AN ABSTRACT OF THE THESIS OF

Jesse L. Neese for the degree of Master of Science in Forest Products presented on June 17, 1997. Title: Characterizing Veneer Roughness and Glue-bond Performance in Douglas-fir Plywood

Abstract approved:
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James E. Reeb

A changing raw material supply and smaller, generally lower quality peeler logs, are causing surface characteristics in veneer that can adversely affect glue-bond performance. When lower quality logs are peeled, rougher veneer is usually produced. The typical response by plywood manufacturers is to increase adhesive spread when using rough veneer. The effectiveness of increasing adhesive spread rates has not been quantified. To do so, a method to quantify roughness is needed so that it can be correlated with percent wood failure, the standard for defining glue-bond quality. The objectives of this research were to define the relationships between seven traditional 2-dimensional measures of surface roughness and glue-bond performance in order to determine if a measure or combination of measures could be used to develop a glue-bond performance prediction model.

Rotary peeled, 1/8 inch thick Douglas-fir veneer was visually categorized as being smooth, intermediate, or rough. Samples on each sheet were selected at random and their locations tracked throughout the study. The surface roughness of each sample was

measured on the tight and loose sides using a modified laser scatter/optical imaging system. The scanning data were used to calculate seven roughness measures. Three-ply plywood panels were manufactured using the measured samples as core material and smooth veneer as face and back plys. Each panel was cut into standard shear specimens according to U. S. Product Standard 1-95. The test area for each shear specimen was the measured sample selected prior to panel assembly. The shear specimens were tested and evaluated for load at failure and percent wood failure. Each of the roughness measures and visual categories were compared to load at failure and percent wood failure data. Each shear specimen was also examined to determine the nature of the failure and with the failure being categorized into one of seven types.

Analysis of variance and multiple linear regression tests indicated no statistically significant relationship between any of the seven roughness measures or combination of measures and load at failure or percent wood failure. There was also no significant difference in roughness between the tight and loose side of the veneer, except for the skewness, kurtosis, and 3rd highest peak measures. Analysis of the visual categories showed there was strong evidence that an increase in surface roughness was associated with a decrease in load at failure and percent wood failure. This indicates that a 3-dimensional measure of surface roughness may be more effective for modeling glue-bond performance. Analysis of the nature of failure data indicated that the samples tended to fail on the loose side of the veneer. This trend was noted across all roughness categories. It is believed that this may be associated with lathe check depth and that an interaction between lathe check depth and veneer roughness may determine glue-bond performance.

Characterizing Veneer Roughness and Glue-bond Performance in Douglas-fir Plywood

by

Jesse. L. Neese

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 17, 1997
Commencement June 1998

Master of Science thesis of Jesse L. Neese presented on June 17, 1997

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Jesse L. Neese, Author

ACKNOWLEDGMENT

First of all, I would like to express my deepest gratitude to my major professor, Dr. James E. Reeb, whose continuous guidance, support, understanding, and most of all, patience during my graduate studies has been invaluable.

I would like to extend my earnest thanks to Dr. James W. Funck and Dr. Philip Humphrey in the Department of Forest Products, for giving me the much needed guidance to complete this project. Without their advice and support, the completion of this thesis would have been impossible.

My sincere thanks is also extended to Dr. Tom McLain, head of the Department of Forest Products, for providing me financial assistance to support my graduate studies. Appreciation is also extended to the many professors and fellow students who gave me valuable advice and assistance.

A special thanks is extended to APA-The Engineered Wood Products Association, Georgia-Pacific, Borden Resins, Willamette Industries, Lane Plywood, and Boise Cascade. Their contribution of materials, lab use, and personnel time were vital to the success of this project.

I thank Richard K. Bower of Georgia-Pacific Resins, Dr. Willam Detlefsen and Ron Hein of Borden Resins, and Jerry Byrd of APA-the Engineered Wood Products Association for their assistance and expert advice.

Most importantly, I dedicate this work to my loving wife Michelle Hooper who always said "You can do it! You can do it! You can! You can!" I thank her for being such a steady and special part of my life. Without her love and support, none of this would have mattered.

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1. INTRODUCTION

Structural grade softwood plywood has been widely used, as construction material in sheathing and decking applications, for decades. However, rising raw material costs (wood and adhesives), decreased wood supply, and the increasing popularity of substitute construction materials like oriented strand board have forced the plywood industry to search for ways to produce more efficiently. Lowering raw material consumption, reducing in-house waste, and increasing energy efficiency, while maintaining structural integrity, are among ongoing industry objectives.

To achieve these objectives, it has become increasingly necessary for plywood manufacturers to gain a more complete understanding of the interactions between plywood manufacturing variables and how manipulation of each affects production of structurally sound panels. Previous work has been conducted relating plywood manufacturing variables to variations in individual process and material parameters (21, 22, 24, 58, 67).

An approach, known as robust design, has gained wide acceptance among manufacturers in various industries (11). Robust design studies focus on quantifying effects of individual process and material variables that affect product quality. This enables researchers and manufacturers to evaluate effects of manipulating manufacturing variables relative to other processing and material variables. Studying one variable at a time allows manufacturers to determine the variable(s) that should be manipulated under specific circumstances to achieve target results. It also provides a basis for determining the degree of process variable manipulation necessary to achieve desired results without over-correcting that could lead to additional problems. This methodology can be used to study the effect of veneer roughness on glue-bond quality. By quantifying veneer roughness as an individual material variable, the robustness of the system as a whole can be better defined. This information is important in determining the allowable variations in other material and processing parameters when various degrees of rough veneer are encountered.

1.1 Objectives of the Study

This study was designed to:

1. determine if traditional 2-dimensional measures for characterizing surface roughness can be used to predict percent wood failure and/or load at failure in Douglas-fir plywood shear tests.

2. determine the surface roughness measure(s) that best predict percent wood failure in Douglas-fir plywood shear tests

3. determine the surface roughness measure(s) that best predict load at failure in Douglas-fir plywood shear tests

4. quantify the effect of veneer surface roughness on percent wood failure and load at failure in Douglas-fir plywood shear tests.

1.2 Veneer Surface Roughness

A common problem faced by plywood manufacturers is panel delamination. A major cause of poor quality glue-bonds is rough veneer (7, 19). A typical response by manufacturers is to increase the adhesive spread rate when rough veneer is encountered (7). Although this appears to be somewhat effective, the increased adhesive consumption is costly, and the benefits of increasing glue spread are not clear. It has yet to be established exactly how much, and under what conditions, an increase is necessary.

Eliminating veneer roughness would be the optimal solution to the problem. The quality of veneer has increased due to improvements in lathe technology and research to determine optimum lathe setup and peeler log conditioning (20, 23). However, due to the decline in the quality of raw material supply, manufacturers are now required to use smaller diameter logs that have a higher occurrence of knots, more taper, and greater sweep. Veneer produced from low quality peeler logs is inherently rougher than those produced from larger diameter, more symmetrical logs (12, 20, 40). Plywood manufacturers need to better understand how rough veneer affects other manufacturing parameters such as glue-bond quality.

Currently, 20 to 70 percent of the veneer produced in a typical plywood mill can be classified as rough (7). When producing rough veneer, Douglas-fir plywood manufacturers typically increase adhesive spread rates by approximately 10% or 3 to 5 lb./1000 square feet (MSF) of single glue-line (7). Current market prices for phenol-formaldehyde adhesives are approximately $9.00/MSF of panel production (3/8" basis) (7). A 10% increase in adhesive consumption equates to adhesive costs of approximately $9.90/MSF. Table 1.1 illustrates the increase in costs associated with an increase in adhesive spread.

Table 1.1. Estimated adhesive cost increases for various percentages of rough veneer production for a typical 350MMSF/year (3/8" basis) Douglas-fir plywood mill.

Percent Rough Veneer	Equivalent Panel Production (3/8" basis) (SQFT)	Adhesive Cost for 350MMSF @ $9.00/MSF	10% Increase in Adhesive Cost to $9.90/MSF	Total Adhesive Cost when rough veneer is used
20	70,000,000	$3,150,000	**$63,000***	$3,213,000
30	105,000,000	$3,150,000	**$94,500**	$3,244,500
40	140,000,000	$3,150,000	**$126,000**	$3,276,000
50	175,000,000	$3,150,000	**$157,500**	$3,307,500
60	210,000,000	$3,150,000	**$189,000**	$3,339,000
70	245,000,000	$3,150,000	**$220,500**	$3,370,500

***Note: Increased adhesive cost will vary with actual production, type of adhesive used, resin solids content, spread rate, and application system.**

Based on a typical annual production of 350 million square feet (3/8" basis), increased adhesive costs can range from $63,000 to $220,500 per year. However, since the relationship between veneer roughness and glue-bond quality has not been quantified, it is not known if increasing glue spread is effective.

Research on evaluating and measuring surface roughness as a material property has been documented for materials in the metals, aeronautics, optics, automotive engineering, pavement science, and wood products industries (4, 34, 65, 66, 70, 71). Surface roughness measurement of veneer has been used to determine the adhesive spread rate for varying degrees of surface roughness (19, 20, 21, 22, 23, 53, 61). When measured with real-time, on-line scanning technology, surface roughness evaluation can be used as an effective tool for process and quality control. If a relationship between veneer roughness measures and glue-bond performance can be established, roughness measurements can be used to better regulate the adhesive spread rate within and between sheets of veneer (19, 20, 21, 22). Manipulation of adhesive spread rate within and between sheets of veneer has the potential to lower total adhesive costs by five percent or more depending on the amount of rough veneer produced. Assuming that an increased spread rate is effective and can be controlled on-line, adhesive costs would decrease by as much as $170,000 in a typical 350 million square feet/year plywood mill. If increasing the adhesive spread rate is found to be ineffective, adhesive costs would decrease by as much as $220,000/year. These savings could range from $16,320,000 to $21,120,000 per year for the softwood plywood industry.

1.3 Overview of Plywood Manufacturing Methods

Many process variables may vary by mill depending on time of year, mill location, and mill specific methods for manufacturing plywood. Thus, the following discussion represents a brief overview of a typical process flow common to many softwood plywood mills.

1.3.1 Debarking, Sawing, and Preconditioning

Plywood production begins at the mill with the removal of bark from the logs. Automated debarkers are equipped with hydraulics and pressure bands that allow for variations in cutting pressure based on stem diameter and shape.

Debarked logs are transported to automated saw banks and cut into different lengths depending on log characteristics. Most saw banks in use today are equipped with infrared or laser sensors and microprocessors to optimize log breakdown. This optimization process maximizes volume recovery and minimizes waste. Logs are evaluated in this manner to yield the highest value products. From a single log, a portion may be processed for peeling into veneer, a portion sent to a stud mill for processing into lumber, and a portion may be sent to a chip mill for processing into chips for pulp and paper or fiberboard. Typically, the logs used for veneer production are cut 8 1/2 feet long and are referred to as peeler bolts or blocks.

Plywood peeler bolts are conditioned in a steam or hot water bath for eight to ten hours or until surface temperatures reach approximately 180°F. At this surface temperature, core temperatures will be between 100° to 120°F depending on log diameter

(2, 32, 58). This conditioning process softens the wood so lathe knife wear and damage is reduced. Conditioning results in smoother veneer by plasticizing the wood thus reducing vibrational forces that occur as a lathe's knife encounters annual growth rings and knots (12, 23).

1.3.2 Rotary Peeling

Most modern plywood facilities employ XY chargers. Laser scanners and micro-processors determine a bolt's geometric center and correctly position it in the lathe's spindles. Since no bolts are perfectly cylindrical due to tree taper and sweep, positioning at the geometric center minimizes veneer loss in round up, which is a process to make the tapered bolt cylindrical (2, 32).

Bolts are rotary peeled at speeds of 500 to 700 linear feet/minute into veneer that is typically 1/6, 1/8, or 1/10 inch thick. Cade and Choong (12) reported that lathe speed can influence veneer quality. In addition, lathe setup (i.e. nose bar pressure, knife angle, veneer target thickness) and knife sharpness can influence veneer quality (12, 23, 37, 41). The effects of lathe setup and knife condition are reflected by the surface characteristics of the veneer produced. Increases in knife angle, nose bar pressure, back-up roll pressure, or veneer thickness will cause vibrational forces that can cause deep lathe checks and rougher veneer (37). A decrease in knife sharpness can cause wood fibers to be torn rather than smoothly severed. This may also result in rougher veneer (33, 37, 40, 58).

1.3.3 Veneer Clipping

As a log is peeled, a continuous sheet of veneer, called a ribbon, travels on a high speed conveyor to an automated veneer clipper. The ribbon is clipped into 54 inch widths called full sheets or narrower pieces, known as random width veneers. Random width veneers occur because of ribbon defects such as fishtail, oversized knots and voids. Depending on the severity of defects and the desired end product, some defects are clipped from veneer. Defective veneers may be used as boiler fuel or chipped for particleboard or paper manufacturing.

1.3.4 Veneer Drying and Grading

Dryers reduce veneer moisture content by passing heated air over the veneer's surface. The target moisture content for softwood plywood is typically 3% to 5% (oven dry weight basis). Drying softwood veneer generally takes 8 to 12 minutes depending on dryer temperature, feed rate, veneer thickness, species, and whether it is heartwood or sapwood (2, 32, 58).

