in forestland harvesting and logging, sawmilling, quality control supervising of logging, sawmilling, and chip production, and finally, as a General manager of a hardwood and softwood operation in the North and Center part of Mexico. The author returned to VPI&SU in August, 1992 to obtain a graduate education in the Department of Wood Science and Forest Products, with emphasis in the area of wood engineering.