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Comparison of the bending-moment resistance of wood-plate and dowel joints in particleboard and lodgepole pine lumber

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COMPARISON OF THE BENDING-MOMENT RESISTANCE OF WOOD-PLATE AND DOWEL JOINTS IN PARTICLEBOARD AND LODGEPOLE PINE LUMBER

by

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Comparison of the Bending Moment Resistance of Wood-plate and Dowel-joints in Particleboard and Lodgepole Pine Lumber (60 pp.)

Director: Dr Edwin J. Burke

ABSTRACT

Elliptical wood-plates and dowels are popularly used in the joints of furniture, cases and cabinets, but the comparative strength information for these two joints is lacking. This study was designed to compare the bending-moment resistance of wood-plate and round dowel-joints in particleboard and lodgepole pine lumber under tension and compression loading.

Results indicated that the bending-moment resistance increased from 1/4" to 1/2" diameter dowels and from the #0 to the #S-6 plates in both substrates. The results also indicated that the 1/2"-diameter dowel and the #S-6 wood-plate provided the maximum average bending-moment resistance under tension and compression loading in both lodgepole pine and particleboard, while the #0 plate and the 1/4" diameter dowel were the weakest configurations in both substrates. The strength of the 1/2" diameter dowel and the #S-6 plate joints were not significantly different in both substrates and loading methods.

Both dowel and wood-plate joints in lodgepole pine had higher resistance under compression loading than those under tension loading, except for the 1/4" dowel joint. Both types of joints did not exhibit significantly different resistance means under tension or compression loading for particleboard, except the 1/2" dowel and #S-6 plate where the compression resistance was greater.

For dowel joints, the substrates were the weakest part when the dowel was 5/16" diameter or larger. In all sizes of wood-plate joints, the substrate was the weakest part. The lodgepole pine group exhibited larger variation in bending-moment resistance than that of the particleboard group.

In summary, the #S-6 plate, 1/2" dowel provided maximum bending-moment resistance and compression loading are recommended for use in the corner-joints of both solid lumber and particleboard furniture.

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CHAPTER 1

INTRODUCTION

Joint design is one of the most important steps in the manufacturing process of furniture, especially in the wood-cased goods segment of that industry (Eckelman 1978). Since joint strength determines the ultimate structural integrity of the finished product, an improperly designed joint can fail when loaded to stress levels normally encountered in daily use. Conversely, correct joint design will provide more than adequate strength for the users and can reduce manufacturing costs by specifying the most appropriate materials and joint configurations. Therefore, the joints used in the structure of furniture must be scientifically designed using valid engineering data for carrying the forces safely while in service.

Hardwood dowel pins are widely used to construct furniture and are of several different types, including those with plain smooth surface, spiral-groove dowel and multiple longitude grooves dowel. The moderate joint strength and low cost of the finished fastener is one of the main advantages of dowel joint. However, attaining the precise alignment required for all styles and grades of furniture and doors is not an easy task, especially for the manufacturers lacking experience and sophisticated boring equipment. Owing to the ease of aliment and assembly, the wood-plate became another good choice.

Elliptical wood-plate joints, developed in the mid-1950's by Swiss cabinetmaker Herman Steiner A wood-plate, or biscuit as it is often refereed to in the US, fitted into a circular kerf made with a small carbide tipped circular saw or router bit. The diagonally-grained, compressed wooden biscuit has the potential of replacing dowels as the principal mechanical fastening member for many types of joints in panels, case-goods, doors and windows. Several secondary forest product manufacturers have been using these beechwood plate joints because they more easily provide precise joint alignment than doweled joints, and generally allow the use of thinner stock. Meanwhile, when compared with the preparation and assembly time of the dowel joint, the wood-plate joint is often faster and less expensive to produce. Two questions often asked by these manufacturers are "How strong are these wood-plate joints?" and "How do they compare with dowel joints in terms of strength?" Obviously, they are very interested in scientific testing and reporting of the strength of the many different joints configurations, and have actively soult answers to these questions.

When case-goods (cabinets, bookcases, chests, etc.) carry forces which are transfered to the joints, two principal types of joint stresses, compression and tension, are generated. Therefore, this study built on the previous work of 2 researches and compared the tension and compression strength of 5 sizes of dowel joints and 4 sizes of plate joionts in lodgepole pine lumber and particleboard.

In addition to comparing the strength of the two joint types, additional objectives were the formulation of strength prediction equations of bending-moment resistance, and the development of testing models and design data for use by manufacturers in designing products.

CHAPTER 2

LITERATURE REVIEW

While many different wood trade journals and magazines (Speas, 1993, Wagner, 1995; Hanson, 1996; Bachman and Hassler, 1975; Eckelman, 1986), have reported on the wood-plate and dowel joints, only vague statements regarding strength of wood plate joints have been made. Meanwhile, a preliminary study quantifying the bending-moment resistance of single-plate joints, testing four plate sizes, is nearing completion. Concerning the comparison of the relative strength of plate and dowel joints , Zhang and Eckelman's equations (Zhang and Eckelman, 1993a, b) are only applicable to single and multiple dowel-joints used in furniture and cabinet design, and are not valid for the wood-plate joints. Currently, the work in progress by Burke (Burke, 1996) is the only study reporting strength of single wood-plate joints. The work of these previous researchers represents the first steps toward developing rational joint designs and provides the starting point for the further research of the dowel and wood-plate joints.

The strength of a furniture joint is effected by the properties of the components of the construction, such as the different types of fasteners, species and types of boards, and adhesive. Strength is also affected by the several factors involved in the assembling process including the fit of the joint components and the method of construction (Eckelman, 1978).

The dowels made from different apecies or parent material with abnormal properties cause variation in joint strength. The dowel made from yellow birch (*Betula alleghaniensis* Britton.), American beech (*Fagus grandifolia* Ehrh.) and sugar maple (*Acer saccharum* Marsh.) possess higher shear strengths parallel to the grain, than dowels from woods such as paper birch (*Betula papyrifera* Marsh.), American basswood (*Tilia americana* L.), have lower shear strengths (USDA, 1987; Eckelman, 1979).

The quality of bonding surface is another affector of withdrawal strength (Eckelman and Cassens, 1985). Therefore, the surface structure of dowels can lead to different bonding strength. A project carried out by Eckelman and Cassens at Purdue University indicated that the plain dowel (smooth surface) and spiral-groove dowel had 18.6 percent higher withdrawal strength than the multi-groove dowel because of the plain and spiral-groove dowels processed more smooth surface area than the muti-groove dowel. Not only can those smooth-surface dowel pins offer more bonding area, but also forced the adhesive into the surrounding substrate and reinforced the bonding structure (Eckelman and Cassens,1985).

The mechanical properties of the substrate board material is another critical factor effecting dowel-joint strength. In 1956, Hoyle found that higher density with higher holding strength among those particleboards with similar properties, and also indicated a relationship of dowel holding strength and particle direction in particleboard (Hoyle, 1956). When the dowel axis was in a direction parallel to the particle alignment direction, the holding strength was the greatest. Englesson and Osterman reported that the dowel withdrawal strengths for 3-layer particleboard face members (dowel inserted perpendicular to the pael surface) were higher than those for edge members, since the embedded dowel was bonded to the higher density outer layer as well as the internal core layer Dowels aligned parallel to the face were not adhered to either of the higher strength layers, but were completely embedded within the lower-strength core, and thus showed lower withdrawal values (Englesson and Osterman, 1972). Bachmann and Hassler also showed a similar relationship between dowel withdrawal strength and the internal bond strength (Bachmann and Hassler, 1975). However, in 1985 Eckelman and Cassens indicated that only face member dowel withdrawal strength was strongly related to the internal bond strength of particleboard and medium density fiberboard (Eckelman and Cassens, 1985). They also found that edge withdrawal strength was independent of internal bond strength for the whole range of boards tested.

The holding strength of a dowel is expected relative to be dependent upon the dowel diameter and the embedded depth of the dowel. In 1975, Bachmann reported a strong relationship of holding strength and dowel diameter. When dowel diameter increased from 0.315" to 0.394" , the face withdrawal strength increased 62 percent, and the edge withdrawal strength also increased 36 percent (Bachmann, 1975). Then Bachmann and Hassler (1975) tested 0.236", 0.315" and 0.394" diameter dowels, showing a near-linear relationship between dowel diameter and withdrawal strength. The strength increased 45 percent as the dowel diameter increased from 0.315" to 0.394", and the strength increased about 46 percent when the diameter increases from 0.315" to 0.394" (Bachmann and Hassler, 1975).

While assembling the fastener and substrate, the gluing methods also influences the ultimate joint strength. Compared with spreading glue on either the dowel's surface or the surface of the dowel hole, coating both dowel and hole walls can increase the holding strength about twenty percent higher, since the adhesive can entirely fill the surfaces of dowel and dowel hole (Englesson, 1973). Another successful glue method is to fully fill the adhesive into the dowel hole and insert the dowel forcing the adhesive squeeze-out (Englesson, 1973; Eckelman and Cassens, 1985). While this overabundance of adhesive can give better strength.

Excessine the squeeze-out is wastful and presents finishing problems later in the manufacturing process.

In addition to the previously mentioned variables, the boring speeds, feed rates and dowel's fitting also affect the bonding strength. Hoyle found that a drill speed of the 2,880 rpm combined with a rapid feed rate gave the greates strength results. The roughness of the dowel hole's surface was less of an influence than the drill speed and feed rate (Hoyle, 1957). The reason for this is that when using a low feed rate, a high drill speed can rapidly generate heat and damage the hole surface. On the other hand, the low drill speed polished and charred the wall of the hole. Englesson and Osterman found that during repeated loading, a good dowel fit can offer better bonding and improve the withdrawal strength, when the loading was repeated (Englesson and Osterman, 1972). Englesson recommended that the dowel hole should be used 0.04 mm (0.0157") undersize for those joints to be used in dynamically loading situations (Englesson, 1973).

In summary, concerning the strength and the embedded depth of dowel, the results by Eckelman and Cassens indicated that a near-linear increase in both face and edge was realized by increasing the embedded depth of the dowels (Eckelman and Cassens, 1985).

In regards to strength of dowel joints, the research carried out by Eckelman and Zhang showed that the bending-moment resistance increased significantly as the dowel diameter increased from 6.35 mm (0.25") to 9.52 mm (0.375") and also as the dowel embedded depth in the face member increased from 6.35 mm (0.25") to 15.87 mm (0.625"). They also showed no obvious strength change with an increased depth of embedment in edge member (Eckelman and Zhang 1993a). Strength of muti-dowel joint corner joints in case construction has been reported by Eckelman and Zhang in 1993 (Eckelman and Zhang, 1993b) with results indicating that maximum bending strength was achieved when the dowel's interval was at least 3 inches. The results also showed the bending-moment resistance in compression to be related to the substrate's internal bond strength and the bending-moment resistance in tension to be related to the surface tensile strength of the substrates (Eckelman and Zhang, 1993b).

The review of literature found no citations pertaining to the strength of compressed wood-plate joints in refered research journals. The few articles that were located were contained in trade and popular journals, and none of the references to joint strength were made following rigorous statistically-controlled investigation. Bearing that in mind, the wood-plate strength articles are reviewed in the remainder of this chapter

A comparison of several joints including the wood-plate carried out by Wagner indicated that the double wood-plates having parellel-face arrangement gave a highest joint strength when comparing seven different types of joints, such as the mortise-tenon, loose-tenon, dowels and lag bolt joints (Wagner, 1995). Two number 20 wood-plates were used in the L-shape hinge of the door frame. Each wood-plate was inserted into the kerfs with 0.5 inches distance from the borders of the substrates to the centers of the dowels. The results showed that the double wood-plate joint failed at 2800 lb. in compression loading. Compared with double wood-plates joint, the double dowels joint with 0.5" diameter and 5.562" long only resisted 1800 lb. (Wagner, 1995). This study are impossible to compare the resistance difference between several types of joints due to lack of measurement of moment arms and statistics analysis.

Besides Wanger's comparison, the results of an uncontrolled experiment comparing loose tenon and multiple wood-plates joints, carried out by Hanson, suggest using the largest and many wood-plates as possible to obtain the maximum joint strength (Hanson, 1996). While this seems to be a reasonable statement, it provides no precise or accurate estimate of the load-carrying capacity of any specific joint design.

Concerning the gluing methods, the single-spread glue method was recommended by Speas. The adhesive was placed in the kerf first, and the wood-plate then inserted into the kerf. The wood-plate rapidly enlarged after bounding with adhesive and caused a difficult assembly, if sulled out and reinserted (Speas, 1993). On the other hand, however, Hanson found that the wood-plate joints were stronger by spraying with water before applying the adhesive as the water enlarged the wood-plate's thickness, and therefore fit the kerfs better than the wood-plates without pretreatment with water (Hanson, 1996).