Due to the inherent variability in wood moisture content and in how wood moisture content changes, about 15% of the veneers in a typical plywood mill must be redried (2). Dry veneers (full and random width sheets) are graded and sorted according to U.S. Product Standard PS 1-95 specifications (64). Grading criteria include allowable knot and void sizes, coloration, and sometimes grain configuration (broken grain is not allowed in some grades) (64). The grade determines a veneer's location within a panel (face, core, back) and type of panel (interior or exterior) in which it may be used. Lower quality veneers are typically used in the core and higher quality veneers are used as faces and backs. As an example, "D-grade" veneer, made up of lower quality material, can only be used in interior grade panels.

1.3.5 Composing

Dried and graded random width veneers may be composed, that is, combined into a continuous ribbon that is reclipped into full sheets and usually used as core material. These composed sheets are occasionally used as face and back plys for interior grade panels.

Some full size and most composed sheets are cut into 4 foot X 4 foot half-sheets to be rotated 90° for use as core material. Rotating alternate plys in plywood manufacturing is referred to as cross-banding (Figure 1.1). Cross-banding results in a stiffer, more dimensionally stable panel (2, 32).

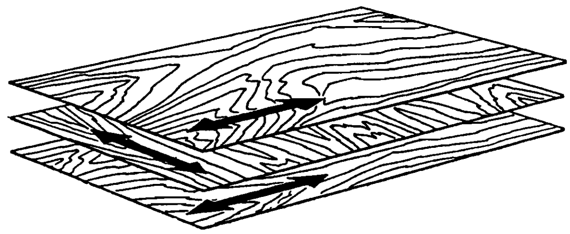

Figure 1.1. Cross-banded veneer used in plywood manufacturing (APA-The Engineered Wood Products Association).

1.3.6 Panel Layup

After drying, grading, and composing, veneers are glued together to produce plywood panels. Veneer travels on a conveyor where adhesive is applied by a sprayer, roller, or curtain coater. The most common adhesive for structural plywood is phenol-formaldehyde resin mixed with water, caustic, and fillers. Extenders such as wheat flour and walnut shell flour may be added to the glue mix. A common filler used in plywood adhesives is corn cob flour. The distinction between fillers and extenders is that extenders exhibit adhesive properties and interact in the bonding process whereas fillers serve only as a bulking agent to control adhesive viscosity. Since pure phenolic resins produce stronger bonds than necessary for plywood, addition of fillers and extenders decreases resin use, thus, reducing adhesive costs (32, 58). Fillers and extenders are used to control adhesive viscosity by absorbing water in the adhesive mix (43, 58). Controlling viscosity allows manufacturers to manipulate adhesive spread and pot life[1] to compensate for temperature, humidity, and veneer moisture content.

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[1] _Pot life refers to the time frame between adhesive mixing and panel lay up when the glue can still be used.

Veneer moisture content is an important factor affecting veneer gluability (2, 19, 58). If the veneer has too high or too low a moisture content, adhesives may not properly wet the wood. Wetting the wood refers to adhesive penetration into the wood. If the wood moisture content is too high (~ 8+% moisture content, oven-dry basis), the adhesive spread rate is too high, and the veneer temperature is too low, the wood may exhibit excessive absorption of the adhesive into the wood cells. If this occurs, the adhesive can "over penetrate" the surface of the wood causing a low strength bond. This condition is referred to as washout due to the washed out appearance of the glue-line. Conversely, if the veneer is at too low a moisture content (1-2% moisture content, oven-dry basis), the adhesive spread rate is too low, and the veneer temperature is too high, adhesive migration into the wood is restricted and can result in a poor bond. This condition is referred to as dryout (2, 19, 43, 58). Conditions for dryout usually occur during the summer months when high ambient temperatures and low ambient humidity are encountered. Poor adhesion caused by conditions of dryout and over penetration affect panel integrity.

After the adhesive is applied, panels stand for a specified time (length of time is dependent on ambient temperature, humidity, and adhesive mix) to allow the adhesive to wet the wood. This is referred to as open assembly time. A typical open assembly time is approximately 10 to 20 minutes. Pot life of most glues in use are designed to be robust against down time and are generally useful up to one hour after application

1.3.7 Pre-pressing and Hot-pressing

Glued veneers are cold pressed (pre-pressed) for about five minutes so they will stick together and not fall apart when handled. Pre-pressed panels are loaded into a steam- or oil-heated platen hot-press. Typical presses can hold 36-72 panels per load. Panels are hot-pressed for 3 to 5 minutes or longer at pressures of approximately 175-250 psi. and temperatures of 280° to 350°F. The thicker the panel, generally the longer the press cycle. Research has shown that interactions between hot-pressing variables (i.e. press time, temperature, and pressure) and material variables (i.e. adhesive mix, veneer moisture content, and veneer surface roughness) affect glue-bond quality in structural plywood (11, 13, 19, 27, 36, 58). Under any given set of conditions, each variable exhibits an effective range over which structurally sound panels can be made. If one or more of the variables are changed, this effective range for the remaining variables may also change (32, 58). For example, if two sets of panels are manufactured with veneers of two distinctly different moisture contents and all other variables remain constant, the bond quality may be very different between the sets of panels. To correct for the different moisture contents, some or all of the other variables may need adjustment or the sets of panels may need to be manufactured under different conditions.

1.3.8 Finishing and Shipment

Following hot-pressing, panels are stacked for at least a 2 hour post cure period (2, 58). Under normal conditions, this ensures complete adhesive cure. Panels are then reintroduced into the production line, trimmed to a typical final 4 foot by 8 foot dimension, sanded if specified by grade, and visually inspected for delamination and surface appearance. Finished panels are sorted and stacked by grade, banded, and prepared for shipment.

2. LITERATURE REVIEW

2.1 Surface Texture and Roughness Defined

2.1.1 Surface Texture

Surface texture and roughness are often used interchangeably. However, distinctions should be made between the two.

The American National Standards Institute (ANSI) defines surface texture as "the repetitive or random deviation from the nominal surface that forms the three-dimensional topography of the surface... including roughness, waviness, lay, and flaws (1)." It also distinguishes between surface texture and error of form defined as "deviation from the nominal surface which is not included in surface texture (1)." From these specific definitions, it should be noted that surface roughness is only one of several factors contributing to a surface's texture.

Stumbo (61) and Marian et.al. (42) defined surface texture as a topographical irregularity between a substance and its environment whether it be air or some other functional contact. Both went on to define surface texture as a complex composite of surface irregularities resulting from three general sources: (1) irregularities caused by anatomical structure; (2) irregularities resulting from manufacturing processes; and, (3) irregularities caused by variations within a specific manufacturing process. However, unlike ANSI, both Marian and Stumbo used the terms surface texture and surface roughness interchangeably.

Although knowledge of waviness, lay, flaws, and error of form is integral to a complete understanding of surface texture, the following discussion will focus on surface roughness only. Explanation of these additional factors contributing to surface texture will be addressed only as needed.

2.1.2 Surface Roughness

The science of evaluating and measuring surface roughness as a material property began prior to 1939 with independent work conducted by Schmaltz, Abbott, Schlesinger, and Nicolou (Germany, United States, England, and France respectively) (62). Although it originated in the metals industry, the study of surface roughness has expanded to aeronautics, automotive engineering, optics, pavement science, wood products, and many other industries (4, 34, 65, 66, 70, 71).

Exactly what is surface roughness? Depending on the material and end use, roughness can have entirely different meanings. What might be considered a "rough surface" and not acceptable in one application, might be considered quite smooth and acceptable in another.

Due to variations in functional performance requirements for different materials in different industries, parameters must be set by manufacturers to define what degree of roughness/smoothness is acceptable for specific materials in specific end use applications (45). For example, sheet metal manufacturers have established allowable tolerances for surface texture depending on a product's end use. However, to optical lens manufacturers, these parameters are completely unacceptable. Production of optical quality lenses requires much tighter tolerances in terms of acceptable surface roughness.

It has been reported that the smoothest surface occurring in nature is that of a liquid at rest which is smooth at the molecular level (14). However, in a technical sense, even liquids at rest are not truly smooth. If examined at the atomic level, variations in structure occur producing both asperities and valleys. Because of this, and due to functional performance requirements for various materials in different end uses, surface roughness has been regarded as a qualitative measure defined by material application.

Bryan et al. (10) defined roughness as "relatively finely spaced surface irregularities, the height, width, and direction of which establish the predominant surface pattern." ANSI (1) expands on this by adding that these irregularities result from the "inherent action of the production process" and "are considered to include traverse feed marks and other irregularities within the limits of the roughness sampling length." For this study, roughness is defined as the occurrence of three-dimensional peaks and valleys that make up a surface's profile.

2.2 Veneer Roughness: Its Causes and Effects on Panel Integrity

2.2.1 Causes of Veneer Roughness

Veneer roughness can be broken down into two types: anatomical roughness and roughness resulting from mechanical processing (23, 42, 61, 62). Following is a brief discussion of each.

Softwoods, typically utilized for structural plywood, are made up almost entirely of hollow, straw-like cells (tracheids) oriented longitudinally along the bolt (32, 52). The dimensions of these structures vary from species to species and also vary between individuals of the same species, as well as within an individual tree (32, 52).

As veneer is peeled, the lathe's knife severs the cells resulting in minute cavities and torn fibers at the veneer's surface (37). Subsequently, the degree of roughness caused by severing these structures depends on: (1) cell dimensions; and (2) cell orientation in relation to the lathe's knife (23, 39, 40, 58).

When viewing a cross-sectional cut of most softwoods, light and dark colored bands (earlywood and latewood respectively) are easily recognized (Figure 2.1). These annual rings are visible due to a change in cell wall thickness. Earlywood cells have thinner cell walls and larger cavities known as cell lumens; whereas, latewood cells have thicker cell walls and smaller lumens. If cut at the same angle, earlywood cells, because of larger lumens, will produce deeper depressions or cavities than latewood cells. Also, due to the difference in wall thickness, earlywood is more inclined than latewood to tear from the surface (33, 40, 58).

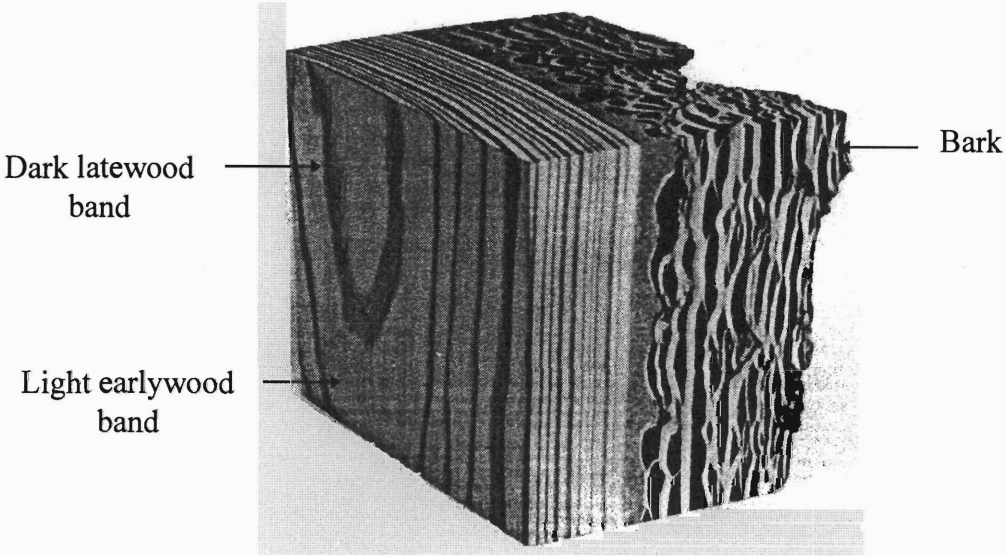

Figure 2.1. Douglas-fir block showing distinctive earlywood and latewood bands (52).

Cell orientation to the lathe's knife can also affect anatomical roughness. Most cells are oriented axially along the bolt and, thus, parallel to the knife's edge. However, if a tree grew in less than optimum conditions (e.g. on a steep slope), changes in its growth characteristics can alter the cell orientation. This can result in spiral grain, curly grain, interlocking grain, wild grain, or compression wood depending on the severity of growing conditions (32, 40, 52). Any alteration in cell orientation has an effect on the degree of anatomical roughness due to changes in how a cell is severed (40, 58). Instead of cutting the cell at a consistent angle parallel to the orientation of the cell, deep cavities and fuzzy grain may result from the lathe knife encountering the wood at an angle perpendicular to the cell orientation (40). This occurs when severing through knots and produces areas of local roughness whereas the remaining surface may be smooth.

Several natural factors affect mechanical processing and, in turn, affect surface roughness of veneer. These include tree growth rate, annual ring symmetry, and size and frequency of knots. Processing variables, such as log conditioning, knife sharpness, knife angle, lathe speed, feed rate, and veneer target thickness also affect veneer quality (30, 37, 39, 40, 42).

Inherent variations in wood density greatly influence veneer surface characteristics (25, 26, 35, 37, 40). Strong vibrational forces occur as the lathe knife encounters wood with varying densities. These vibrations cause a snapping action and rough veneer is produced (12, 20, 22, 23, 30, 37, 40, 42). Growth rate, ring symmetry, and the size and frequency of knots are anatomical characteristics of wood that influence the degree of macro roughness. A common property among these anatomical characteristics is that each represents a difference in material density. Depending on species, softwood latewood is twice as dense as earlywood (32, 52). Thus, ring symmetry, because of the variation in density of earlywood and latewood, represents an important component relating to veneer roughness. When eccentric or non-symmetrical growth rings are present, changes in material density are more erratic than if the growth rings were perfectly symmetrical from one end of the log to the other and from one side of the log to the other. When peeling a log with eccentric growth rings, the lathe knife may sever two sets of earlywood and latewood growth rings on one side and four or five sets of earlywood and latewood growth rings on the other side for each rotation.

A knot represents a change in density and cell orientation from the wood surrounding it. Knots are typically as dense or more dense than latewood and the cell orientation is perpendicular to the lathe knife. The result is that the lathe must sever alternately high density and low density material without the ability to adjust for these rapid changes. Manufacturers can minimize veneer roughness due to manufacturing by correctly conditioning peeler bolts, maintaining knife sharpness, and ensuring correct lathe setup (20, 22, 23, 30, 37, 40, 42).

2.2.2 Effects on Gluability

Effects of surface roughness on softwood gluability has been well researched (14, 21, 22, 24, 42, 43, 49, 58). Rough veneer is difficult to glue because: (1) of the lack of intimate contact between veneer surfaces; (2) rough veneer promotes conditions that can result in dryout; and, (3) rough veneer promotes conditions that can result in over penetration.

As veneer is peeled, peaks and valleys are created at the veneer's surface. When veneers are rotated 90° for cross-banding, the tips of these asperaties are all that touch. In relation to total surface area, this can be a small proportion (19, 32). Also, severed anatomical structures increase true surface area and decrease the relative proportion of area in intimate contact (Figure 2.2).

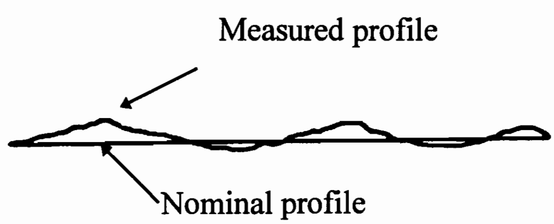

Figure 2.2. True vs. Nominal surface area for rough surfaces.

It is possible to apply enough pressure to bring nearly all surface area into intimate contact, however, veneers would have to be peeled thicker to compensate for compression losses. Thus, more wood would have to be used per plywood panel to meet specifications (20, 21, 22). A 1% increase in required veneer thickness results in additional wood cost of approximately $100,000 annually for a typical plywood mill based on a study conducted in the 1970's (28). At today's market prices, additional wood cost would be considerably higher.

Under conditions of dryout (e.g. high veneer temperature, low veneer moisture content, low adhesive spread), plywood adhesives will puddle in cracks and valleys of rough veneer. Less adhesive is available at the bonding surfaces (14, 20, 21, 22, 24, 30, 49). This results in a starved joint and reduced bond quality.

Rough veneer, in conjunction with conditions of overpenetration (e.g. low veneer temperature, high veneer moisture content, high adhesive spread) can promote problems when the adhesive is overly absorbed by the veneer. Rough veneer represents an increase in true surface area. As surface area increases, the proportion of glue decreases in relation to that surface area. The correct amount of adhesive for a smooth surface will fill the voids in the veneer (Figure 2.3).

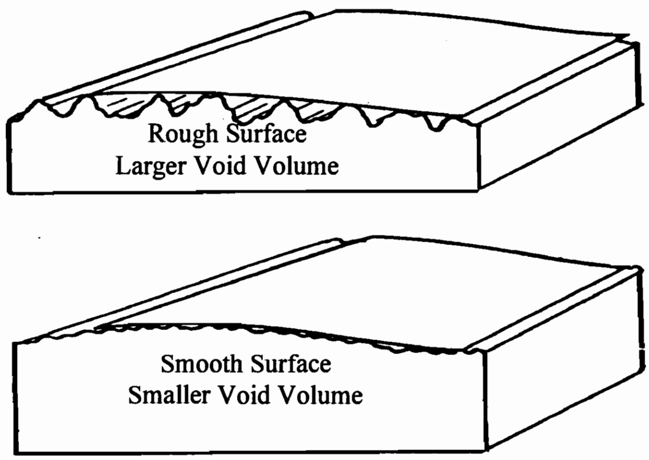

Figure 2.3. Relative void volumes for rough and smooth surfaces (1).

Because of the increase in the surface area of rough veneer, there is inadequate adhesive to fill the voids in the veneer. Adhesive migration into the veneer leaves little available for adhesion of the two surfaces. This may result in a starved joint and reduced bond quality (14, 20, 21, 22, 24, 30, 49).

2.3. Methods of Measuring Surface Roughness

Since the early development of surface measurement techniques, the challenge has been to develop a method to gain reliable, quantitative information about a surface's ability to fulfill some functional requirement (17, 45). Peters and Mergen (54) noted that "there are nearly as many different unrelated surface measuring methods used as there are authors." These methods include the use of visual and tactual evaluations, photomicrographs, ink prints, light transmission through photographic negatives, pneumatic devices based on air flow measurements, shadowing techniques, light reflectance techniques, scanning electron microscopes, stylus tracing, and numerous optical techniques (6, 9, 18, 20, 29, 31, 39, 49, 50, 51, 55, 56, 59, 71). Attempts have been made to apply these techniques to wood surface measurements, however, no method has been accepted as a standard for measuring wood surface characteristics. For research, the stylus tracing technique is the most often used method for taking surface measurements of wood. Data collected by the stylus technique is frequently used as a reference for testing new methods (19, 20, 28, 53, 59). The stylus technique is not a practical method of measuring veneer roughness in a plywood mill. It is apparent that the objective over the years has been to develop a method capable of yielding laboratory quality results at production speeds.

Any surface measurement technique must meet several criteria: (1) it should be relatively simple in design and operation; (2) it should be relatively inexpensive; (3) it should be capable of measuring minute surface characteristics such as anatomical features of wood; and, (4) it must yield meaningful information (54). In addition, the ideal measuring system would be non-contact, yield 3-dimensional (topographic) measurements, and be accurate and repeatable at production speeds (5, 20, 46). It should also be rugged enough to yield accurate data in different environmental conditions found in a typical plywood mill.

2.3.1 Visual and Tactual Techniques

Two of the earliest techniques for evaluating surface characteristics were visual and tactual methods (10, 50). Northcott and Walsher (50) devised a "veneer roughness scale." A series of ten veneer samples were visually categorized from smooth to rough. They used a scale, 0 smoothest to 9 roughest, to estimate values of veneer roughness by comparison. The system was designed so that a veneer was categorized in one of the 10 levels and its corresponding level was multiplied by 5 to estimate veneer roughness (50). However, these methods were qualitative and repeatability of results was not good. Average adults can visually detect variations in roughness as little as one micrometer under normal lighting. Tactile judgments alone are considerably more sensitive when compared to visual estimates made under normal lighting. However, only gross comparisons can be made regarding surface characteristics (49). The natural grain patterns present in most wood species adds to the difficulty of visually judging roughness (50). Schwaner (57) found that "a visual evaluation of surfaces was not accurate because luster, grain characteristics, and light source confused the appearance of the surface" (31). Brown (9) stated that the ability to make visual comparisons comes naturally and, in general, does not improve significantly with training.

Most industrial environments have inadequate lighting for making visual roughness estimations. Thus, roughness detection is based almost entirely on tactual information (9). However, if oblique lighting is used, faster comparisons can be made and visual techniques become nearly as precise as the tactual methods. Nevertheless, visual estimates are not reliable as a quantitative method for measuring surface characteristics (9, 10, 62).

2.3.2 Stylus Techniques

One of the most widely recognized and used techniques for measuring surface characteristics is stylus profilometry (10, 19, 20, 29, 53). This technique utilizes a small stylus, much like that of a phonograph, attached to a mechanical arm that moves up and down as the stylus is moved over a surface, or as the measured surface is moved under the stylus. This movement is used to generate information in the form of electronic signals through the use of transducers. Several types of transducers, direct displacement, capacitance, linear variable differential transformers, strain gages, and potentiometers, have been used (53). The output from this technique is a 2-dimensional profile of the traced surface. A variation of the traditional stylus tracing technique is the Forester Instrument, a profilometer that uses a stylus that oscillates vertically at a rate of 50 to 100 times per second (18). Although the mechanisms are different, the output is similar.

Important considerations for using the stylus technique are: stylus tip size, tip force, and tracing rate (18, 19, 20, 28, 44, 68). Stylus tip sizes generally range from 2.5 to 60 microns in diameter, depending on the surface characteristic of interest (18, 29). The smaller the features to be measured, the smaller the tip size must be. However, using a very small tip size to trace macro structures may result in too detailed information. Unwanted information can be removed through the use of passive filter networks prior to recording or by using a larger tip size (53). If the tip size is too large, much of the profile characteristics of interest may be smoothed out of the trace and not recorded. Thus, stylus tip size is based on the size of the structure being measured and the sensitivity required (4).

The amount of tip force is important when using this technique. As the trace is conducted, and the stylus follows the contour of the surface over peaks and valleys, a certain amount of force on the tip is required to prevent bouncing. If the stylus bounces, a distorted representation of the surface profile will be generated. Acceptable stylus tip force is dependent on the rate of scanning. A faster scan requires greater stylus force (18, 28).

It has been reported that the stylus technique can be destructive by leaving a groove in the traced surface due to using too much force to keep the tip from bouncing. If the stylus digs into the surface, this can result in a distorted profile (18, 19, 20, 53). Bennett and Dancy (4) reported that if an appropriately slow trace rate is used, and the system is isolated from external vibrations, there will be no grooves in the surface of most materials as a result of stylus tracing. The major factor is the trace rate that must be kept relatively slow (<2 inches/minute for wood). In maintaining a slow enough trace rate to prevent stylus bounce, it is impossible to measure surface roughness on-line in a plywood mill using the stylus technique. Thus, the stylus technique has been limited to laboratory use (19, 20). The ANSI standards do define tip size, force, and trace rate. However, most researchers did not use them on wood.

2.3.3 Optical Techniques

Over the last few years, several optical techniques have been developed for measuring surface roughness (29). Most of these methods have been developed to produce 2-dimensional profiles, but some produce 3-dimensional maps of the measured surface. None of the 3-dimensional techniques have been applied to wood surfaces (28). All optical techniques are based on theories regarding the behavior of light as it contacts a rough surface and the method employed to measure this behavior (47). As a highly collimated beam of light encounters a surface, a portion is reflected as a specular beam, a portion is scattered into an angular distribution, and a portion is absorbed. The angle of reflection and the extent of scattering are functions of roughness (5, 47, 48, 71).

Optical techniques based on specular reflectance theory can be classified as interferometry, speckle pattern analysis, reflected light intensity measurements, or, variations in the position of reflected specular beam (71). Optical techniques based on scatter theory are classified as Total Integrated Scattering (TIS), Angle-Resolved Scattering (ARS), or, Bi-directional Reflectance Distribution Function (BRDF) (5). Some optical systems developed for making profile measurements incorporate a combination of techniques. Faust (20) reported success using a modification of the straight-line shadow-sectioning technique described by Lutz (39) integrated with an image analysis system.

Lutz's method, originally a purely qualitative visual method, uses a highly collimated beam of light (in this case a projector) projected onto the surface at a high angle of incidence. When viewed from directly over the point of contact of the light and surface, shadows are cast and the light appears as a wavy line that corresponds to the surface profile (20, 39, 66). Using an image analysis system and a pixel count approach, an image of the wavy line was used to quantitatively measure veneer surface roughness. This technique was later coupled with a strobing system to get a "freeze-frame" image while moving the veneer at production speeds (20).

Funck et. al. (28) described a modified laser scatter/optical imaging system used to measure veneer surface roughness (Figure 2.4).

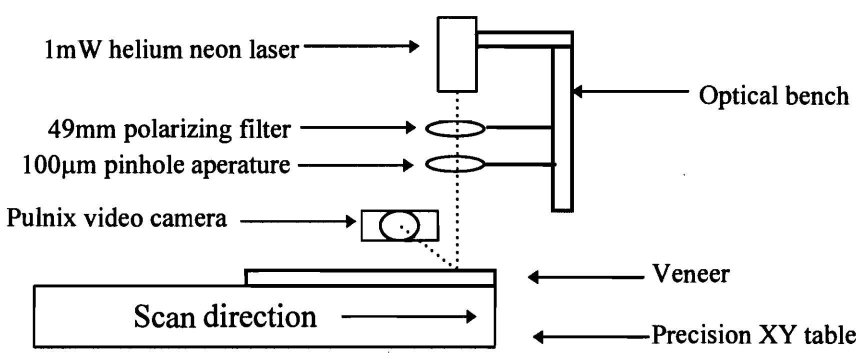

Figure 2.4. Simplified schematic of modified laser/scatter optical imaging system

This system utilizes reflectance, scatter, and imaging concepts as a basis for its operation. The system employes a 1.0mW helium neon laser mounted perpendicular to the veneer surface. The laser beam is passed through a polarizing filter and a pinhole aperture, thus producing a focused 3mm diameter laser dot on the surface. Scattered laser light reflected from the veneer surface is captured with an interline transfer CCD Pulnix Tm-7CN video camera equipped with a 55mm, f1:2.8 Micro-NIKKOR lens mounted at an angle of 19° to the sample surface. A microcomputer equipped with a framegrabber board and a high performance video display is used to digitize the signals from the video camera system. A gray-scale thresholding approach is used. A 200 pixel square window is placed around the laser-dot to improve processing speed.

This system measures displacement of the laser dot's centroid position by detecting the shape of the fringe around that centroid position. Setting a threshold value allows the scattered light to be measured as all white or all black depending on the light intensity. Thus, any change in centroid displacement becomes readily measurable using various imaging concepts. If the surface were perfectly smooth, there would be no change in scatter or centroid displacement. However, as the roughness of the surface changes, the shape of the laser dot changes proportionally to the displacement of the laser dot's centroid position. This displacement is measured as changes in pixels using the imaging components of the system. Funck et. al. (28) found that known displacement yielded nearly a perfect 1.0 relationship with corresponding changes in centroid displacement. Each pixel change represented a 0.0015 inch change in surface height.