For cutting kerf, Speas recommended that the feed speed of jointers should be rapidly feed into the substrate with a slow withdrawal. He found this method to afford better control and also reduced the variation of the kerf width. When cutting the kerf, any out-of-plane movement could enlarge the kerf thickness and cause a losse-fitting plate joint (Speas, 1993). In 1995 Lauziere tested several different brands of the wood-plate jointers and found that the lack of precision of some fences and plunge mechanisms led to imprecise and weak joints (Lauziere, 1995).

It is obvious from this review that definite data for wood-plate joints are completely lacking, and a need for fundamental research of wood-plate joints strength is required.

CHAPTER 3

MATERIALS AND METHODS

Substrate Preparation:

Lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) is a species native to western North America, from New Mexico to north of the Arctic circle and from the eastern foothills of the Rocky Mountains to the Pacific Ocean (Koch, 1996). It is a species known for growing in dense fire and insect-generated stands which pose significant management problems for forest managers. Recently, the secondary product industry has begun increased utilization of this tight-grained wood with characteristically small knots for interior and exposed parts in furniture and cabinets and solid lumber panels.

Mixed western softwood particleboard was easily obtained from a local manufacturer and was chosen as it is a major raw material for furniture and cabinet manufacturing. Both the solid lodgepole pine and the western softwood particleboard were chosen as a substrate in this study for applicability to "real world needs"

Modeling previous work, the study used L-shaped (Fig. 3-1), corner-joint test specimens which were made from the industrial grade particleboard (density: 0.715 ± 0.006g/cm^3, 44.63 ± 0.384lb./ft^3; thickness: 19.0 mm/0.75") obtained from Louisiana-Pacific Corp., and the defect-free lodgepole pine lumber having a thickness of 19.0 mm (0.75"). In order to have comparable results, dimensions of the test specimens duplicated those used in previous corner-joint studies (Zhang and Eckelman, 1993a; Burke, 1996). The face (dowel/plate located in the face of the piece) member size was 158.5 mm x 127.0 mm x 19.0 mm (6.25" x 5.00" x 0.75") and the edge (dowel/plate located in the edge of the piece) member was 139 7 mm x 127 0 mm x 19 0 mm (5.50" x 5.00" x 0.75") (Fig. 3-1).

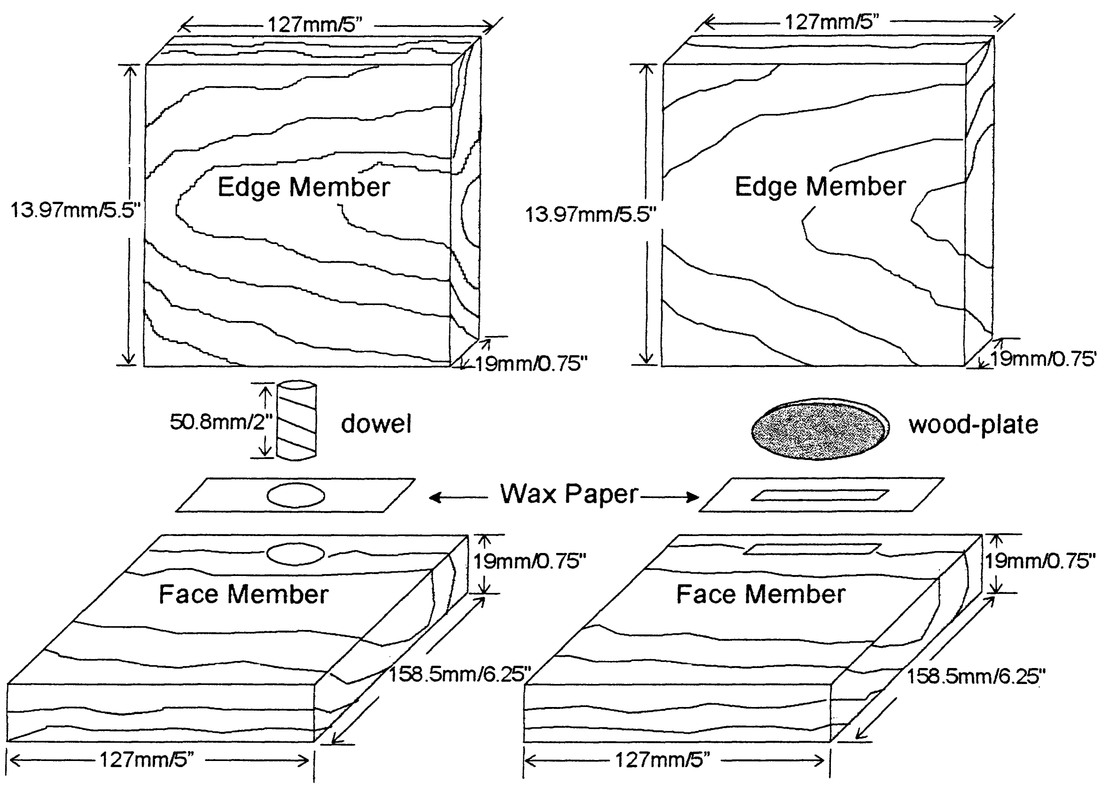

Figure 3-1.
Diagrams of the configurations of dowel joints and
wood-plate joints in lodgepole pine and particleboard corner joints

The particleboard's face and edge members were randomly selected from several different sheets selected at the factory, and the dried lodgepole pine lumber was also randomly selected at a local sawmill, being sawn from different trees. Both the particleboard and lodgepole pine substrates were allowed to equilibrate at room temperature period to and after cutting into individual edge and face members, and subsequent final assembly

To convert both particleboard and lodgepole pine lumber into face and edge members, the 50.8 mm x 203.2 mm (2" x 8") (nominal) lumber and 12-inch wide strips of particleboard (including 1.05 mm/0.041" for saw blade) were cut into 299.5 mm x 127.0 mm x 19.0 mm (11.79" x 5.00" x 0.75") (Fig. 3-2) pieces first. These pieces were then selected at random and cut into a face and edge members substrates as a pair. For lodgepole pine, all substrates were laid up in a side-grain configuration (Fig. 3-1, 3-2). Any particleboard and solid wood substrates showing any defects, such as knots, splits, checks, etc.were rejected.

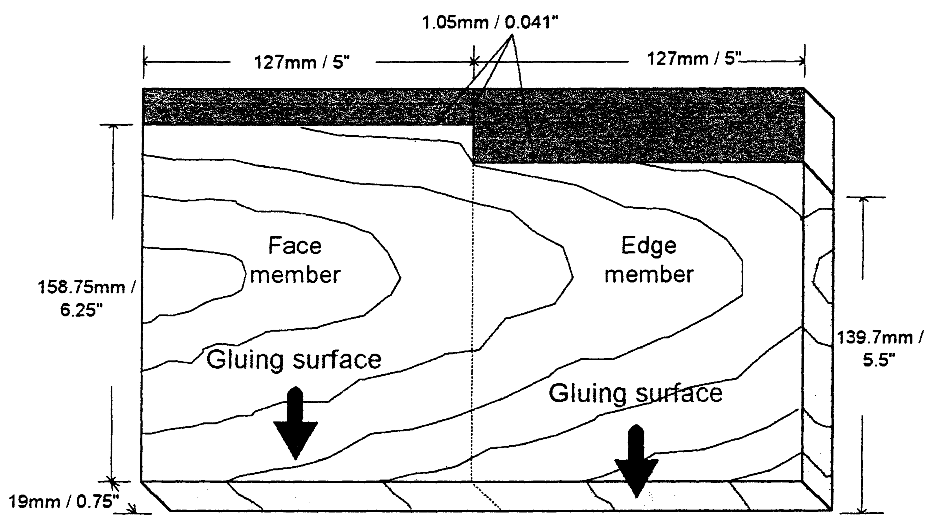

Figure 3-2.
Layout diagram of specimen members cut from lodgepole pine lumber
(Particleboard used the same layout)

A pre-test of five samples for each configuration of dowel and wood-plate joints yielded an average coefficient of variation (CV) for the bending-moment resistance (dependent variable) of 14 percent in tension loading and 12.5 percent in compression loading. This study used alpha level of 0.05 and 10% allowable error, the desired difference between the sample mean and population mean as a percentage of the sample mean. Following this, the sample size was determined by using the equation shown below (Zuuring, 1996).

$$n = \frac{t^2 \times CV^2}{A^2}$$

where: n = sample size

t = student's t value at specified alpha level

CV = the coefficient of variation

A = percent allowable error

As a result, eight replications of each configuration (2 substrate types by 2 stress loadings by 5 dowel diameters and 4 plate sizes) were constructed for a total of 288 specimens (Table 3-1).

Table 3-1.
Number of specimens by configuration type

Configuration type	Number of specimens
Wood-plate joints: 4 areas x 2 stress-loadings x 2 substrates x 8 replications	128
Dowel joints: 5 diameters x 2 stress-loadings x 2 substrates x 8 replications	160
Total	288

Dowel joint preparation:

To determine the relationship between dowel diameter and joint strength, the dowel-joint configuration consisted of five diameters: 6.35, 8.38, 9.52, 11.09, 12.70 mm/ 0.25, 0.33, 0.375, 0.437, 0.50 inches. All dowels having a spiral-groove were 50.8 mm (2 inches) long and were made from solid birch (*Betula spp.*) wood. One hundred dowels were randomly selected from a large supply of each diameter class to calculate descriptive statistics for actual diameter, length and surface area (Table 3-2). Ten dowels were randomly selected from each group of one hundred dowels to compute the means and the standard deviations for diameter, length and surface area (Fig. 3-3, Table 3-2).

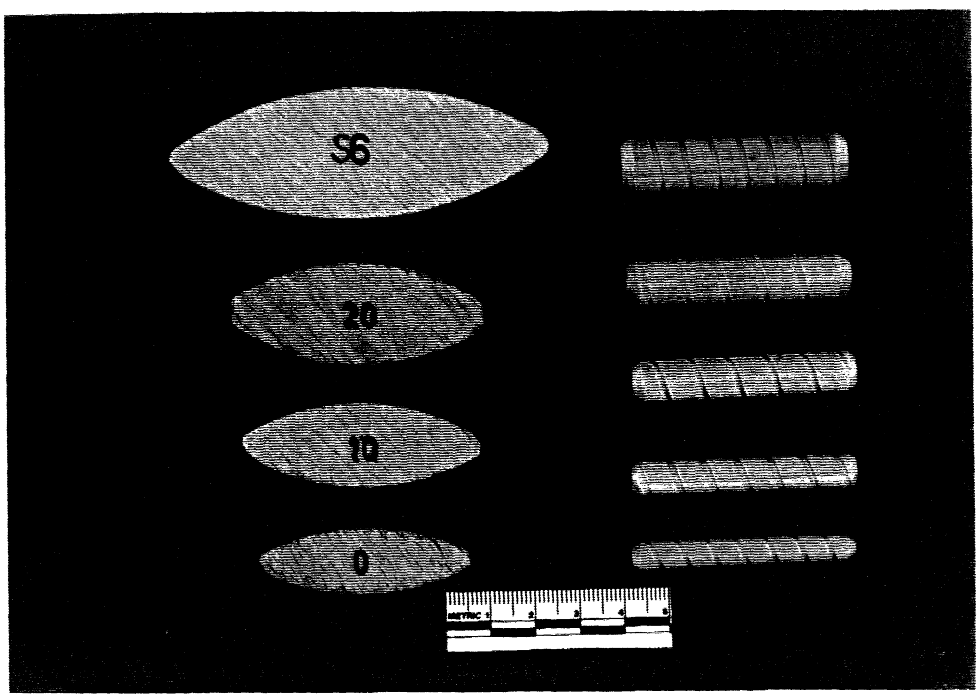

Figure 3-3
Photo of dowels and wood-plates used in furniture joints

Table 3-2.
Means and standard deviations of dowel diameter and wetted surface area by size class

Dowel size class	diameter mean	standard deviation	wetted area mean	standard deviation
(mm /inch)	(mm / inch)	(mm / inch)	(mm^2 / $inch^2$)	(mm^2 / $inch^2$)
6.35 /0.25	6.350 / 0.250	0.045 / 0.0017	815.794 / 1.264	9.528 / 0.0147
8.38 / 0.3125	7.902 / 0.311	0.048 / 0.0019	1035.710 / 1.605	9.806 / 0.0152
9.52 / 0.375	9.564 / 0.376	0.041 / 0.0016	1245.217 / 1.930	11.223 / 0.0174
11.09 / 0.4375	10.986 / 0.433	0.051 / 0.002	1441.300 / 2.234	6.458 / 0.0100
12.70 / 0.50	12.725 / 0.501	0.046 / 0.0018	1711.864 / 2.653	17.227 / 0.0267

(based on sample of 10 for each size class)

Identical drilling and gluing methods were used for both the lodgepole pine and particleboard substrates. The dowel-holes in both the face and edge members were drilled using industry-standard equipment and methods.