The advantages shared by all optical systems is the relative speed at which measurements can be taken making them ideal for real-time, on-line measurements (29). The disadvantage of optical systems is the potential complexity of the system as a whole. One must consider the difficulty of attempting to integrate light sources, cameras or detectors, alignment systems, and data processors in a mill environment (20, 29). However, similar technology has been integrated into the mill environment. Scanners have been used to make high speed thickness, width, and other measurements (28). A major challenge for measuring surface roughness is that surface measurements are very sensitive to vibration encountered with in-line mill operations.

2.4 Mathematical Measures for Characterizing Veneer Roughness

There are many mathematical measures that can be used for characterizing surface roughness. Following is a brief description of some of the more common measures and the advantages and/or disadvantages associated with each. Depending on the standard, American National Standards Institute (ANSI), British Standards Institution (BSI), or Deutschee Institut fur Normung (DIN) (1, 8, 16), the formula for surface roughness measures may be slightly different (46). Mathematical formulas for the parameters used in this study are reported later. A more comprehensive discussion of parameters for characterizing surface roughness may be found in Sherrington and Smith's "Parameters for characterizing the surface topography of engineering components", and in the ANSI, BSI, and DIN standards (1, 8, 16, 60).

Full characterization of surface roughness requires three-dimensional measurements that evaluate the height, width, and length of asperities or the depth, width, and length of depressions that occur along a surface profile (30, 46, 60, 63, 69). However, most of the measures traditionally used to evaluate surface roughness are two-dimensional. Thus, a combination of measures must be used to completely define surface roughness (60, 63). The combination of mathematical measures varies depending on what aspects of topography are being studied (63).

The mathematical measures used to quantify surface roughness can be categorized into three general types: those based on amplitude (height or depth) of asperities, those based on the frequency of asperities (spatial or wavelength characteristics), and hybrid measures that evaluate both amplitude and spatial characteristics of a two-dimensional profile (15, 20, 23, 46, 60, 63, 65). Profile amplitude is the variation of the profile height along the y-axis perpendicular to the surface plane (23). Frequency is a measure of the number of variations within the surface plane along the scan line (x-axis) (Figure 2.5) (23).

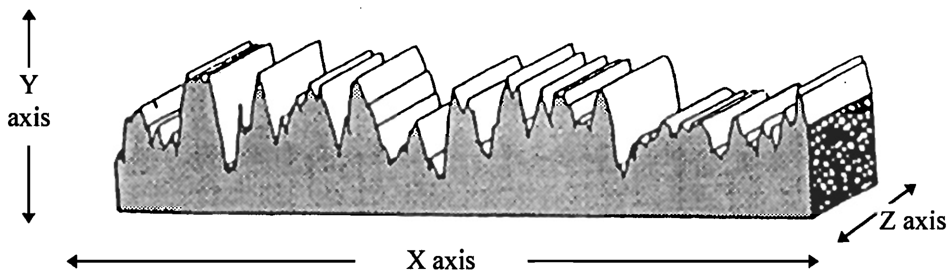

Figure 2.5. Three-dimensional surface showing the x, y, and z axes (46).

2.4.1 Measures that Characterize Profile Amplitude

Many of the parameters characterizing surface roughness are based on measured amplitude at points along a profile length. The most widely used amplitude sensitive measure, average roughness (R_a), is defined as the absolute deviation of a profile height from its mean line (45, 60, 65). It has also been defined as "a mathematical measurement of the variances of the profile from a center line that is parallel to the general direction of the profile with the areas above and below equal (61)." Average roughness, is also referred to as arithmetic average (AA) and center-line average (CLA) (60).

Weaknesses of R_a include its sensitivity to recording error (38) and its inability to distinguish between profiles with significantly different frequency characteristics (38, 60, 69). Since R_a is strictly an amplitude derived measure, a surface with a few deep valleys may have the same R_a value as one with many shallower valleys. Although the measured value for R_a is the same, the two surfaces may perform very differently (60). Despite these criticisms, R_a is perhaps the most widely used measure of roughness for quality and process control because it is easy to calculate (46).

Another amplitude sensitive measure used to characterize surface roughness is root mean square roughness (R_q). Root mean square roughness is defined as one standard deviation of the profile height distribution and is more representative of the variation within a profile than R_a (60, 65). If the measured surface has a profile with a Gaussian or even a nearly symmetric height distribution, the calculated value for R_q can be used to estimate R_a (60).

The main advantage of using R_q, as opposed to R_a, is that it responds to differences in profile shape with redistribution of surface characteristics from one side of the mean line to the other such as valleys to peaks or peaks to valleys (60, 65). When using R_q, the mean line can shift and the value for R_q will be adjusted to reflect the differences between the profiles. Whereas, the value for R_a will remain unchanged.

Several of the amplitude sensitive parameters are based on extreme values along a profile length. Some of these include: maximum amplitude values above and below the mean line know as R_p and R_v respectively, maximum peak-to-valley height (R_t), and the 10-point height (R_z) (46, 60). The value for 10-point height, the most commonly used extreme value parameter, is the average peak-to-valley distance between the average amplitude of the five highest peaks and the average amplitude of the five lowest valleys in the height distribution. Although commonly used, R_z ignores the spatial characteristics of the profile as do R_a and R_q (65).

Other parameters used to characterize surface roughness are based on moments of the amplitude distribution. Skewness (R_{sk}) and kurtosis (R_k) are the third and fourth moments respectively. Values for R_{sk} can be used to identify the dominant topographical features in a profile. Profiles that are symmetric and have an equal number of peaks and valleys exhibit an R_{sk} value of zero. Whereas, surface profiles dominated by peaks or valleys will exhibit either positive or negative skewness respectively (60, 65).

R_k reflects the shape of the peaks and valleys that make up a surface profile. For example, if R_k<3, the profile has relatively few narrow peaks or valleys. As R_k approaches a value of 3, the distribution becomes more Gaussian in appearance. And, as R_k increases above three, the peaks and valleys become less rounded and more pointed (60).

R_{sk} and R_k have been found to be especially useful when the material's surface characteristics are directly related to the functional requirements of the material (60, 65). However, these measures only emphasize height distribution and do not measure the frequency of peaks and valleys. Frequency is especially important when establishing the functional requirements for materials used in gluing applications because the frequency of peaks and valleys determines the degree of intimate contact that can be expected between gluing substrates.

2.4.2 Measures of Spatial Characteristics of Surface Profiles

The most common measures that reflect a surface profile's spatial or frequency characteristics are average wavelength (λ_a), root mean square wavelength (λ_q), and high spot count (HSC). Average wavelength characterizes the openness of a surface profile and usually correlates well with the surface's visual appearance. It is sensitive to surface characteristics such as feed marks formed during machining (60). Changes in the frequency of peaks and valleys dramatically affect the values for λ_a and λ_q while values for the amplitude sensitive measures may remain unchanged or adjust only slightly.

High spot count or frequency is determined by counting the number of peaks per unit length of profile above the mean line. HSC, λ_a and λ_q ignore the amplitude characteristics of surface profiles while emphasizing the spatial characteristics. Thus, changes in the height distribution that may alter the performance of a surface may not be identified using these spatial sensitive measures (54, 60, 63, 65).

2.4.3 Hybrid Measures That Characterize Amplitude and Frequency

A few parameters have been developed that reflect both amplitude and spatial characteristics of surface profiles. Some of these are average slope (Δa), root mean square slope (Δq), autocorrelation function (ACF), the Fast Fourier Transform (FFT), and the power spectral density (PSD) function (15, 46, 60, 65).

The value for Δa is obtained by dividing the profile into segments along its length and calculating the slope for each segment and averaging them to get a single value. Although this parameter is effective in detecting dominant features in profile geometry, it tends to smooth extreme values (45, 60). However, the same technique can be used to calculate Δq . The difference between Δa and Δq is that Δq is the root mean square of the average slope rather than the arithmetic average. Δq is more sensitive to extreme values (46).

Another hybrid parameter is the autocorrelation function (ACF): "a measure of the likeness between two similar but laterally shifted profiles (5, 28)." It is found by taking a profile, shifting it laterally, and dividing it into equal segments. Upon comparison of the segments, the ACF value within a profile length will be low if no two segments are identical. This indicates that the profile features are random or isotropic (5, 46). However, if the profile has periodic or anisotropic features, the ACF value will be high indicating the similarity between segments (5, 46). This information is helpful in determining the cause of roughness. Periodic features indicate process variation due to some identifiable cause. Random features indicate natural process variation.

If a Fast Fourier Transform (FFT) is calculated on the autocorrelation function, the power spectral density (PSD) function can be plotted (5, 28, 46). Mummery (46) defined FFT as " the method by which a series of sine waves, or harmonics, is generated that, when added together, make up the original profile." Since a surface profile is made up of a finite number of asperities exhibiting finite amplitude and spatial characteristics, this procedure can be used to separate it into its dominant components (5, 46). This type of analysis is helpful in determining the dominant characteristics based on both amplitude and frequency. It is important to note that the information represented by the ACF, FFT, and the PSD are identical yet presented in different forms.

3. METHODS

3.1 Initial Veneer Selection

Veneer used in this study was obtained from Willamette Industries' Dallas, Oregon, Plywood Complex and Lane Plywood's Eugene, Oregon, Complex. All veneer used in this study was 1/8 inch rotary peeled and dried Douglas-fir (*Pseudotsuga menziesii*). Veneer was selected from stacks of C-grade random width veneer and A-grade half sheets. Selected veneer was divided into three categories, smooth, intermediate, or rough based on overall visual characteristics. Roughness categories were defined so there is a clear visual distinction between the categories. Twenty-eight sheets were collected for each of the three roughness categories. In addition, 20 full sheets of smooth veneer were selected to serve as face plys in panel lay-up. A total of 94 sheets were collected for the study. All veneers were transported to Oregon State University's Forest Research Laboratory in Corvallis, Oregon, for further examination.

3.2 Sample Selection

U.S. Product Standard PS 1-95 definition for rough grain was used as a basis for determining visual categories (64). Each sheet was visually examined under well lit conditions to enhance surface characteristics. Errors of form such as broken grain were not included in the study. Selected samples met the surface roughness criteria established for this study. Smooth veneer was free of surface characteristics that would otherwise prevent the sample from being sanded smooth. Rough veneer exhibited substantial peaks and valleys that would prevent sanding to a smooth surface. Veneer of intermediate roughness exhibited surface characteristics common to both the rough and smooth categories but not dominated by either.

A rigid 12in. X 12in. aluminum template was placed over the selected area to identify 27 potential samples (Figure 3.1). Five 2 digit random numbers (01 to 27) were generated to select five 1in. X 1in. samples out of the 27 possible. This process was repeated once per sample sheet for twenty-eight sheets for each roughness category.

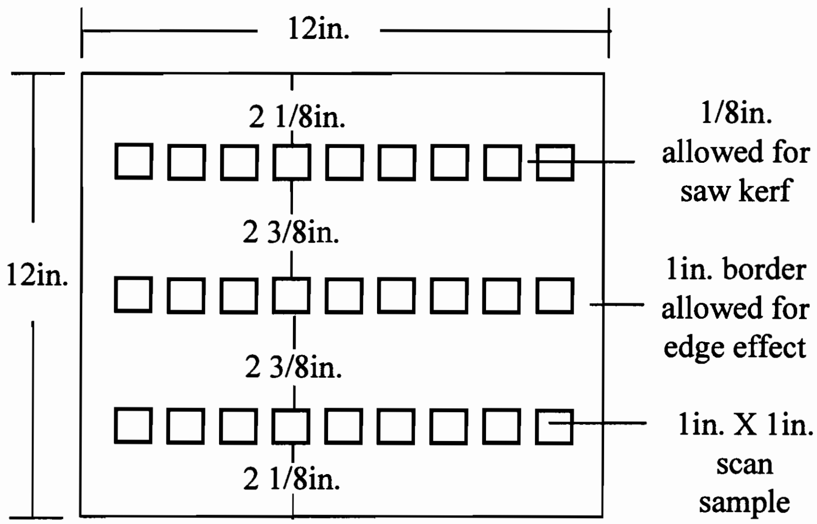

Figure 3.1. Template used for sample identification.

Selected samples were representative of the overall surface characteristics for that sheet. The area containing the twenty-seven potential 1in. X 1in. samples was cut from the full sheet. Twenty sample sheets were conditioned to ~8% moisture content (oven-dry basis) and eight were conditioned to ~2% moisture content and were used in separate panel assemblies. A total of 420 1in. X 1in. samples were selected for the study. Selected samples were identified by full sheet, grid location, roughness category, and tight (smoothest) or loose (roughest) side. For example, the tight side of a 1in. X 1in. sample from sheet 1 and grid position 23 exhibiting smooth surface characteristics would be labeled as follows: t1s-23. This labeling scheme was used for each sample throughout the study.

3.3 Scanning and Roughness Measurements

Each randomly selected 1in. X 1in. sample was scanned in the across-grain direction on the tight and loose sides of the veneer with a laser scatter/optical imaging system described by Funck et.al. (28). The system employed a 1.0mW helium neon laser mounted perpendicular to, and 37.5cm from, the veneer surface. The laser beam was passed through a 49mm polarizing filter and a 100 μm diameter pinhole aperture, thus producing a 3mm diameter laser dot on the veneer surface. An optical bench was used to ensure proper alignment of all components and a precision X-Y table was used to insure accurate, straight-line movement under the scanning system. Scanning was conducted at a rate of one inch per minute. Displacement lateral (DL) (distance between points along the scan line) and displacement parallel (DP) (distance between scan lines) was conducted at 0.03in. intervals. Thus, each 1in. X 1in. sample comprised 33 scan lines with 33 data points per scan line.

Scattered laser light reflected from the veneer surface was captured with an interline transfer CCD Pulnix Tm-7CN video camera equipped with a 55mm, f1:2.8 Micro-NIKKOR lens mounted at an angle of 19° to the sample surface. As determined by Funck et. al. (28), the gamma correction was set to 0.45 and the automatic gain control was enabled. A microcomputer equipped with a framegrabber board and a high performance video display was used to digitize the signals from the video camera system. A gray-scale thresholding approach with a threshold value of 160 was used for this study.

Rather than attempt to capture all scattered light from the sample surface, a 200 pixel square window was placed around the laser-dot to improve processing speed and offset potential limitations resulting from low camera angle and short focal distance.

Immediately following scanning, the samples were returned to the conditioning chamber to prevent excessive changes in moisture content, thus minimizing dimensional changes in sample surface characteristics resulting from shrinking or swelling.

3.4 Mathematical Roughness Characterization

The 2-dimensional measures used in this study are given as follows:

Center line average (CLA or R_a) (46)

$$R_a = \frac{1}{L_m} \int_0^{Ll_m} |y(x)| dx \qquad [1]$$

Where: L_m is the profile length and $y(x)$ is the departure of the profile from the mean line.

Root-mean square (RMS or R_q) (46)

$$R_q = \sqrt{\frac{1}{L_m} \int_0^{L_m} y^2(x) dx} \qquad 2]$$

Where: L_m is the profile length and $y(x)$ is the departure of the profile from the mean line.

Skewness (3)

$$R_{sk} = \frac{n^2 S_3 - 3nS_2 S_1 + 2S_1^{\ 3}}{n(n-1)(n-2)} \qquad [3]$$

Where: n is the number in the sample and $S_\Gamma = \Sigma_i \, x_i^{\ \Gamma}$

Kurtosis (3)

$$R_k = \frac{(n^3+n^2)S_4 - 4(n^2+n)S_3S_1 - 3(n^2-n)S_2{}^2 + 12nS_2S_1{}^2 - 6S_1{}^4}{n(n-1)(n-2)(n-3)} \quad [4]$$

Where: n is the number in the

sample and $S_\Gamma = \Sigma_i x_i^\Gamma$

Maximum peak-to-valley height is determined as the maximum peak height minus the maximum valley depth obtained from the normalized mean line. Third highest peak is the data point with the third highest amplitude from the normalized mean line. Third lowest valley is the data point with the third lowest amplitude from the normalized mean line.

3.5 Test Specimen Lay-up: Adhesive Application, Pressing, and Hot-stacking

Two sets of panels were laid up: twenty of each roughness category at Georgia-Pacific's (G-P) research and development laboratory in Albany, Oregon, and eight of each roughness category at Borden Resin's research and development laboratory in Springfield, Oregon. The two assemblies were similar, but will be discussed separately due to minor differences between them. Table 3.1 outlines the manufacturing variables and process for each assembly.

3.5.1 G-P Assembly

A phenol-formaldehyde adhesive, G-P 4890 (Table 3.2), was applied on two 12in. X 12in. sheets of smooth veneer using a portable roller glue spreader. Adhesive viscosity was measured at 4560 centipoise at 25.5°C prior to panel lay-up at the G-P facility.

Table 3.1. Overview of plywood manufacturing variables used in the G-P and Borden assemblies.

VARIABLE	G-P LAY-UP	BORDEN LAY-UP
Veneer MC % (OD basis)	8.37% +/- 0.20%	1.87 +/- 0.09%
Adhesive	G-P 4890 (Table 3.5.2)	G-P 4890 (Table 3.5.2)
Adhesive Viscosity @ 25°C	4560 cps	5780 cps
Application	portable roller spreader	portable roller spreader
Adhesive Spread Rate	29.8 lbs./Mbdft (+/- 2.38 lbs.)	27.69 lbs./Mbdft (+/- 1.30 lbs.)
Average Stand Time After Adhesive Application	10 minutes	10 minutes
Pre-press:		
Time	5 minutes	5 minutes
Pressure	125 psi.	125 psi.
Stand Time after Pre-press	10 minutes	10 minutes
Total Assembly Time	25 minutes	25 minutes
Hot-press:		
Time	3 minutes	3 1/2 minutes
Temperature	290°F	290°F
Pressure	175 psi.	175 psi.
Hot-stacking	24 hours in insulated box	24 hours at 90°F in conditioning room

Table 3.2. Phenolic adhesive mix formulation procedures for the G-P and Borden assemblies.

Ingredients and Proceedure	G-P Assembly		Borden Assembly	
	Mix 1	Mix 2	Mix 1	Mix 2
Water (g)	435.6	435.6	435.6	435.6
Modal (g)	83.4	83.4	83.4	83.4
Wheat Flour (g)	185.4	185.4	185.4	185.4
GP-4890 Resin (g)	500	400	450	500
50% NaOH (Caustic) (g)	63	63	63	63
Mix 10 minutes				
Soda Ash (g)	9.3	9.3	9.3	9.3
GP-4890 Resin (g)	723.4	823.4	773.4	723.4
ASC 5058 (g)	2.0	2.0	2.0	2.0
Mix 5 minutes				
Total mix Wt. (g)	2002.1	2002.1	2002.1	2002.1
Total Resin Wt. (g)	1223.4	1223.4	1223.4	1223.4
% Resin Solids	27.50	27.50	27.50	27.50
% Total Dry Solids	42.96	42.96	42.96	42.96
Initial Viscosity (cps)	1800 @26°C	7000@28°C	6900@26°C	4100@25°C
Viscosity after 1 day (cps)	1675@28°C	9400@25°C	5650@25°C	8555@25°C
Viscosity of combined mixes	4560@ 25.5°C		5780 @ 26°C	

A 12in. X 12in. sample sheet was positioned between two smooth face sheets. Both face veneers were oriented so that the tight side of each was bonded to the scanned veneer. This orientation yielded one glue-bond with tight/tight construction and one glue-bond with tight/loose construction. The panels averaged 10 minutes of stand time.

Each 3-ply test panel was pre-pressed for five minutes in a hydraulic press at 125 psi. and then hot-pressed for 3 minutes at 290°F and 175 psi. All panels were pressed to pressure, mimicking the press strategy typically used by industry, to reduce panel thickness loss during hot-pressing. Hot-pressing variables such as press time, press temperature, and press pressure were held constant for all test panels. Four panels were made in each of 15 press cycles, at the G-P facility, for a total of 60 panels, 20 3-ply panels for each roughness category. All test panels were stacked and weighted down in an insulated box to maintain pressure and temperature for a 24 hour post cure.

3.5.2 Borden Assembly

A phenol-formaldehyde adhesive, G-P 4890 (Table 3.2), was applied on two 12in. X 12in. sheets of smooth veneer using a portable roller glue spreader. Adhesive viscosity was measured at 5780 centipoise at 26°C prior to panel lay-up at the Borden facility.

A 12in. X 12in. sample sheet was positioned between two smooth face sheets. Unlike the G-P lay-up, each face veneer was touch sanded with an orbital sander using 100 grit sand paper and then cleaned with air prior to panel assembly to ensure uniform smoothness. Both face veneers were oriented so that the tight side of each was bonded to the scanned veneer. This orientation yielded one glue-bond with tight/tight construction and one glue-bond with tight/loose construction. The panels averaged 10 minutes stand time.

Each 3-ply test panel was pre-pressed for five minutes in a hydraulic press at 125 psi. and then hot-pressed for 3 1/2 minutes at 290°F and 175 psi. Three panels were made in each of eight press cycles for a total of 24 panels. All panels were pressed to pressure, mimicking the press strategy typically used by industry, to reduce panel thickness loss during hot-pressing. Hot-pressing variables such as press time, press temperature, and press pressure were held constant for all test panels. Eight 3-ply panels were made for each roughness category at the Borden facility. All test panels were stacked in a temperature and humidity controlled room at 90°C and 10% relative humidity for a 24 hour post cure period.

3.6 Bond Testing

Five randomly selected standard shear samples, were cut from each 12in. X 12in. 3-ply panel (Figure 3.2).

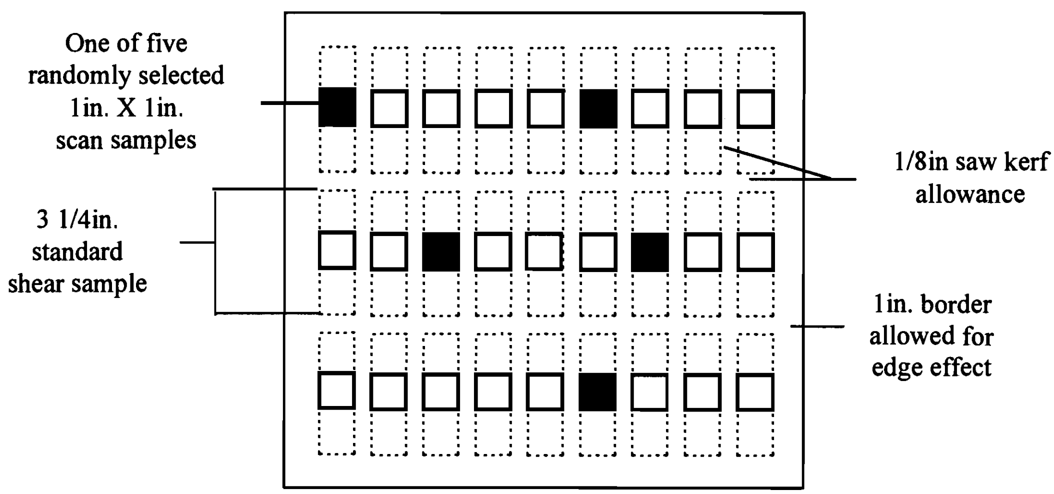

Figure 3.2. Schematic of test panel construction.

Each shear sample was prepared according to U.S. Product Standard PS 1-95 test 4.5.1 for exterior type panels bonded with exterior glue (Figure 3.3) (64).

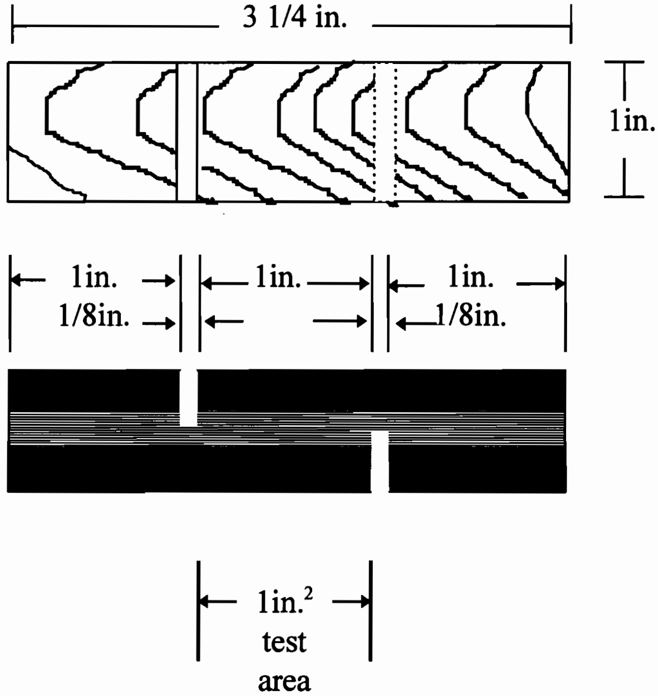

Figure 3.3. Shear test specimen.

The test samples were cut 3 1/4in. long and 1in. wide, and kerfed 1/3 of the length of the specimen from each end to provide a 1in.^{2} test area (64). Each sample was tested in shear using an Instrom testing machine equipped with grips and load cells designed for standard shear testing. After testing, each sample was sent to the APA-The Engineered Wood Products Association's laboratory in Eugene, Oregon, for analysis. All non-blow samples from the G-P assembly and all samples from the Borden assembly were evaluated by one inspector who had no prior knowledge of the study. All samples were mixed and no distinctions were made as to where the samples were assembled.

3.8 Relating Roughness Characterization to Bond Performance

The high moisture content samples obtained from the G-P lay-up were used to make generalizations about the effectiveness of increasing adhesive spread rates when rough veneer is encountered. Two-sample analysis of variance was used to test for differences in percent wood failure between the smooth, intermediate, and rough groups.

Mathematical parameters for characterizing surface roughness obtained from the modified laser scatter/optical imaging system were compared to glue-bond failure data from the Borden assembly to determine if 2-dimensional measures of roughness provided a good estimate of bond performance. Correlation analysis was used to determine the relationship between the roughness measures used for this study and load at failure and percent wood failure from standard shear testing. Simple linear regression, multiple regression analysis and analysis of variance (ANOVA) were used to test all roughness measures and interactions against load at failure and percent wood failure data to determine the measure or combination of measures that best predicted glue-bond performance.

Shear test data were compared to the original visual categories, smooth, intermediate, and rough to determine if there was a relationship between the visual roughness categories and percent wood failure and/or load at failure. Multiple regression analysis and ANOVA were used to determine if there was a significant difference among the true group means for load at failure and percent wood failure for each visual roughness category.