Spur-point, twist drills using a drill speed of 2200 rpm and a feed rate of 6.09 M (20 feet)/min were used to avoid charring the hole (Zhang and Eckelman, 1993a). Drilling depth was 34.925 mm/1.375" in the edge member and 15.875 mm/0.625" in the face member In order to leave some space for adhesive while inserting the dowels into the holes, the hole depths were drilled 1.58 mm (0.0625 inches) deeper than necessary The diameters of ten randomly selected dowel-holes were measured for each size class in order to compute descriptive statistics (Table 3-3).

Table 3-3.
Means and standard deviations of dowel holes by size class

Dowel diameter mean	Hole diameter mean	Standard deviation
(mm /inch)	(mm /inch)	(mm /inch)
6.350 / 0.250	6.325 /0.249	0.076 / 0.003
7.902 / 0.311	7.925 / 0.314	0.025 / 0.001
9.564 / 0.376	9.525 / 0.375	0.025 / 0.001
10.986 / 0.433	11.034 / 0.434	0.050 / 0.002
12.725 / 0.501	12.7 / 0.500	0.050 / 0.002

(df = 9 for each diameter group)

Dowel joints were constructed with industry-standard, water-based fortified polyvinyl acetate adhesive with 65 percent solids content. Prior to gluing, the holes were cleaned with compressed air and an adequate amount of adhesive was applied on the walls of the holes and onto the dowel pins, i.e. double spreading.

This double-spread gluing method was used to ensure that the bonding surface had an adequate amount of adhesive after being placed in a tight-fitting hole. Dowel pins were inserted into the face members first in order to ensure that the dowels were embedded to the required depth. A layer of waxed paper was placed between the two joint members (Fig. 3-1) in order to prevent any excess adhesive from forming a bond in the common joint area (Zhang and Eckelman, 1993a). All test specimens were cured under light pressure and stored under test room conditions having an equilibrium moisture content of 10 percent for a minimum of 72 hours.

Wood-plate joint preparation:

Compressed beech-wood plates (Lamello Inc.) were used in this study, the 4 sizes of wooden ellipsoids all exhibiting the same 50.8 mm (2-inch) radius of curvature (Fig 3-4). The wood-plate joints used four sizes of plates, #0, #10, #20, #S-6, with single-surface areas of 525.36, 762.26, 1050.45, 1784.02 mm^2/ 0.814, 1 182, 1.628, 2.77 $inch^2$ (Fig 3-4). Ten plates were randomly selected from a large supply of each size group for computing the means and standard deviations of the single surface areas, widths (long axis), depth (short axis) and thickness (Fig 3-4 and Table 3-4).

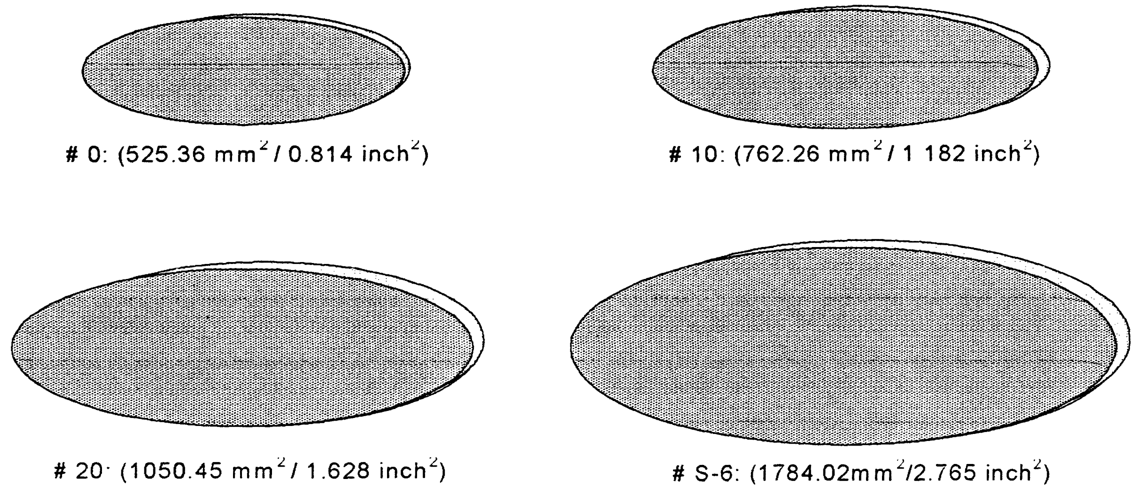

Figure 3-4
Four sizes of wood-plates (shown actual size)

Table 3-4
Descriptive statistics for single surface area, distance of the long axis and short axis, thickness of wood-plates by size class

Single surface area		
size class	mean (mm2 / inch2)	standard deviation (mm2 / inch2)
# 0	525.360 / 0.814	0.675 / 0.001
# 10	762.256 / 1.182	0.677 / 0.001
# 20	1050.450 / 1.628	3.250 / 0.005
# S-6	1784.016 / 2.765	2.874 / 0.004
Long axis distance		
size class	mean (mm / inch)	standard deviation (mm / inch)
# 0	46.965 / 1.849	0.051 / 0.002
# 10	53.010 / 2.087	0.254 / 0.010
# 20	56.693 / 2.232	0.127 / 0.005
# S-6	85.344 / 3.360	0.203 / 0.008
Short axis distance		
# 0	15.210 / 0.599	0.005 / 0.002
# 10	19.126 / 0.753	0.076 / 0.003
# 20	23.418 / 0.922	0.177 / 0.006
# S-6	30.429 / 1.198	0.127 / 0.005
Thickness		
# 0	3.912 / 0.154	0.076 / 0.003
# 10	19.126 / 0.753	0.076 / 0.003
# 20	3.912 / 0.154	0.102 / 0.004
# S-6	3.962 / 0.156	0.076 / 0.003

For the wood-plate joints, the kerf (incision) in both substrates of particleboard and lodgepole pine was made with a DeWalt plate-joint kerfing tool, fixed with a 6-tooth, carbide-tipped, 101.6 mm (4 inches)-diameter blade with a 3.937 mm (0.155") kerf thickness.

As with the dowel joints, industry-standard, water-based, fortified polyvinyl acetate adhesive with 65 percent solids content, was also used for the wood-plate joints. The holes and kerfs were cleaned with compressed air and an adequate amount of adhesive was applied into the incisions and on the plates.

A double-spread gluing method was used where the wood-plate as well as the kerf walls were covered with enough adhesive to ensure a proper bond. The glue-covered plates were inserted into the kerfs (also coated with adhesive) of face members first in order to ensure that the plates were embedded to the required depth. A layer of waxed paper was placed between the two joint members (Fig. 3-1) in order to prevent any excess adhesive from forming a bond in the common joint area. All test specimens were cured under light pressure and stored at 20° C (68° F) and 15% relative humidity (equilibrium moisture content = 10%) for several days prior to testing.

Testing Methods:

In every day use, the corner joints of a case or cabinet are exposed to two main forces, compression and tension Most of these forces are applied through cantilevers (long sides) and can generate sizable bending moments. Compression forces tend to close joints, while tension forces tend to open corner joints (Figs. 3-5, 3-6). Both tension and compression loadings were used to compute the bending-moment resistance (R). The relationships between the bending-moment resistance (R) and two forces (Ft and Fc) were different. Bending-moment resistance values (R) were calculated by using the following equations:

$$\mathbf{R}_{(tension)} = \mathbf{0.5\ F_t \times 0.5\ L_t}$$

$$\mathbf{R}_{(compression)} = \mathbf{F_c \times \{ \sqrt{(6.25)^2 - (0.5\ L_c)^2} - 1.0607 \}}$$

where **R** = bending-moment resistance (lb.-inch)

$\mathbf{F_t}$ = applied force of tension loading (lb.)

$\mathbf{L_t}$ = length of two members in tension loading (inches)

$\mathbf{F_c}$ = applied force of compression loading (lb.)

$\mathbf{L_c}$ = length of two members in compression loading (inches)

A 60,000 Lb. Tinius-Olson universal testing machine (Figs. 3-7, 3-8) was used to apply a load to each specimen with a cross head speed of 0.635 mm (0.025 inches) per minute (Burke, 1996). Same specimen received a compression load and others received a tension load. The arms of tension test specimens rested on roller assemblies so that the two joint members were free to move on the testing machine bed (Fig. 3-5, 3-7). Recoded data included loading force, distance between the arms of the two members under compression and tension loading, dry-basis moisture content, density of the substrates and failure conditions.