Each shear sample taken from the Borden and G-P assemblies was examined to determine if veneer orientation (tight/tight or tight/loose) had an effect on where the sample failed. The type of failure was categorized into one of seven groups (Figure 3.4): (1) face; (2) face/tight; (3) tight; (4) core; (5) loose; (6) back/loose; and, (7) back.

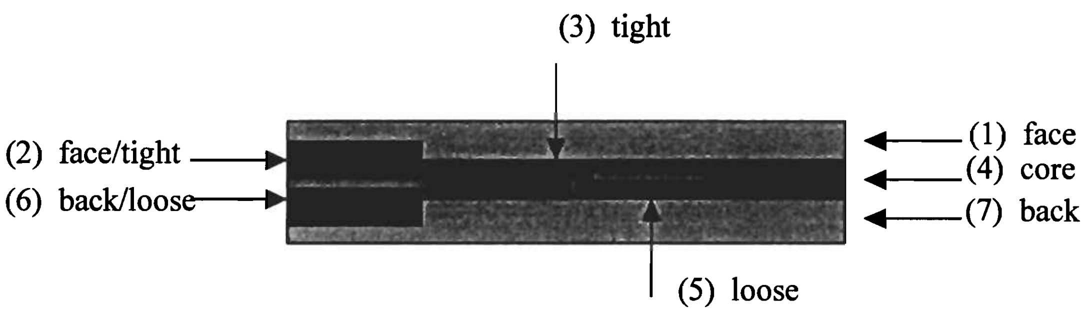

Figure 3.4. Failure zones for standard shear samples.

Frequency of failure was compared for the groups of samples to determine if there were any differences between the groups.

4. RESULTS AND DISCUSSION

4.1 G-P Assembly

High veneer moisture content (8.37% +/- 0.2%) and high adhesive spread (29.8 lb/Msqft SGL +/- 2.38 lbs), relative to the moisture content, resulted in a loss of samples caused by blows. During hot-pressing, it was noted that the hot-press lost and regained pressure cyclically, approximately once per minute. The pressure fluctuated from 175psi. to approximately 140psi. A 10°F temperature drop from the center to the edge of the hot-press plattens was also noted. The high glue spreads, pressure fluctuations, and temperature drop across the platens were not noted until after pressing had started. Because the panels were assembled at random, it was not known if the blows were a result of poor assembly conditions or a function of the roughness. Under these conditions, it was determined that the assembly should continue and be replicated if necessary rather than change interacting manufacturing variables mid assembly.

Samples exhibiting 0% wood failure were classified as blows. Fifty five smooth, 53 intermediate, and 77 rough samples were lost due to blows (Table 4.1)

Table 4.1. Number of samples lost due to panel blows for each roughness category during the G-P assembly.

Roughness Category	Samples Lost Due to Blows	Samples remaining for testing
Smooth	55	45
Intermediate	53	47
Rough	77	23

A possible reason for the high number of blows is the 3 minute press time for G-P assembly was too short for this gluing system. This, in combination with high veneer moisture content, a high glue spread, and the temperature and pressure fluctuations probably contributed to the high number of blows.

Due to the high occurrence of blows, no attempt was made to compare measured roughness values to the results of standard shear testing for any of the G-P assembly samples. However, using the visual classifications, smooth, intermediate, and rough, two-sample analysis was conducted to test for differences in group means for percent wood failure for the non-blow samples. Table 4.2 is a summary of the data obtained from the G-P assembly.

Table 4.2. Summary statistics for percent wood failure values from the G-P assembly.

Variable	Smooth	Intermediate	Rough
sample size	45	47	23
Average	78.4	68.72	55.95
Variance	724.8	728.77	664.05
Standard Deviation	26.92	26.99	25.77
Standard Error	4.01	3.94	5.63
Minimum	5	0	5
Maximum	100	100	100
Range	95	100	95
Coefficient of variation	34.32	39.28	46.05

There was a significant difference in the sample means between the smooth and rough groups (one-sided p-value 0.002 from a two sample analysis). However, there was no significant difference in sample means between the smooth and intermediate (one-sided p-value 0.07 from a two sample analysis) and the intermediate and rough groups (one-sided p-value 0.09 from a two sample analysis). Multifactor analysis of variance

(ANOVA) indicated there was significant statistical evidence that an increase in roughness is associated with a decrease in the expected value of percent wood failure for the G-P samples. This association was noted despite the poor assembly conditions and number of blows that resulted.

4.2 Borden Assembly

Table 4.3 is a summary of the data collected from the Borden assembly.

Table 4.3. Summary statistics for percent wood failure and load at failure values from the Borden assembly.

Variable	Smooth		Intermediate		Rough	
	Wood Failure (%)	Load at Failure (lb.)	Wood Failure (%)	Load at Failure (lb.)	Wood Failure (%)	Load at Failure (lb.)
Sample size	40	40	40	40	40	40
Average	96.5	209.4	87	204.6	88.4	175.3
Variance	59.23	478.86	325.39	3692.45	214.60	1993.44
Standard Deviation	7.70	21.89	18.04	60.77	14.65	44.65
Standard Error	1.21	3.46	2.85	9.61	2.32	7.06
Minimum	65	153	35	94	35	83
Maximum	100	257	100	365	100	306
Range	35	104	65	271	65	223
Coefficient of variation	7.98	10.45	20.73	29.70	16.58	25.47

Correlation analysis indicated there was statistical evidence of a relationship between percent wood failure and all tested roughness measures except for skewness, kurtosis, and 3rd lowest valley. Simple linear regression analysis indicated that the relationships were weak and of no practical significance (Table 4.4).

Table 4.4. Correlation coefficients, significance levels, and R-squared values from correlation analysis and simple linear regression analysis used to test each roughness measure against percent wood failure values.

Roughness Measure	Correlation Coefficient and Significance Level	R-squared values
CLA	-0.256 / 0.005	6.56%
RMS	-0.268 / 0.003	7.17%
Skewness	-0.074 / 0.421	0.55%
Kurtosis	-0.020 / 0.830	0.04%
Maximum P-V Height	-0.269 / 0.003	7.23%
3rd Highest Peak	-0.299 / 0.001	8.94%
3rd Lowest Valley	0.149 / 0.104	2.23%

Although correlation analysis and simple linear regression showed significant relationships, the low R-squared values indicate these relationships between the 2-dimensional measures and results of standard shear testing cannot be used to effectively predict percent wood failure and load at failure. The R-squared values indicate the amount of variability in the dependent variable accounted for by the explanatory variable, in this case the roughness measures. The low R-squared values indicate that very little of the within group variation was explained by these models.

Multiple regression and ANOVA indicated there was no significant evidence that the roughness measures in the full model are related to the expected values of load at failure and percent wood failure from standard shear testing. These tests support the results of the simple linear regression analysis.

Since the 2-dimensional measures did not effectively predict glue-bond performance, a 3-dimensional method was tested. Visual categorization, although qualitative, was used because it is fundamentally a 3-dimensional measure. Multiple regression analysis and ANOVA indicated there was a significant difference among group means for both load at failure and percent wood failure at different levels of visually classified roughness.

Means for load at failure for roughness groups 1, 2, and 3 (smooth, intermediate, and rough respectively) are illustrated in Figure 4.1. There was a significant difference in the mean load at failure between the smooth and rough (one-sided p-value 0.00004 from a two sample analysis), and intermediate and rough groups (one-sided p-value 0.016 from a two sample analysis), with no significant difference between smooth and intermediate groups (one-sided p-value 0.470 from a two sample analysis).

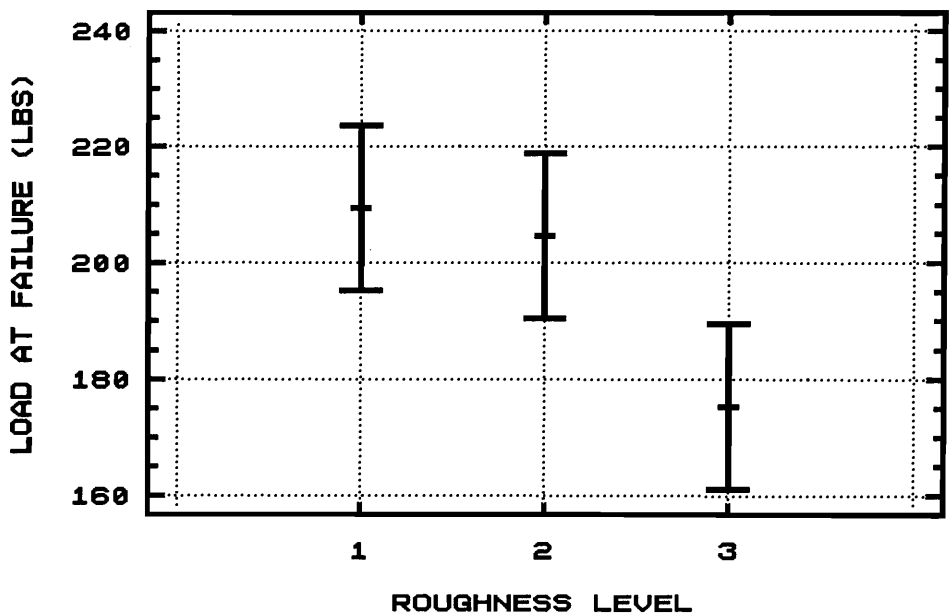

Figure 4.1. 95 percent confidence intervals for mean load at failure at three levels of roughness for the Borden samples.

Greater variation is evident in the intermediate group than in the smooth and rough groups (Figure 4.2).

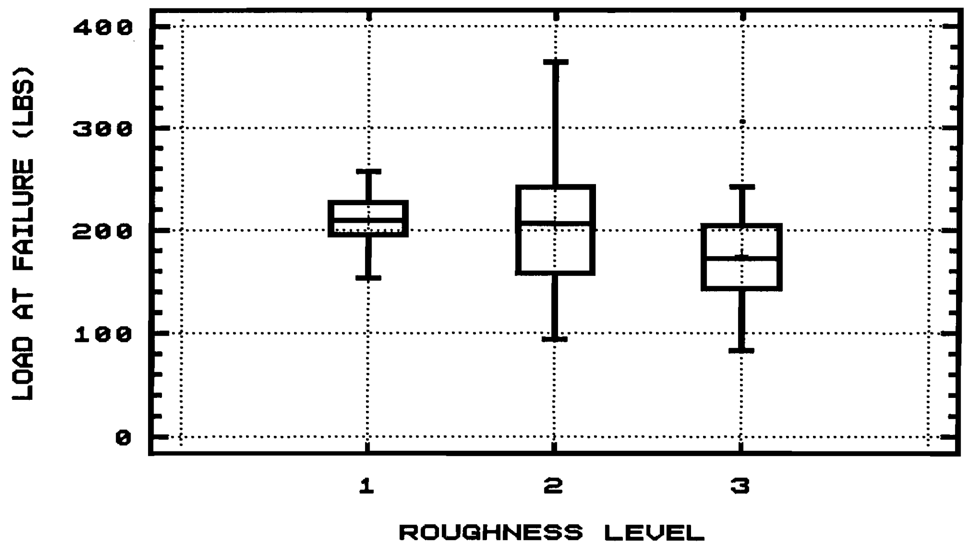

Figure 4.2. Multiple box plots for load at failure at three levels of roughness for the Borden samples.

The intermediate category exhibits both smooth and rough characteristics. This combination of characteristics may explain the greater variation in these samples. In this case, it appears that the smooth component of the intermediate samples tended to increase glue-bond performance leading to overall higher values for load at failure than that of the rough group. Thus, there was no significant difference in the mean load at failure between the smooth and intermediate groups. However, the rough component seemed to have enough influence on glue-bond performance to prevent the intermediate group from consistently reaching the level of load at failure of the smooth samples. This may explain the greater variation exhibited by the intermediate category.

Means for percent wood failure are illustrated in Figure 4.3.

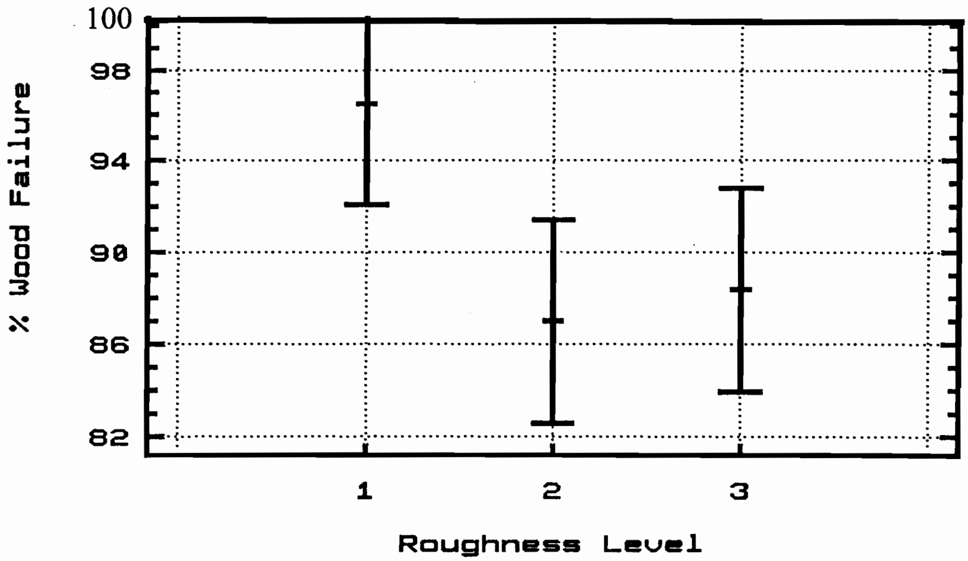

Figure 4.3. 95 Percent confidence intervals for mean percent wood failure at three levels of roughness for the Borden samples.