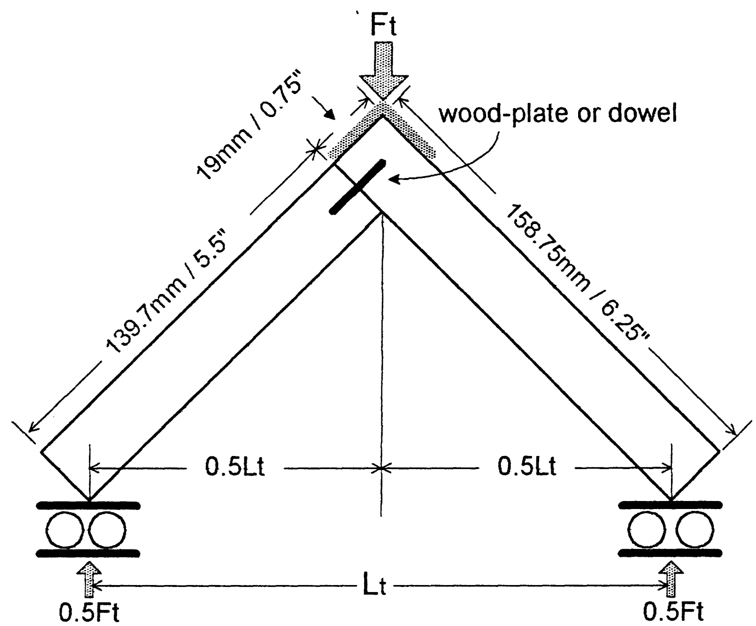

Figure 3-5
Diagram of tension loading test specimen

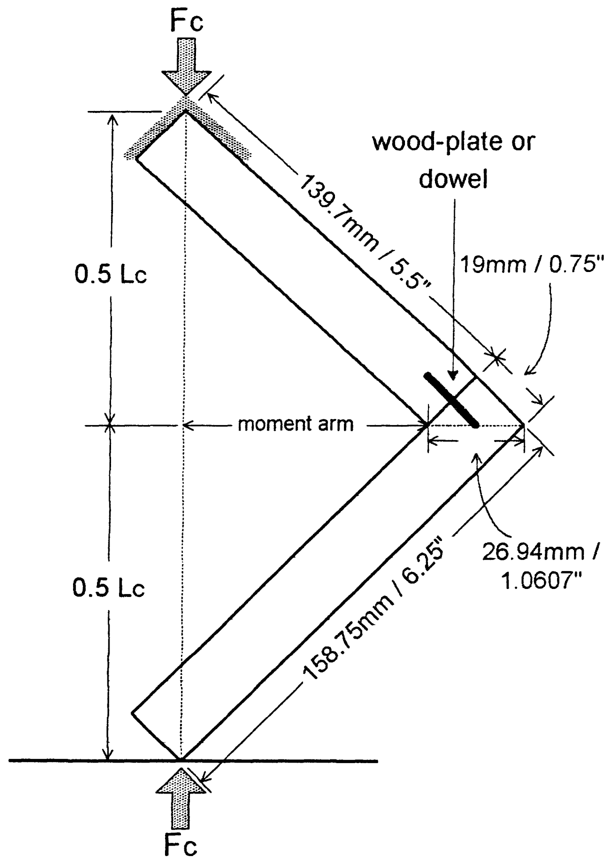

Figure 3-6.
Diagram of compression loading test specimen

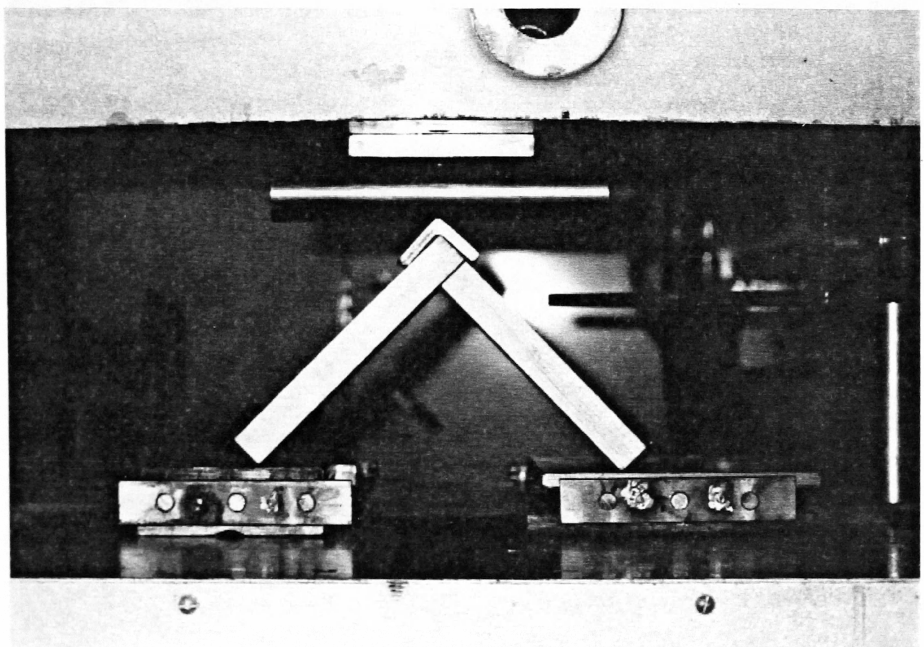

Figure 3-7.
Photo of test specimen under tension loading in testing machine

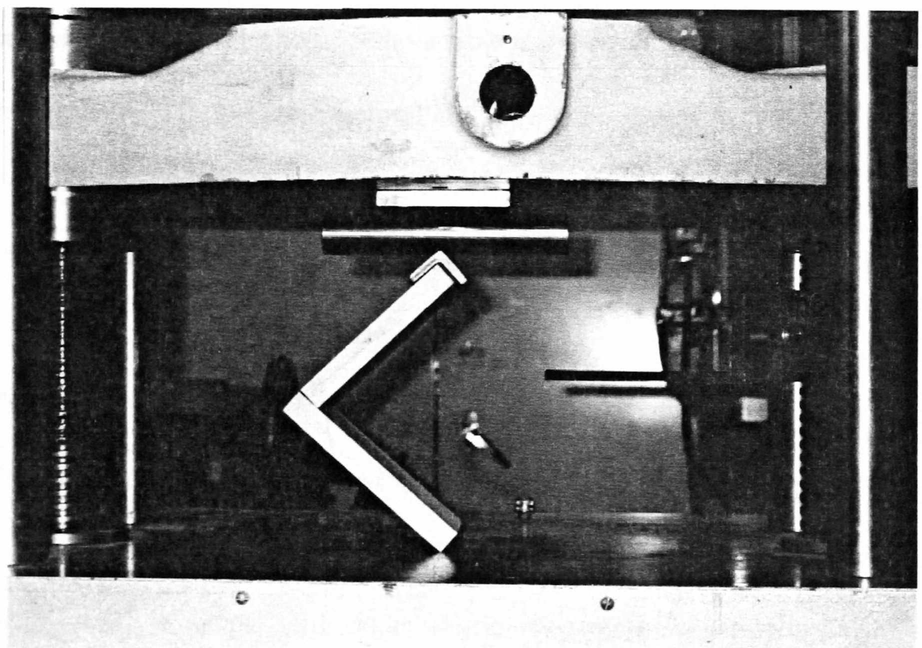

Figure 3-8.
Photo of test specimen under compression loading in testing machine

Analyses:

H_0: The population mean bending-moment resistance values are equal due to the board type, joint type with different sizes, stress-loading configuration and the interactions between these factors at the 0.05 alpha level.

H_1: Not H_0.

The statistical analysis package, SPSS 6.0 for Windows 95, was used to conduct various data analyses. The dependent variable is the bending-moment resistance value and the independent factors (3 main factors) are:

- Two joint types:
  - (a) Wood-plate joints: 4 sizes surface areas of plates
  - (b) Dowel joints: 5 diameters of dowels
- Two substrates: (lodgepole pine lumber and mixed conifer industrial particleboard).
- Two joint-loading configurations: (compression loading and tension loading).

If any of the null hypotheses are rejected, a multiple-comparison procedure (Duncan's multiple comparison) will be used to investigate the nature of the differences between mean bending-moment resistance values. The modeling techniques will be used to examine the functional relationships between the bending-moment resistance values and the factors.

CHAPTER 4

RESULTS AND DISCUSSION

Failure Modes:

Most joint-failures were traced to fractures within the substrates, as well as the fastener that often carried some material from the bonding surface during withdrawal from the failure zone. Three failure modes can be identified in terms of the location of the failure and are classified as follows:

Type 1. The face member's edge failed alone.

For lodgepole pine in tension and compression loadings, the face member's edge crushed as a linear-shape, parallel to the wood grain through the edge of the face member (Figure 4-1). For particleboard, the face member's edge crushed in the form of a half elliptical shape (bell-shaped with 2" to 4" width) from the center of the joint area (Figure 4-1).

Type 2. The dowel failed alone.

Dowel failure occurred in both lodgepole pine and particleboard. The small diameter dowels crushed owing to the bending stress, since they were weaker than the substrates (Figure 4-2).

Type 3. The edge member's edge failed alone.

For lodgepole pine, the edge member's edge crushed as a linear-shaped region parallel to the wood grain through the edge of the edge member (Figure 4-3). For particleboard, the edge member's edge crushed as a half elliptical shaped (bell-shaped with 2" to 4" width) area from the center of the joint area (Figure 4-3).

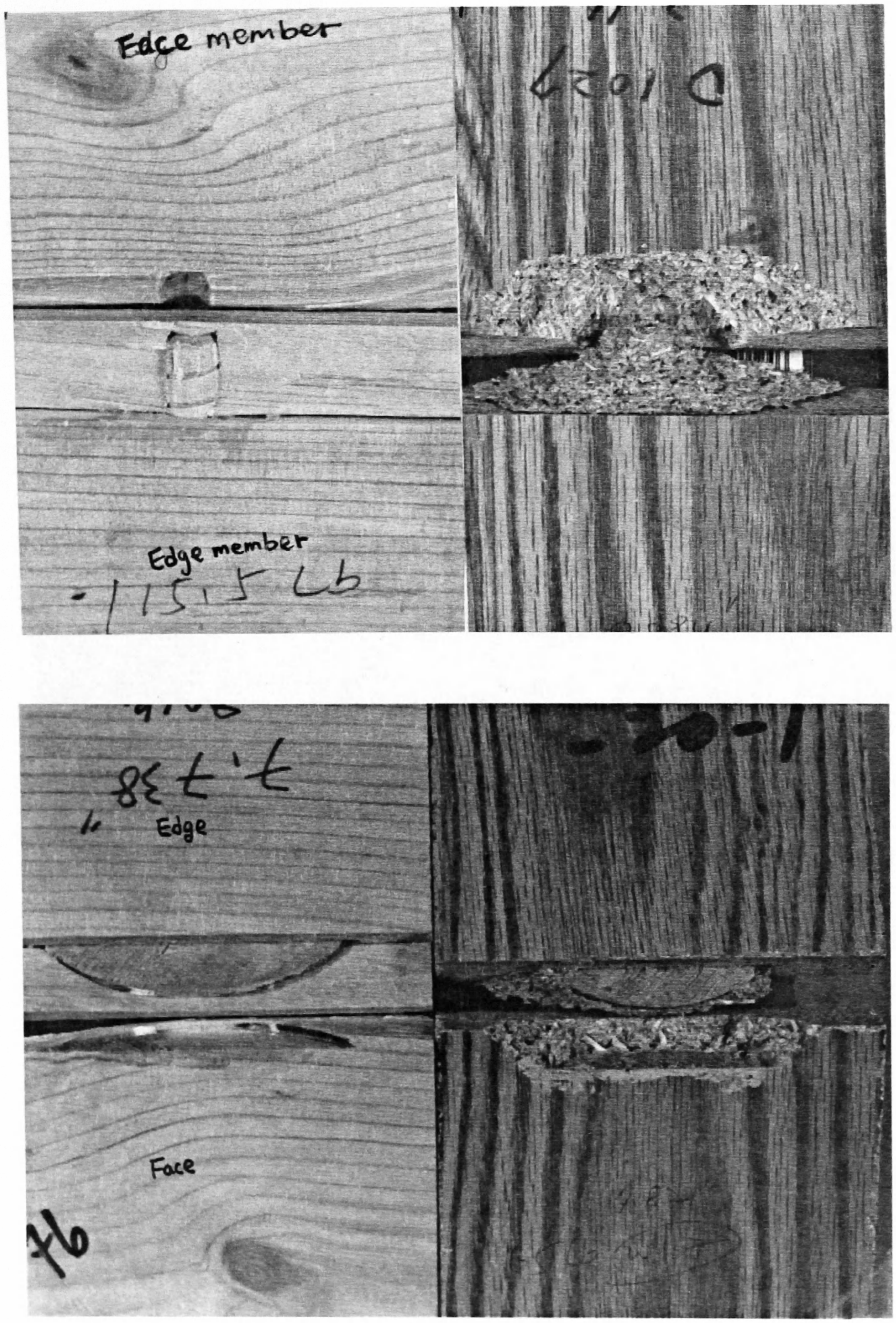

Figure 4-1.
Photos of type 1 failure mode of wood-plate joint in lodgepole pine and particleboard

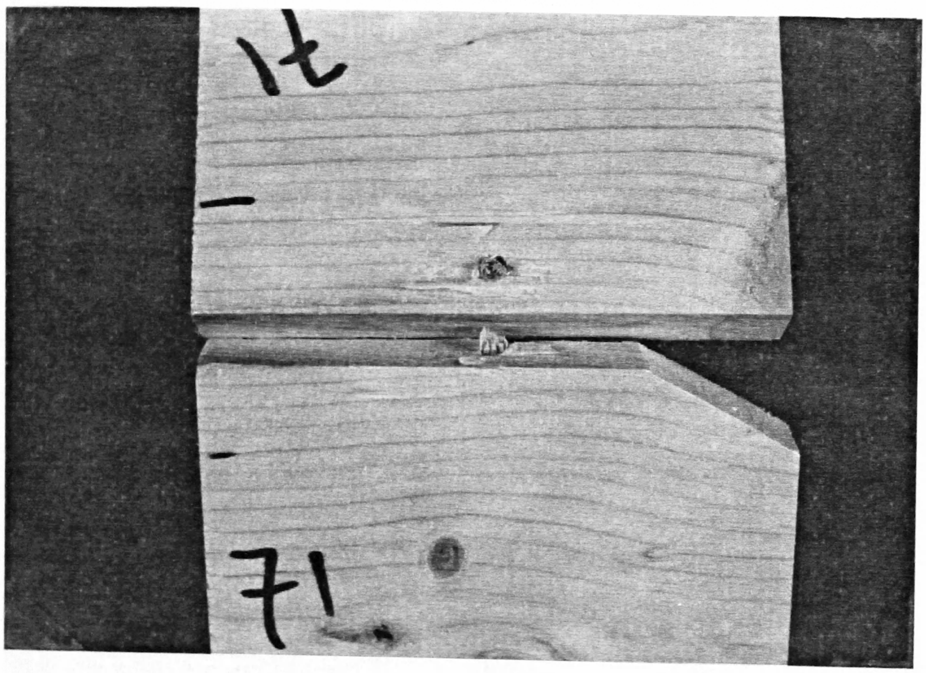

Figure 4-2.
Photo of type 2 failure mode of dowel-joint in lodgepole pine

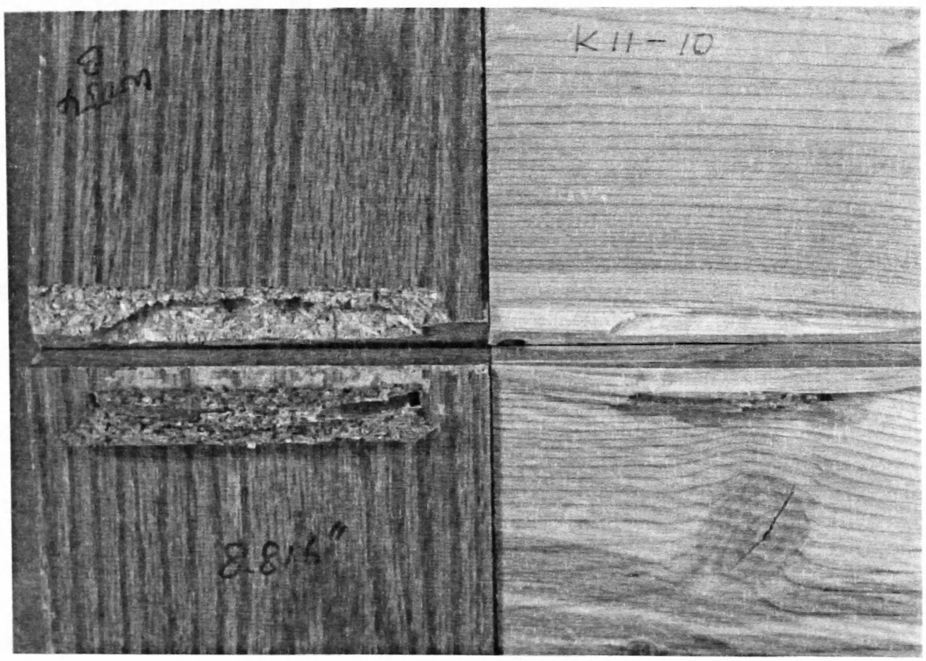

Figure 4-3.
Photos of type 3 failure mode of wood-plate joint in lodgepole pine and particleboard

Dowel joint failure:

1) solid lodgepole pine:

Dowel-joint failures in lodgepole pine were only of Type 1 or Type 2 failures modes under compression and tension loading. The percentage of Type 1 failures increased from 0% to 100% in compression loading and from 0% to 88% in tension loading as the dowel diameter increased from 1/4" to 1/2" (Table 4-1). For Type 2 failures, the percentage decreased from 100% to 0% in compression and from 100% to 12% in tension loading as the dowel diameter increased from 1/4" to 1/2" No Type 3 failures occurred in the lodgepole pine. (Table 4-1) and was caused by the deeper dowel embedding-depth in the edge member

2) particleboard:

Dowel-joint failures in particleboard were only of Type 1 or Type 2 failures modes under tension and compression loading. The percentage of Type 1 failures increased from 75% to 100% in both compression and tension loadings as the dowel diameter increased from 1/4" to 1/2" For Type 2 failures, the percentage decreased from 25% to 12% in both compression and tension loadings as the dowel diameter increased from 1/4" to 3/8". No Type 3 failures occured (Table 4-1), because the deeper embedding-depth in the edge member

The failure mode change in dowel joints indicated that the weakest part of the joint changed from the dowel pin having the 1/4" diameter to the face members for 1/2" diameter dowels. Since the edge members of the dowel joints had deeper embedding depths than face members, the joint zones of edge members were stronger than those of the face members. Hence, Type 3 failures did not occur in any dowel-joints.

Table 4-1
Percentages of Type 1 and 2 failure modes for dowel joints by substrate Type and loading method

Lodgepole pine				
	Compression Loading		Tension Loading	
Dowel's diameter	Type 1	Type 2	Type 1	Type 2
1/4"	0 %	100%	0%	100%
5/16"	12%	88%	50%	50%
3/8"	50%	50%	75%	25%
7/16"	75%	25%	88%	12%
1/2"	100%	0%	88%	12%
Particleboard				
	Compression loading		Tension loading	
Dowel 's diameter	Type 1	Type 2	Type 1	Type 2
1/4"	75%	25%	75%	25%
5/16"	75%	25%	88%	12%
3/8"	88%	12%	88%	12%
7/16"	100%	0%	100%	0%
1/2"	100%	0%	100%	0%

Wood-plate failure:

The wood-plate joints only exhibited Type 1 and Type 3 failures (Table 4-2). The results indicated that the weakest part of the wood-plate joint was the substrate.

1) Lodgepole pine:

The percentage of Type 1 failures in wood-plate joints increased from 12% to 75% in compression loading and from 50% to 88% in tension loading as the size (area) of wood-plate increased from #0 to #S-6 (0.814 in^2 to 2.765 in^2). For Type 3 failures, the percentage decreased from 88% to 25% in compression loading and from 50% to 0% in tension loading as the size of the wood-plate increased from #0 to #S-6 (0.814 in^2 to 2.765 in^2) . Type 2 failure did not occur in wood-plate joints in lodgepole pine (Table 4-2).

2) Particleboard:

For Type 1 failures, the percentage increased from 25% to 88% in both compression and tension loadings as the size of wood-plate increased from 0.814 in^2 to 2.765 in^2 Type 2 failures did not occured. The percentage of Type 3 failures decreased from 75% to 12% in both compression and tension loadings as the size of the wood-plate increased from the 0.814 in^2 to 2.765 in^2 (Table 4-2).

Table 4-2.
Percentages of failure modes for wood-plate joints by substrate Type and loading method

Lodgepole pine					
		Compression Loading		Tension Loading	
Wood-plate	single surface area ($inch^2$)	Type 1	Type 3	Type 1	Type 3
# 0	0.814	12%	88%	50%	50%
# 10	1.182	50%	50%	50%	50%
# 20	1.628	75%	25%	88%	12%
# S-6	2.765	75%	25%	88%	12%
Particleboard					
		Compression loading		Tension loading	
Wood-plate	single surface area ($inch^2$)	Type 1	Type 3	Type 1	Type 3
# 0	0.814	25%	75%	25%	75%
# 10	1.182	50%	50%	50%	50%
# 20	1.628	50%	50%	88%	12%
# S-6	2.765	88%	12%	88%	12%

Bending-moment resistance:

The 1/2" diameter dowel joint had the highest average bending-moment resistance (Table 4-3) in tension loading configurations, while the #S-6 plate (2.765 in^2) showed the greatest strength in compression loading, with each having the highest mean bending-moment resistances of their joint group. The #0 (0.814 in^2) plate had the lowest average strength except in lodgepole pine with compression loading where the 1/4" dowel was slightly weaker (Table 4-3).

A two-way analysis of variance (alpha level 0.05) indicated that the type of joint was the most important factor which significantly influenced the bending-moment resistance, while the method of loading was shown to be the second most important factor affecting the bending-moment resistance. The substrate had little influence on the bending-moment resistance when compared to joint-type and loading-method. For example, the average bending-moment resistance of wood-plate or dowel joints increased significantly from the smallest fastener to the largest fastener in each group (wood-plate and dowel), but it did not change significantly between loading-method and substrate-type groups (Table 4-3).

Table 4-3.
Ordered means and standard deviations of bending-moment resistance (lb.-in)
by joint, loading and substrate types

Lodgepole pine					
Tension loading			Compression loading		
Joint type	Mean	Standard deviation	Joint type	Mean	Standard deviation
1/2" dowel	183.3	26.6	# S-6 plate	205.5	31.5
# S-6 plate	170.1	25.2	1/2 " dowel	194.4	14.7
# 20 plate	162.6	22.1	7/16" dowel	193.5	26.3
7/16" dowel	156.7	22.2	# 20 plate	188.6	36.5
3/8" dowel	147.2	18.1	3/8" dowel	169.1	33.4
# 10 plate	138.7	23.3	# 10 plate	163.8	23.1
5/16" dowel	135.9	6.7	5/16" dowel	147.3	33.9
1/4" dowel	119.5	20.2	# 0 plate	139.7	28.1
# 0 plate	106.0	24.4	1/4" dowel	110.5	18.1
Particleboard					
1/2 " dowel	193.8	22.4	# S-6 plate	247 7	28.7
# S-6 plate	188.5	30.0	1/2 " dowel	239.0	26.8
7/16" dowel	187 0	16.2	# 20 plate	171 9	26.7
3/8" dowel	159.9	20.2	7/16" dowel	165.2	18.1
5/16" dowel	159.4	19.6	3/8" dowel	158.8	19.1
# 20 plate	148.2	12.0	5/16" dowel	143.4	18.9
# 10 plate	139.4	9.1	# 10 plate	137.8	8.2
1/4" dowel	137.3	16 9	1/4" dowel	111.2	4.8
# 0 plate	100.8	13.7	# 0 plate	100.4	11.0

Unit: lb.-in

- **Dowel joints:**

1) Tension loading:

The average bending-moment resistance of dowel joints in tension loading increased gradually in a near-linear tend from the 1/4" to 1/2" sized dowels in lodgepole pine (Fig 4-4). In particleboard, the means increased from 1/4" to 5/16" sized dowel and from 3/8" to 1/2" sized dowel, but did not increased significantly from 5/16" to 3/8" sized dowel (Table 4-2). The situation was discussed in discussion section.

2) Compression loading:

Values for the average bending-moment resistance in compression loading for lodgepole pine increased from the 1/4" to 7/16" sized dowel, but did not increase significantly from the 7/16" to 1/2" diameter dowel (Fig. 4-4). Meanwhile, the average bending-moment resistance under compression loading in particleboard increased significantly from the 1/4" to 1/2" diameter dowel (Fig. 4-5), because particleboard had a more uniform compressed-particle structure than the lodgepole pine having different sized growth ring and the exterior layer of particleboard consisted of high density particles that could provide greater strength.

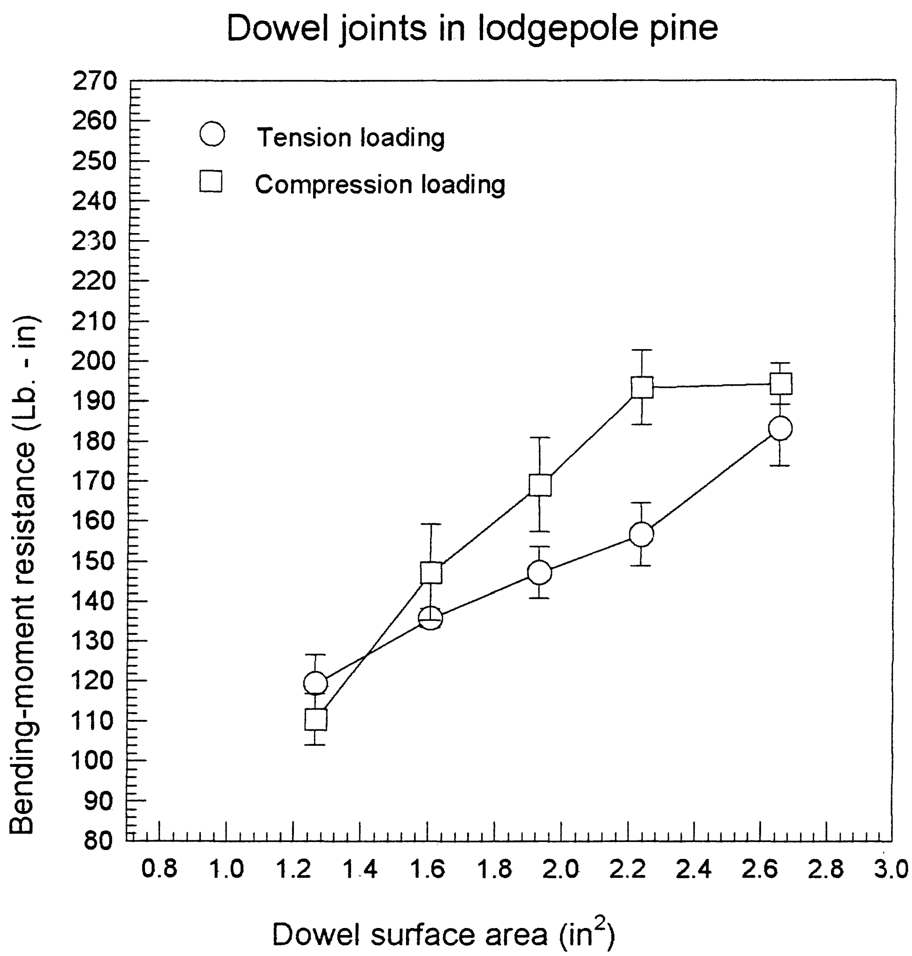

Figure 4-4
Line charts with error bars of the average bending-moment resistance for dowel joints in lodgepole pine
(from left to right are 1/4" to 1/2" dowel)