There was a significant difference in the mean percent wood failure between the smooth and intermediate (one-sided p-value 0.003 from a two sample analysis), and smooth and rough groups (one-sided p-value 0.002 from a two sample analysis), with no significant difference between the intermediate and rough groups (one-sided p-value 0.709 from a two sample analysis). When using percent wood failure as a glue-bond predictor, the results were opposite that noted in the load at failure data. This difference may be a factor of the intermediate group having a combination of roughness characteristics. Note the variation in the intermediate group as compared to the smooth and rough groups (Figure 4.4).

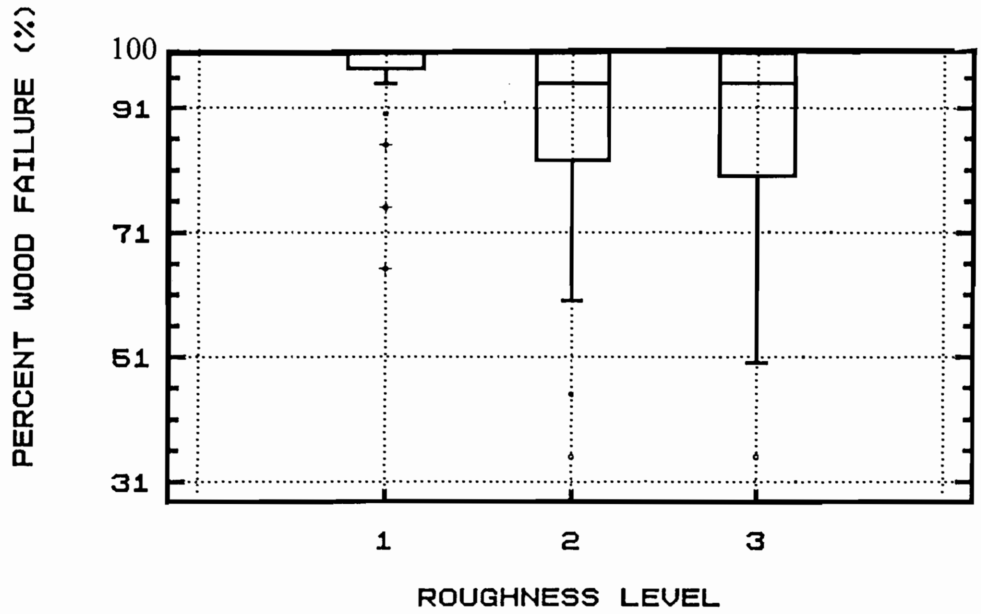

Figure 4.4. Multiple box plots for percent wood failure at three levels of roughness for the Borden samples.

When using percent wood failure as the glue-bond performance predictor, the intermediate group behaved more like the rough category. The rough component of the intermediate group may lead to overall lower values for percent wood failure while the smooth component may allow for higher loads at failure. Although the smooth component seemed to increase the load at failure, as roughness increased, larger gaps may have led to overall lower wood failure due to a reduction in intimate contact. This may be an indication that surface characteristics influence glue-bond performance directly. However, the relationship between roughness measures and glue-bond performance must be established before the degree of influence can be quantified.

There was no significant difference (two-sample analysis and ANOVA) in any of the roughness measures tested between the tight and loose sides of the veneer except for skewness and kurtosis. The skewness and kurtosis measures were able to differentiate between the tight and loose sides of the veneer.

The glue-bonds tended to fail along the loose side of the veneer for all roughness categories. Figures 4.5, 4.6, and 4.7, illustrate this trend. All categories combined, 71 of 120 samples tested failed in this manner (Figure 4.8). Since there was no evidence of a difference in the roughness between the tight and smooth sides of the veneer, this indicates that the mode of failure may be lathe checks typically found on the loose side of the veneer. G-P samples, when blows were removed, exhibited the same relationship as the Borden samples (Figure 4.9).

This trend occurred across all roughness categories indicating that lathe checks may be the initial zone of weakness and, interacting with the roughness categories, define the actual glue-bond performance. If very rough veneer is used, the lack of intimate contact, due to gaps between peaks, may lead to an overall lower percent wood failure. If deep lathe checks are present, the failure may occur at a lower load. It is not known whether rough veneer exhibits deeper lathe checks than smooth veneer and how interactions between lathe checks and roughness affects glue-bond performance. To make this determination, lathe check depth must be measured at different levels of roughness and considered as a material variable.

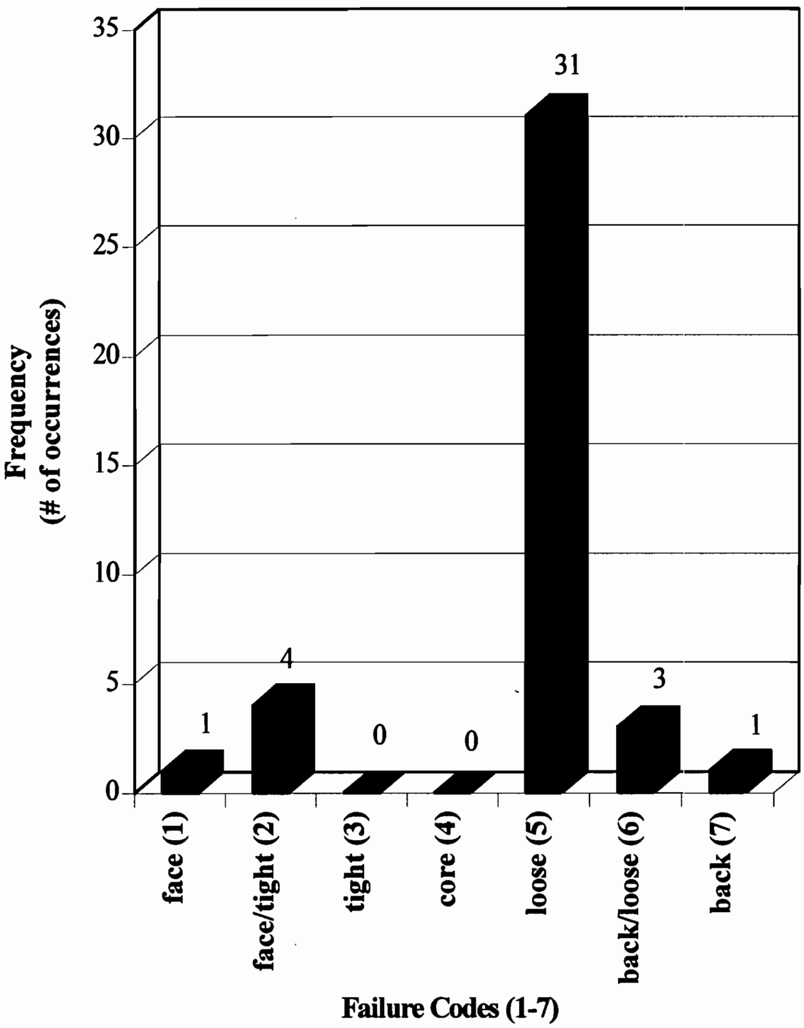

Figure 4.5. Glue-bond failure for smooth samples from the Borden assembly.

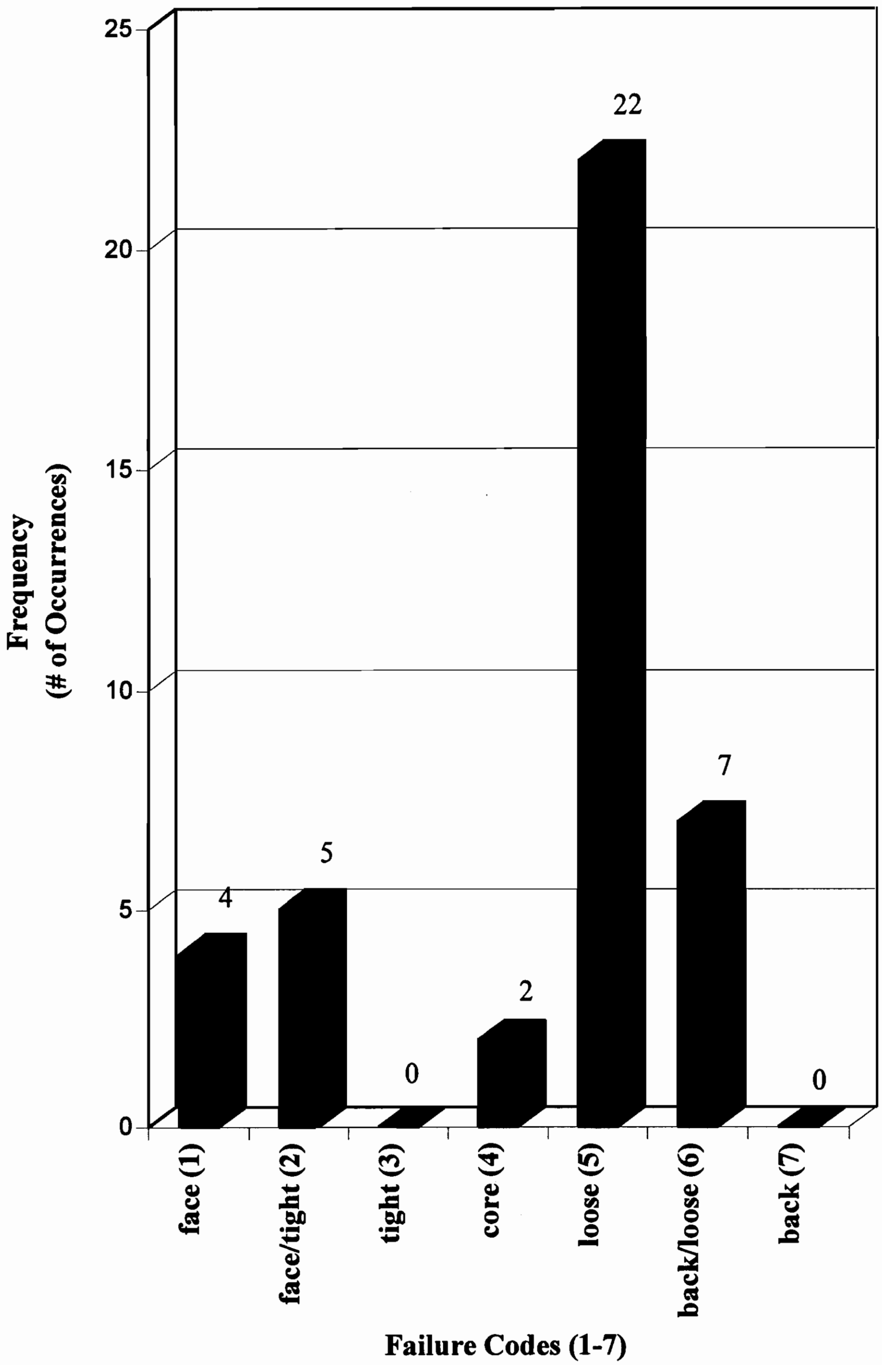

Figure 4.6. Glue-bond failure for intermediate samples from the Borden assembly.

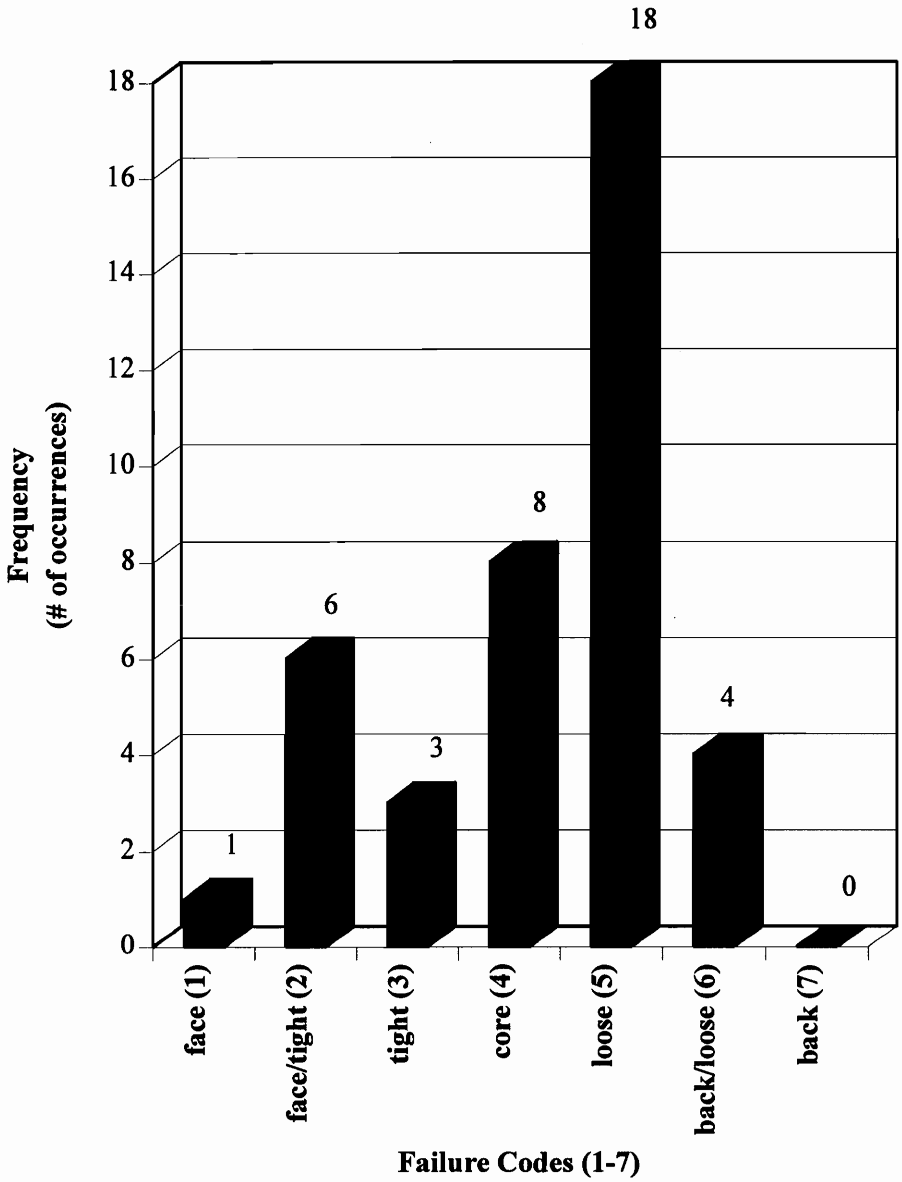

Figure 4.7. Glue-bond failure for rough samples from the Borden assembly.