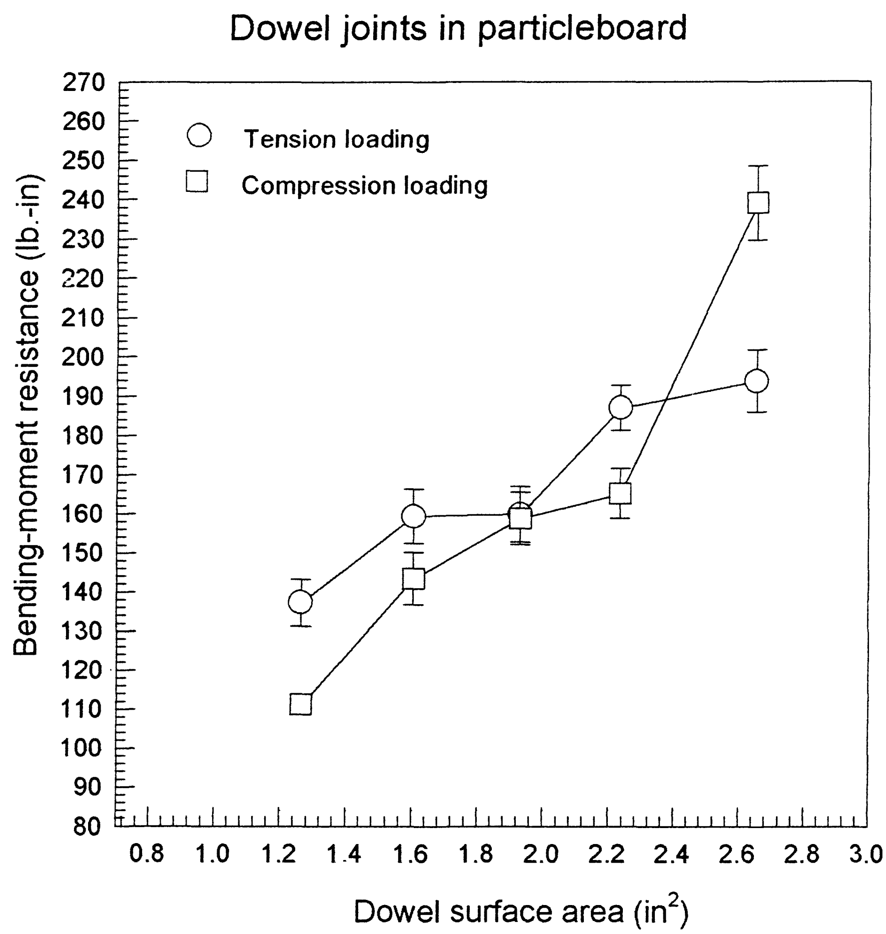

Figure 4-5

Line charts with error bars of the average bending-moment resistance for dowel joints in particleboard

(from left to right are 1/4" to 1/2" dowel)

- **Wood-plate joints:**

1) Tension loading:

The average bending-moment resistance under tension loading in lodgepole pine increased in a near linear fashion from 0.814 in^2 to 2.765 in^2 plates. The average bending-moment resistance under tension loading in particleboard also increased from 0.814 in^2 to 2.765 in^2 plates (Figs. 4-6, 4-7).

2) Compression loading:

For lodgepole pine, the average bending-moment resistance increased from 0.814 in^2 to 2.765 in^2 plates with a near linear tendency Compared with the tendency of mean strengths in lodgepole pine, the strength means of the strength for particleboard increased more rapidly from #0 to #S-6 plates (Figs. 4-6, 4-7).

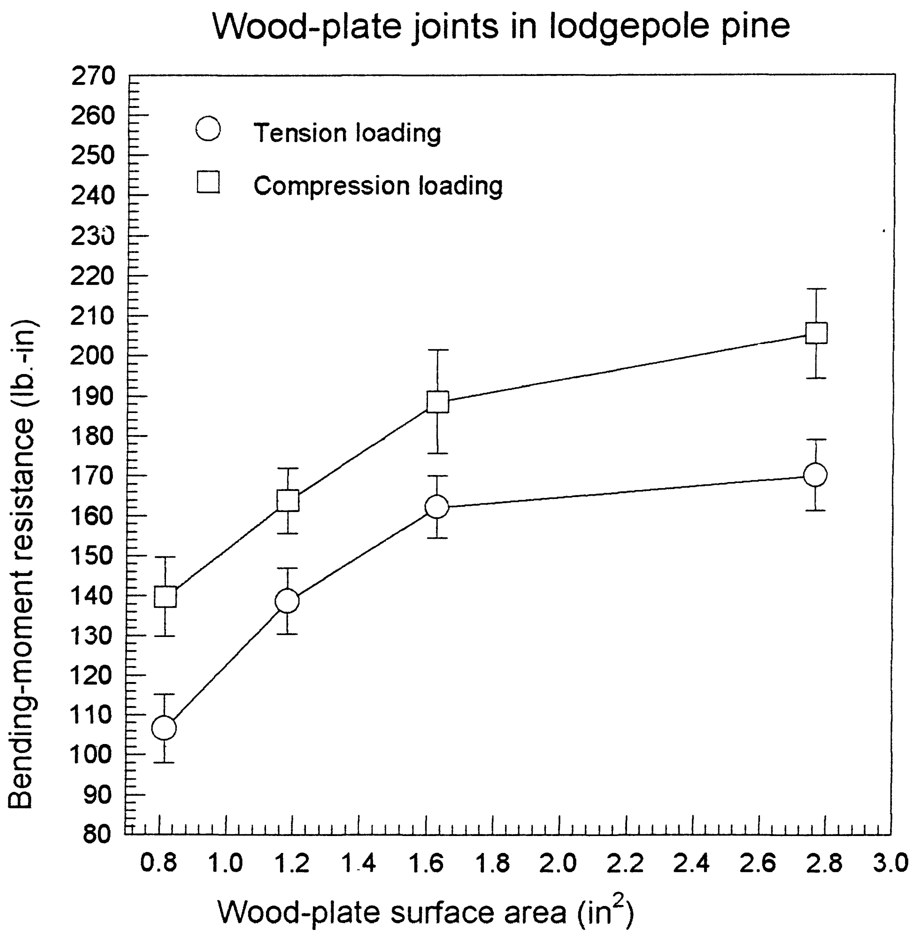

Figure 4-6.
Line charts with error bars of the average bending-moment resistance for wood-plate joints in lodgepole pine
(from left to right are #0, #10, #20, #S-6 plates)

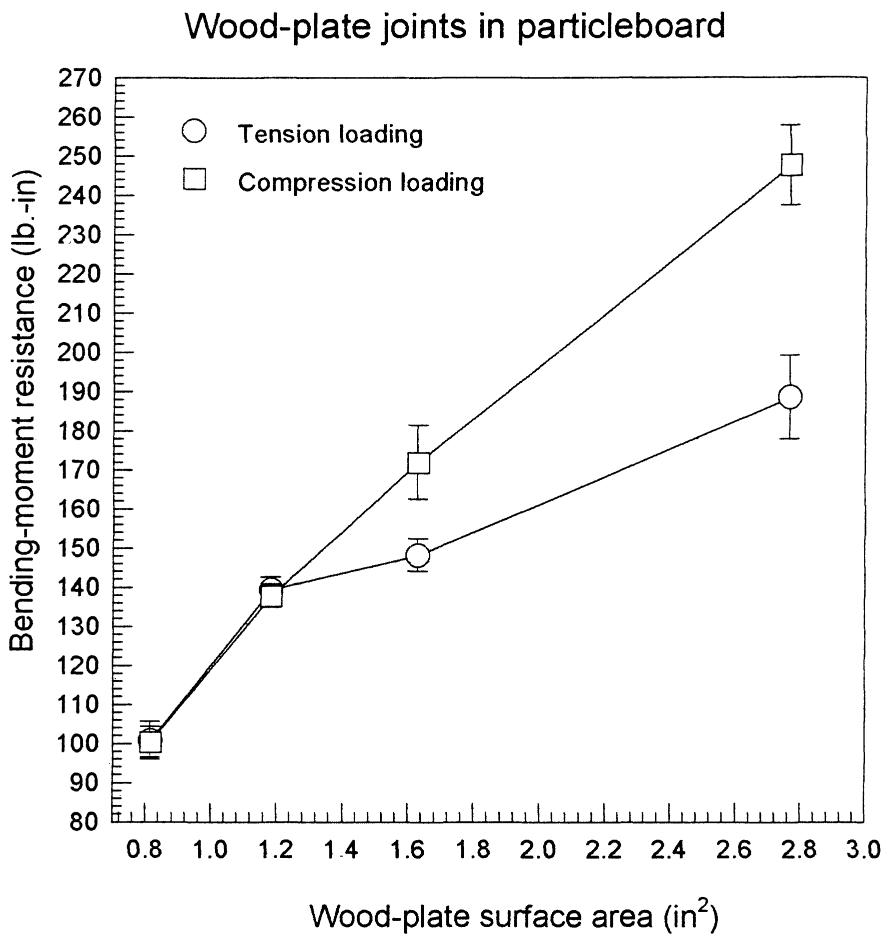

Figure 4-7
Boxplots of the bending-moment resistance of wood-plate joints in particleboard
(from left to right are #0, #10, #20, #S-6 plates)

Statistical analysis:

The 2-way ANOVA indicated that the mean bending -moment resistance under tension and compression loading was significantly different due to joint type, substrate type and their interaction (Table 4-4, 4-5, 4-6). To determinate which means were different and by how much. Duncan's Multiple Comparisons procedure was used (Table 4-7, 4-8, 4-9, 4-10).

Table 4-4
2-way ANOVA for $\log_{10}$ (bending-moment resistance) due to joint type, loading method and substrate type and interaction

Univariate Homogeneity of Variance Tests (alpha level = 0.05)
Variable .. LG10RES Log10(Resistance)
Cochrans C(7,36) = .08402, P = .102 (approx.)

Tests of Significance for LG10RES using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
JOINTTYP	2.15	8	.27	69.23*	.000
LOADING	.07	1	.07	18.52*	.000
WOOD	.00	1	.00	1.20	.275
JOINTTYP BY LOADING	.14	8	.02	4.64*	.000
JOINTTYP BY WOOD	.14	8	.02	4.47*	.000
LOADING BY WOOD	.04	1	.04	10.04*	.002
JOINTTYP BY LOADING BY WOOD	.07	8	.01	2.24*	.025
(Model)	2.62	35	.07	19.27	.000
WITHIN+RESIDUAL	.98	252	.00		
(Total)	3.60	287	.01		

R-Squared = .728
Adjusted R-Squared = .690 (alpha level = 0.05)

(JOINTTYP = Joint type, LOADING = Loading method, WOOD = Substrate type)

Table 4-5

2-way ANOVA for $\log_{10}$ (bending-moment resistance) due to joint type, loading method and interaction by substrate type

Lodgepole pine:

Univariate Homogeneity of Variance Tests (alpha level = 0.05)
Variable .. LG10RES Log10(Resistance)
Cochrans C(7,18) = .12320, P = .457 (approx.)

Tests of Significance for LG10RES using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
JOINTTYP	.82	8	.10	19.22*	.000
LOADING	.11	1	.11	20.46*	.000
JOINTTYP BY LOADING	.07	8	.01	1.63	.122
(Model)	.99	17	.06	11.02	.000
WITHIN+RESIDUAL	.67	126	.01		
(Total)	1.66	143	.01		

R-Squared = .598
Adjusted R-Squared = .544 (alpha level = 0.05)

Particleboard:

Univariate Homogeneity of Variance Tests (alpha level = 0.05)
Variable .. LG10RES Log10(Resistance)
Cochrans C(7,18) = .11175, P = .803 (approx.)

Tests of Significance for LG10RES using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
JOINTTYP	1.48	8	.18	74.65*	.000
LOADING	.00	1	.00	1.01	.316
JOINTTYP BY LOADING	.14	8	.02	7.33*	.000
(Model)	1.62	17	.10	38.64*	.000
WITHIN+RESIDUAL	.31	126	.00		
(Total)	1.94	143	.01		

R-Squared = .839
Adjusted R-Squared = .817 (alpha level = 0.05)

(JOINTTYP = Joint type, LOADING = Loading method, WOOD = Substrate type)

Table 4-6.
2-way ANOVA for $\log_{10}$ (bending-moment resistance) due to joint type, substrate type and interaction by loading method

Tension loading:

Univariate Homogeneity of Variance Tests (alpha level = 0.05)
Variable .. LG10RES Log10(Resistance)
Cochrans C(7,18) = .15966, P = .065 (approx.)

Tests of Significance for LG10RES using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
JOINTTYP	.84	8	.11	29.74*	.000
WOOD	.04	1	.04	9.97*	.002
JOINTTYP BY WOOD	.04	8	.01	1.48	.172
(Model)	.92	17	.05	15.28	.000
WITHIN+RESIDUAL	.45	126	.00		
(Total)	1.37	143	.01		

R-Squared = .673
Adjusted R-Squared = .629 (alpha level = 0.05)

Compression loading:

Univariate Homogeneity of Variance Tests (alpha level = 0.05)
Variable .. LG10RES Log10(Resistance)
Cochrans C(7,18) = .15436, P = .087 (approx.)

Tests of Significance for LG10RES using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
JOINTTYP	1.45	8	.18	42.96*	.000
WOOD	.01	1	.01	1.98	.162
JOINTTYP BY WOOD	.17	8	.02	4.93*	.000
(Model)	1.63	17	.10	22.65	.000
WITHIN+RESIDUAL	.53	126	.00		
(Total)	2.16	143	.02		

R-Squared = .753
Adjusted R-Squared = .720 (alpha level = 0.05)

(JOINTTYP = Joint type, LOADING = Loading method, WOOD = Substrate type)

The Duncan's Multiple Comparisons for lodgepole pine under tension loading showed 18 pairwise differences between the joint types due to their sizes, and indicated that 1/2" dowel joint had 5 pairwise differences and highest mean resistance while the #0 (0.814 in^2) wood-plate joint had lowest mean resistance and 7 pairwise differences (Table 4-7). For lodgepole pine under compression loading, also 18 pairwise differences were found. #S-6 (2.765 in^2) wood-plate joint having 5 pairwise differences was the highest mean resistance while the 1/4" dowel joint had the lowest mean resistance and 8 pairwise differences (Table 4-8).

For particleboard under tension loading, the Duncan's Multiple Comparisons showed 27 pairwise differences (Table 4-9). 1/2" dowel joint including 6 pairwise differences was the highest mean resistance while the #0 (0.814 in^2) wood-plate joint was the lowest resistance and had 8 pairwise differences. The comparisons also indicated 29 pairwise differences in particleboard under compression loading (Table 4-10). The #S-6 (2.765 in^2) plate with 7 pairwise differences was also the highest resistance while the #0 (0.814 in^2) wood-plate joint having 7 pairwise differences was the lowest resistance.

The number of pairwise differences in particleboard (27 and 29) were higher than those in lodgepole pine (18 and 18), since this could be caused by the difference of substrate property and was addressed in discussion section.

Table 4-7
Duncan's Multiple Compression of $\log_{10}$ (bending-moment resistance) under tension loading for lodgepole pine

```
Lodgepole pine under tension loading:

Variable  LG10RES    Log10(bending-moment resistance)
By Variable  JOINTTYP   Joint types
                                 Analysis of Variance
                                 Sum of         Mean              F       F
       Source           D.F.    Squares        Squares          Ratio   Prob.
Between Groups            8         .3788          .0474       10.4433   .0000
Within Groups            63         .2857          .0045
Total                    71         .6645
Multiple Range Tests:  Duncan test with significance level .05
(*) Indicates significant differences which are shown in the lower triangle
                              5     7
                            1 /   3 /     1
                          # / 1 # / 1 # # /
                            4 6 1 8 6 2 S 2
                          0 " " 0 " " 0 6 "
    Mean       JOINTTYP
    2.0152     # 0
    2.0723     1/4"
    2.1327     5/16"      *
    2.1361     #10        *
    2.1649     3/8"       * *
    2.1910     7/16"      * *
    2.2078     #20        * * *
    2.2262     #S6        * * * *
    2.2592     1/2"       * * * * *
```

(Total 18 pairwise differences were significant at 0.05 alpha level)

Table 4-8.
Duncan's Multiple Comparisons of $\log_{10}$ (bending-moment resistance) under compression loading for lodgepole pine

Lodgepole pine under compression loading:

Variable LG10RES Log10(bending-moment resistance)
By Variable JOINTTYP Joint types

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Between Groups	8	.5060	.0633	10.4173	.0000
Within Groups	63	.3825	.0061		
Total	71	.8886			

Multiple Range Tests: Duncan test with significance level .05
(*) Indicates significant differences which are shown in the lower triangle

Mean	JOINTTYP	1/4"	# 0	5/16"	#10	3/8"	#20	7/16"	1/2"	#S6
2.0383	1/4"									
2.1374	# 0	*								
2.1465	5/16"	*								
2.2103	#10	*								
2.2202	3/8"	*								
2.2683	#20	*	*	*						
2.2829	7/16"	*	*	*						
2.2876	1/2"	*	*	*						
2.3082	#S6	*	*	*	*	*				

(Total 18 pairwise differences were significant at 0.05 alpha level)

Table 4-9
Duncan's Multiple Comparisons of $\log_{10}$ (bending-moment resistance) under tension loading for particleboard

```
Particleboard under tension loading:

Variable  LG10RES    Log10(Resistance)
By Variable  JOINTTYP   Joint types
                                  Analysis of Variance
                                  Sum of        Mean             F      F
        Source            D.F.   Squares       Squares         Ratio  Prob.
Between Groups              8      .5059         .0632       24.7860  .0000
Within Groups              63      .1607         .0026
Total                      71      .6667

Multiple Range Tests:  Duncan test with significance level .05
(*) Indicates significant differences which are shown in the lower triangle
                                  5   7
                            1     / 3 /   1
                          # / # # 1 / 1 # /
                            4 1 2 6 8 6 S 2
                          0 " 0 0 " " " 6 "
     Mean       JOINTTYP
     2.0001     # 0
     2.1348     1/4"      *
     2.1435     #10       *
     2.1838     #20       *
     2.1996     5/16"     * * *
     2.2008     3/8"      * * *
     2.2696     7/16"     * * * * * *
     2.2703     #S6       * * * * * *
     2.2847     1/2"      * * * * * *
```

(Total 27 pairwise differences were significant at 0.05 alpha level)

Table 4-10.
Duncan's Multiple Comparisons of $\log_{10}$ (bending-moment resistance) under compression loading for particleboard

Particleboard under compression loading:

Variable LG10RES Log10(Resistance)
By Variable JOINTTYP Joint types

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Between Groups	8	1.1155	.1394	58.2635	.0000
Within Groups	63	.1508	.0024		
Total	71	1.2662			

Multiple Range Tests: Duncan test with significance level .05
(*) Indicates significant differences which are shown in the lower triangle

Mean	JOINTTYP	# 0	1/4"	#10	5/16"	3/8"	7/16"	#20	1/2"	#S6
1.9991	# 0									
2.0456	1/4"									
2.1386	#10	*	*							
2.1532	5/16"	*	*							
2.1979	3/8"	*	*	*						
2.2302	7/16"	*	*	*	*					
2.2306	#20	*	*	*	*					
2.3760	1/2"	*	*	*	*	*	*	*		
2.3913	#S6	*	*	*	*	*	*	*		

(Total 29 pairwise differences were significant at 0.05 alpha level)

For each substrate type pairwise comparisons of ordered means of bending-moment resistance under tension and compression loading were made between joint types. The underscores indicated those means which were not significantly different from each other at the 0.05 alpha level (Table 4-11).

Table 4-11
Delineation of homogeneous subsets based on average bending-moment resistance by the joint, loading and substrate Types

(Duncan Multiple Comparison: alpha level =0.05)

Lodgepole pine			
Joint	Tension loading	Joint	Compression loading
1/2" dowel	a	# S-6 plate	a
# S-6 plate	a b	1/2 " dowel	a b
# 20 plate	a b c	7/16" dowel	a b
7/16" dowel	a b c d	# 20 plate	a b
3/8" dowel	b c d	3/8" dowel	b c
# 10 plate	c d e	# 10 plate	b c
5/16" dowel	d e	5/16" dowel	c
1/4" dowel	e f	# 0 plate	c
# 0 plate	f	1/4" dowel	d
Particleboard			
Joint	Tension loading	Joint	Compression loading
1/2 " dowel	a	# S-6 plate	a
# S-6 plate	a	1/2 " dowel	a
7/16" dowel	a	# 20 plate	b
3/8" dowel	b	7/16" dowel	b
5/16" dowel	b	3/8" dowel	b c
# 20 plate	b c	5/16" dowel	c d
# 10 plate	c	# 10 plate	d
1/4" dowel	c	1/4" dowel	e
# 0 plate	d	# 0 plate	e

The line represents the homogeneous subsets where the highest and lowest means are not significantly different.

For lodgepole pine under tension and compression loading, the comparisons of homogeneous indicated that mean resistance of 1/2" dowel, 7/16" dowel, #20 (0.814 in^2) plate and #S-6 (2.765 in^2) plate had no significant difference (Table 4-11). The 1/4" dowel and #0 (0.814 in^2) wood-plate had the lowest resistance. In particleboard under tension and compression loading, the results indicated that 1/2" dowel and #S-6 (2.765 in^2) plate were not significantly different in both loading methods. #0 (0.814 in^2) plate joint was the lowest resistance in tension and compression loading (Table 4-11).

The results also indicated that the particleboard group had a higher number of significant pairwise differences than those in the lodgepole pine group and that joint strength was higher across all joint types for particleboard over those in lodgepole pine.

In generally, the #S-6 (2.765 in^2) plate and 1/2" diameter dowel exhibited the highest resistance regardless of loading method or substrate type, while the #0 (0.814 in^2) plate yielded the lowest resistance in all instances except in lodgepole pine with compression loading case where the 1/4" dowel joint had the lowest resistance (Table 4-11).

The modeling techniques examined the linear, exponential, quadratic, compound, inverse, cubic, S-shape and logistic equations to the resistance values to determine the functional relationships between bending-moment resistance (Y) and wetted surface area (X). Log_{10} of the bending-moment resistance was used as the dependent variable, while log_{10} of the wetted areas of dowels and wood-plates was used as the independent variable. The results indicated that the polynomial regression was the best fitting model for all configurations in this study In general, the bending-moment resistance increased with the wetted surface area of the joint. Therefore, the polynomial regression model had the following form:

$$Y = b_0 + b_1 X + b_2 X^2 + b_3 X^3$$

where:

$Y = \log_{10}$ of the bending-moment resistance (lb.-in).

$X = \log_{10}$ of the wetted surface area of a joint (in^2) or the single surface area of wood-plate were used in the regression.

b_0, b_1, b_2, b_3 = the regression coefficients.

The regressions analysis results for dowel joints are displaced in Table 4-12.

Table 4-12.
Regression coefficients and associated statistics for dowel joints

	Tension loading		Compression loading	
Coefficients	Lodgepole pine	Particleboard	Lodgepole pine	Particleboard
b_0	1.9297	2.0720	2.0061	1.7046
b_1	1.9847	0.7342	-0.2231	4.9608
b_2	-6.6722	-1.0946	6.4035	-18.611
b_3	9.0177	1.3433	-10.150	25.0731
R^2	0.571	0.536	0.621	0.857
SEE	0.0566	0.0513	0.0770	0.0463
N	40	40	40	40

The regressions analysis for wood-plate joints are displayed in Table 4-13

Table 4-13
Regression coefficients and associated statistics for wood-plate joints

	Tension loading		Compression loading	
Coefficients	Lodgepole pine	Particleboard	Lodgepole pine	Particleboard
b_0	2.0859	2.0978	2.1769	2.0823
b_1	0.7417	0.8107	0.4585	0.8357
b_2	-0.6219	-2.7882	0.0912	-0.9375
b_3	-0.7626	4.1527	-1.0326	1.4174
R^2	0.563	0.806	0.438	0.897
SEE	0.0780	0.0501	0.0778	0.0517
N	32	32	32	32

Discussion:

This study used two joint types having different sizes, two loading methods and two substrates to identify the factors effecting the mean bending-moment resistance of L-shaped corner joints and to derive the functional relationships between the dependent variable (bending-moment resistance) and joint surface area. In general, the average bending-moment resistance increased as the wetted areas of the joints increased in both tension and compression loading for the dowel and the wood-plate joints. The relationship was not linear.

Regarding the failure modes in lodgepole pine, Type 1 failures (face member failed) of dowel joints was caused by edge members having a deeper embedding depth than that in the face members. This factor influenced the loading failure more than the loading methods. In particleboard, the edge member of the dowel joint having deeper embedding depth were still the main factor causing the Type 1 failures.

Compared with the dowel joints; the wood-plate joint had same embedding depth in both edge and face members. Therefore, the type of the substrates and loading method effected the failure modes. The Type 1 failures mode of wood-plate joints in compression loading for lodgepole pine was caused by the face member having a better support line away from the edge (Fig 4-8). But in the larger sized wood-plate joints, the face member having growth rings nearly parallel to the wood-plate face caused the most Type 1 failures (Fig 4-8).