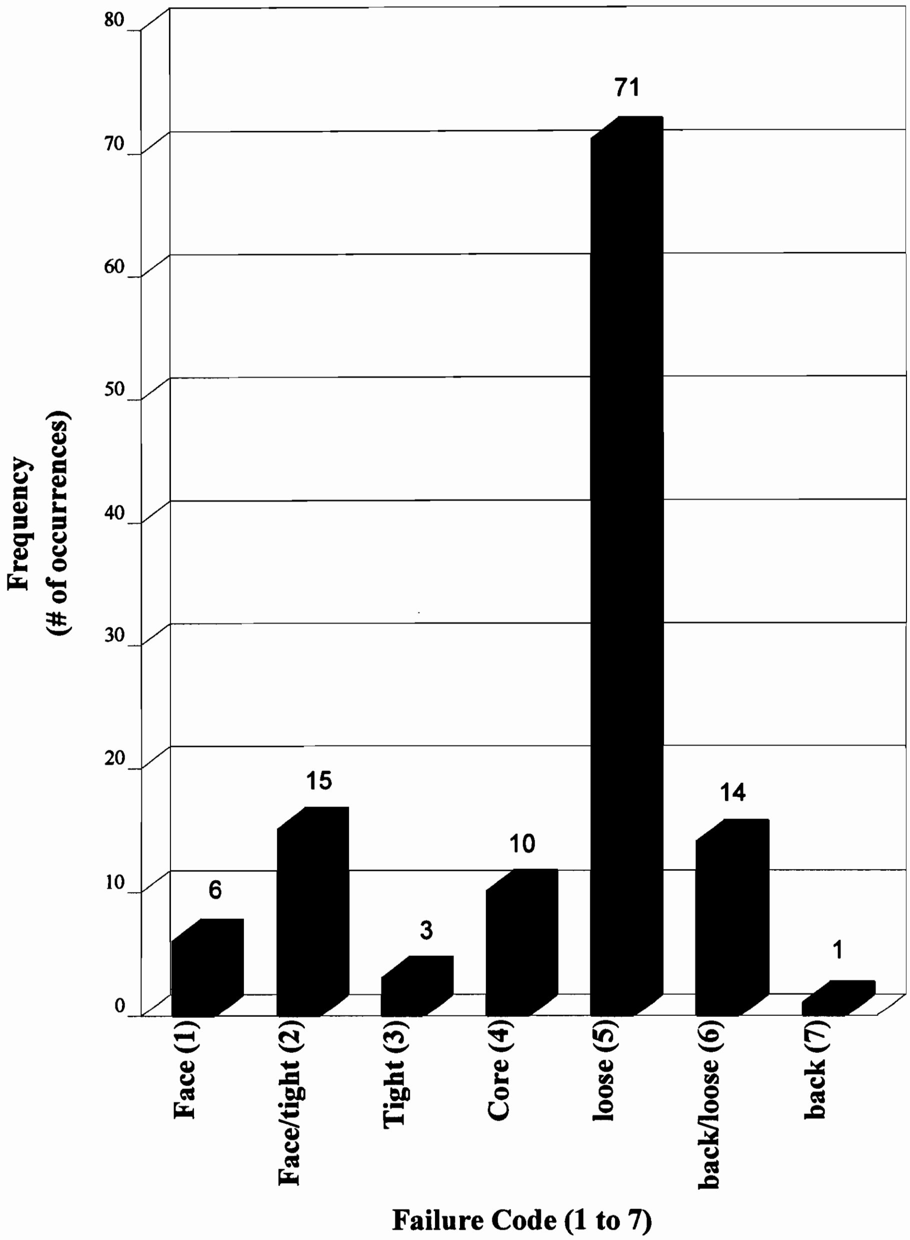

Figure 4.8. Glue-bond failure for all samples from the Borden assembly.

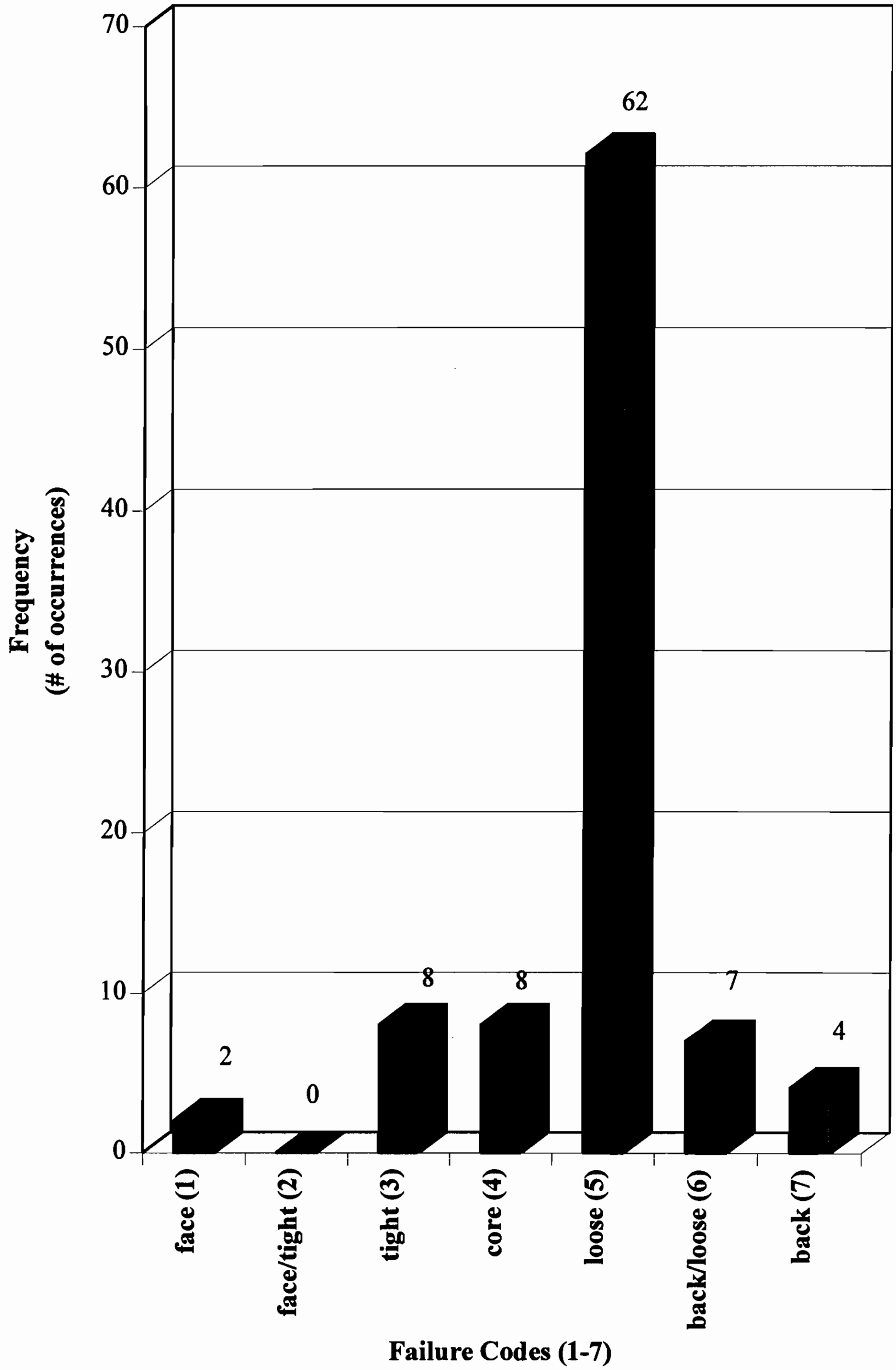

Figure 4.9. Glue-bond failure for smooth, intermediate, and rough samples from the G-P assembly with blows removed.

5. CONCLUSIONS AND RECOMMENDATIONS

This study examined how veneer roughness affects plywood panel glue-bonds. It was designed to determine if traditional two-dimensional measures of surface roughness can be used to predict glue-bond performance in Douglas-fir plywood. When rough veneer is used, plywood manufacturers typically increase glue-spread about 10%. It is believed that under some manufacturing conditions this may lead to problems associated with over penetration. The researcher had the opportunity to observe glue-bond performance under these conditions and more ideal laboratory conditions. Two sets of panels were assembled that reflect each of these scenarios.

The G-P assembly mimicked conditions of high moisture content veneer assembly using a high glue spread. Based on these results, increasing glue-spread when encountering rough veneer probably increased the number of panel blows and reduced overall glue-bond quality. High veneer moisture content, low ambient temperature, and high humidity probably promote over penetration of the glue into the wood fibers.

The effective range of manufacturing variables such as adhesive spread rate, press time and temperature, and assembly time may be narrower when rough veneer is used. Since an increase in veneer roughness may promote conditions of over penetration and dryout, effective ranges for other manufacturing variables need to be determined for various degrees of veneer roughness. It is recommended that veneer surface roughness be researched further to quantify the effects of veneer roughness with regard to manufacturing variables specifically associated with dryout and over penetration. Before this can be done, a glue-bond performance prediction model must be developed that can relate surface characteristics to a glue-bond performance descriptor whether it be percent wood failure or some other measure of glue-bond quality. After this initial step is accomplished, quantified levels of veneer roughness should be assembled under conditions known to cause problems with over penetration and dryout to determine if the degree of veneer roughness narrows the effective range of process parameters in adverse conditions that frequently occur in a mill environment. Information obtained from this type of research may allow for a more robust gluing system when these conditions occur.

The Borden assembly mimicked conditions often encountered in the plywood industry where veneer is typically dried to 2% to 5% moisture content. The results from this assembly indicate that veneer roughness influences glue-bond quality when that quality is measured using percent wood failure and load at failure.

The 2-dimensional measures tested in this study do not effectively predict glue-bond performance as measured by percent wood failure and load at failure from standard shear samples. It is not know whether this is due to an inadequacy of the measures at distinguishing between surface characteristics or an inadequacy of percent wood failure and load at failure as glue-bond performance descriptors. The occurrence of high wood failure and corresponding low load at failure indicates that using percent wood failure and/or load at failure for characterizing glue-bond quality may not be an effective method to define glue-bond quality and structural integrity of plywood. Plywood manufacturers use percent wood failure as a "pass/fail" descriptor of glue-bond quality.

If high percent wood failure indicates a good bond while load at failure indicates poor strength properties, values for percent wood failure may be misleading. However, if the load at failure is adequate for most practical plywood applications, this may not be an issue. In this case, it is recommended that other descriptors of glue-bond quality be examined for more direct use in the plywood industry.

If, using quantified veneer roughness, it is determined that increasing glue spread on rough veneer is ineffective, savings to the plywood industry would be considerable. If it is determined that increasing glue spread is effective, roughness measures could be used to optimize adhesive spread rates within and between sheets of veneer yielding an overall higher quality bond while reducing total adhesive consumption by as much as 5 percent. However, we must first be able to measure the roughness in such a way as to relate it to glue-bond quality before this determination can be made.

Based on visual analysis, 3-dimensional measures may be more effective for measuring surface characteristics to predict glue-bond performance. A technique for 3-dimensional surface evaluation needs to be developed for measuring wood surface characteristics.

Hybrid measures such as autocorrelation function, autocovariance function, power spectral density function, and cumulative power spectral density function may show more promise for glue-bond performance prediction than 2-dimensional measures alone. These hybrid measures reflect both amplitude and spatial characteristics and tend to characterize surface features more like 3-dimensional measures than traditional 2-dimensional measures. They may be effective for predicting glue-bond performance. These hybrid measures based on 2-dimensional profiles should be explored before testing more complicated 3-dimensional techniques.

This study indicates that, independent of conditions, bond failure occurs mostly on the loose side of the veneer. Lathe check depth may interact with surface roughness characteristics to determine glue-bond performance as measured by percent wood failure and load at failure from standard shear testing. It is possible that, when deep lathe checks and very rough characteristics are present, load at failure may decrease and gaps between surface peaks may decrease the percent wood failure due to lack of intimate contact. Conversely, when deep lathe checks are present in combination with smooth surface characteristics, the load at failure may be low while percent wood failure may be high. This also raises concerns regarding the effectiveness of percent wood failure as a glue-bond performance descriptor for use by industry. It is recommended that research be conducted to determine if an increase in lathe check depth is associated with an increase in surface roughness and if the combination of these factors can be used to better understand the dynamics of glue-bond performance.

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