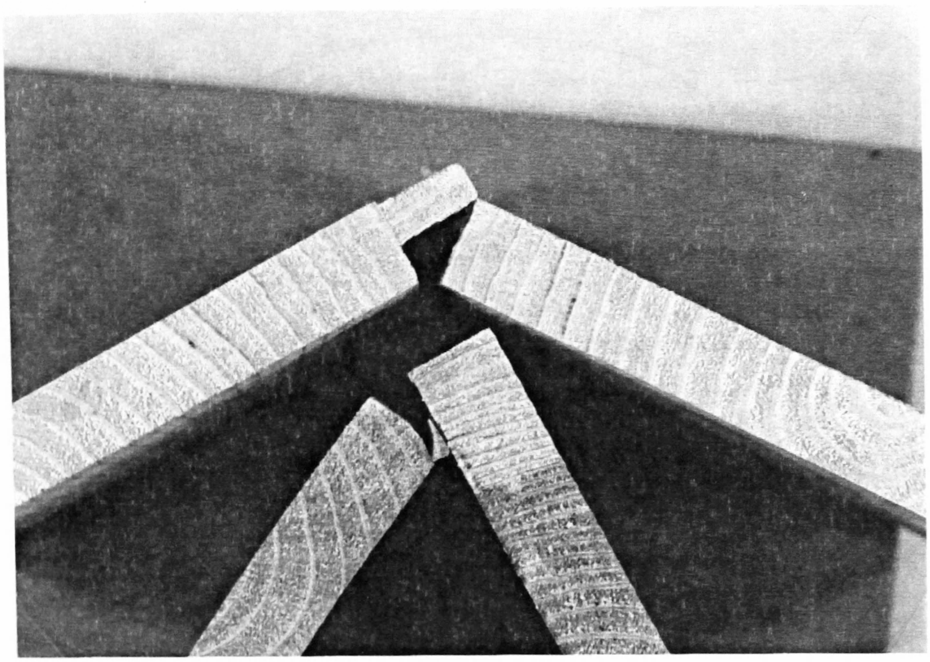

Figure 4-8.
Photo of various types of failures under tension and compression loading, and the relationship between growth rings and wood-plate face (the upper specimen was tension loading , the lower specimen was compression loading)

The wood-plate joints in particleboard having the high density exterior layer and the low density interior layer altered the change from Type 3 to Type 1 failures when the wood-plate size increased. The larger sized wood-plate joints had a lower percentage of their total glue-surface area in the high density exterior layer of the face members than those of the smaller wood-plate joints (Fig 4-9).

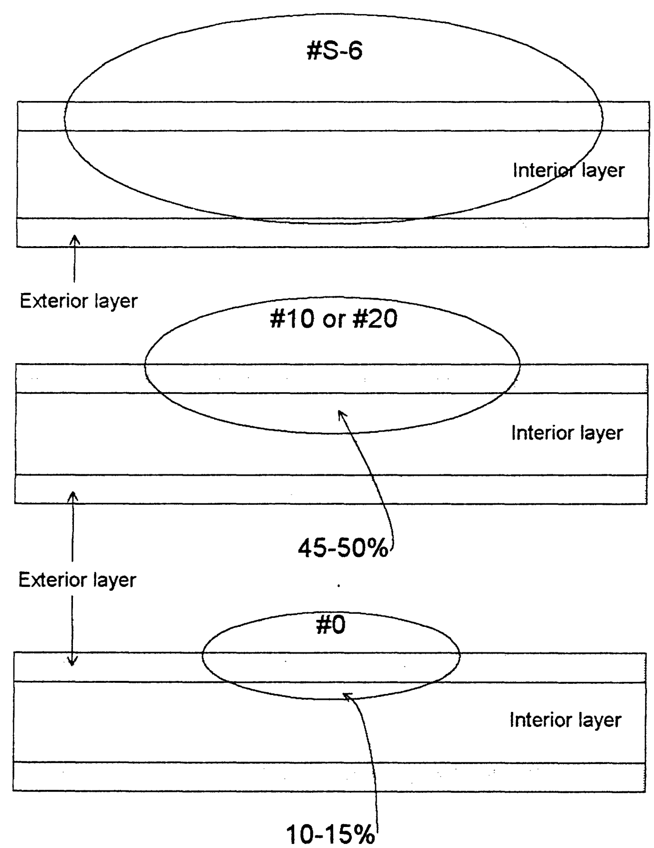

Figure 4-9.
Diagrams of the area of exterior particle layer on the bonding surface of wood-plate joints

The compression loading method yield higher bending-moment resistance than tension loading in all sizes dowel and wood-plate joints for lodgepole pine. Since the face members in compression loading had a support line away from the edge to provide a stronger resistance, but the support lines in tension loading located on the edges of both members (Fig 4-8). This situation did not cause the difference in failure of particleboard because the particleboard having low density interior layer that broke more easily than the exterior layers.

Regarding the bending-moment resistance, the dowel joints in lodgepole pine was roughly equal to the resistance values in particleboard group except for the 1/2" diameter dowel joint under compression loading in particleboard had a greater values, but the resistance means did not increase significantly from 5/16" to 3/8" dowel joints under tension loading in particleboard. These could be caused by the failure of dowel joints in particleboard where the 7/16" diameter dowel had better force-distribution on bonding area than the 5/16" and 3/8" dowel joints. The change of mean resistance and dowel's wetted-area was not exactly linear Eckelman also indicated the same tendency that the resistance did not increased significantly from 5/16" to 3/8" diameter dowel joints, but in his study was lacking data of the 7/16" and 1/2" diameter dowels.

For wood-plate, the mean of bending-moment resistance in particleboard rapidly increased from #20 (1.628 in^2) to #S-6 (2.765 in^2) plates in particleboard, because the #S-6 plate had 0.6" embedding depth in face member where bonding surface included two exterior layers on both plate's center and border (Fig. 4-9).

The accuracy of the assembly process could be another important factor effecting the bending-moment resistance of the wood-plate joints. While both joints need accurate components and holes / kerfs in the members, compared with the dowel joints, the assembly process of wood-plate joints required the operator to employ precise uniform use of the plate-jointer Every effort must be made to eliminate any vertical movement of the blade that would serve to enlarge the width of the kerf and a loose joint. The particleboard's propensity to swell with water-based adhesives would reduce the loose fit caused by operation errors. The accuracy of the plate-jointer also need to be monitored to avoid the inaccuracies from a faulty machine.

This study used lodgepole pine and particleboard as substrates and results indicated that the substrate was the weakest part of the joint design. The results showed that the strength of the substrate could effect the maximum strength of a corner-joint. For instance, medium density fiberboard, northern red oak (*Quercus rubra* L.) or sugar maple (*Acer saccharum* Marsh.) may have very different results from those obtained with industrial-grade particleboard and lodgepole pine.

The regression analysis revealed that the lodgepole group had lower R^2 values than those of the particleboard group. Lodgepole pine had higher variation in the wood properties such as different width of growth rings and higher density standard deviation than particleboard that caused the lower R^2 values in lodgepole pine group (Table 4-14).

Table 4-14
Means and standard deviations of density and moisture content for lodgepole pine and particleboard

	Lodgepole pine		Particleboard	
	Mean	Standard deviation	Mean	Standard deviation
Density (g / cc) / (lb./ ft^3)	0.512 / 31.949	0.065 / 4.056	0.714 / 44.553	0.028 / 1 747
Moisture content (%)	4.827	0.507	4.746	0.329

Not only are the engineers interested in the single wood-plate, but they are also interested in the factors effecting the strength of multiple wood-plate joints which can be used in an automatic control product line in the real world. The relationships between substrate physical properties and the space-structure of multiple-dowel joints are still unknown and need further study.

CHAPTER 5

CONCLUSIONS

1) In general, the bending-moment resistance increased from 1/4" to 1/2" diameter dowels and from the #0 to the #S-6 plates in both substrates. The Particleboard had more significant increase from #0 to #S-6 than those in lodgepole pine.

2) The results indicated that the 1/2" diameter dowel and the #S-6 wood-plate provided the maximum average bending-moment resistance under tension and compression loading in both lodgepole pine and particleboard, while the #0 plate and the 1/4" diameter dowel were the weakest configurations.

3) The strength of the 1/2" diameter dowel and the #S-6 plate joints were not significantly different in both substrates and loading methods.

4) Both dowel and wood-plate joints had higher resistance under compression loading for lodgepole pine than those under tension loading except the 1/4" dowel joint.

5) Both joints did not exhibited significant difference of mean resistance under tension and compression loading for particleboard except the 1/2" dowel and #S-6 plate.

6) For dowel joints, the substrates were the weakest part when the dowel joints size was 5/16" or larger. In all the wood-plate joints, the substrate was the weakest part in the joints.

7) The lodgepole pine group exhibited larger variation in bending-moment resistance than did particleboard group, since the particleboard had more uniform and denser particle structure than those in lodgepole pine.

Based on this study, in order to obtain the maximum bending-moment resistance, the #S-6 plate, 1/2" dowel and compression loading method are recommended to use in the corner-joint structures in both lodgepole pine and particleboard.

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Appendix A.
List of raw data

WOOD = wood type, where 1 = lodgepole pine, 2 = particleboard
JOINTS = wood-plate and dowel, where 1 = wood-plate, 2 = dowel
LOAD = loading method, where 1 = tension loading, 2 = compression loading
FORCE = loading force
DISTANCE =Lt or Lc
RES = bending-moment resistance
AREA = wetted-area
JOINT TYPE, where 1 = 1/4" dowel, 2 = 5/16" dowel, 3 = 3/8" dowel, 4 = 7/16" dowel, 5 = 1/2" dowel, 6 = #0 plate, 7 = #10 plate, 8 = #20 plate, 9 = #S-6 plate

SPECIMEN NUMBER	WOOD	JOINTS	LOAD	FORCE (Lb.)	DISTANCE (in)	RES (Lb.-in)	AREA (in^2)	JOINT TYPE	Lg10(RES)	Lg10(AREA)
006	i	2	1	72.500	7 774	140.904	1.264	1	2.149	102
007	1	2	1	79.000	7.810	154.248	1.264	1	2.188	102
008	1	2	1	64.500	7.750	124.969	1.264	1	2.097	102
010	1	2	1	60.500	7.560	114.345	1.264	1	2.058	102
011	1	2	1	62.500	7.280	113.750	1.264	1	2.056	102
032	2	2	1	57.600	7 741	111.470	1.264	1	2.047	102
033	2	2	1	72.500	7.860	142.463	1.264	1	2.154	102
034	2	2	1	72.700	7 786	141.511	1.264	1	2.151	102
035	2	2	1	68.500	7 782	133.267	1.264	1	2.125	102
036	2	2	1	85.500	7.822	167 195	1.264	1	2.223	102
037	2	2	2	30.000	8.850	102.416	1.264	1	2.010	102
038	2	2	2	32.700	8.870	111.310	1.264	1	2.047	102
039	2	2	2	32.500	8.820	111.432	1.264	1	2.047	102
040	2	2	2	32.500	8.830	111.272	1.264	1	2.046	102
041	2	2	2	31.000	8.792	106.714	1.264	1	2.028	102
043	1	2	2	41.000	8.683	143.293	1.264	1	2.156	102
045a	1	2	2	30.000	8.657	105.219	1.264	1	2.022	102
045b	1	2	2	29.500	8.690	103.002	1.264	1	2.013	102
061	1	2	2	31.000	8.750	107.346	1.264	1	2.031	102
062	1	2	2	29.500	8.690	103.002	1.264	1	2.013	102
135	2	2	1	68.500	7.825	134.003	1.264	1	2.127	102
136	2	2	1	75.000	7.871	147.581	1.264	1	2.169	102
137	2	2	1	61.500	7.870	121.001	1.264	1	2.083	102
138	2	2	2	34.500	8.874	117.368	1.264	1	2.070	102
139	2	2	2	34.000	8.850	116.072	1.264	1	2.065	102
140	2	2	2	33.000	8.841	112.805	1.264	1	2.052	102
141	1	2	1	60.000	7.654	114.810	1.264	1	2.060	102
142	1	2	1	48.750	7.653	93.271	1.264	1	1.970	102
143	1	2	1	51.500	7.773	100.077	1.264	1	2.000	102
144	1	2	2	22.500	8.442	81.153	1.264	1	1.909	102
145	1	2	2	35.000	8.620	123.366	1.264	1	2.091	102
146	1	2	2	33.500	8.639	117.780	1.264	1	2.071	102
001	1	2	1	75.000	7.660	143.625	1.605	2	2.157	.205
002	1	2	1	67.000	7.721	129.327	1.605	2	2.112	.205
003	1	2	1	68.000	7.720	131.240	1.605	2	2.118	.205
004	1	2	1	68.500	7.856	134.534	1.605	2	2.129	.205
005	1	2	1	66.500	7.753	128.894	1.605	2	2.110	.205
017	2	2	1	84.100	7 722	162.355	1.605	2	2.210	.205
018	2	2	1	69.500	7.780	135.178	1.605	2	2.131	.205
019	2	2	1	94.100	7.780	183.025	1.605	2	2.263	.205
020	2	2	1	75.100	7.770	145.882	1.605	2	2.164	.205

021	1	2	2	26.000	8.388	94.408	1.605	2	1.975	.205
022	1	2	2	44.000	8.647	154.529	1.605	2	2.189	.205
023	1	2	2	35.000	8.750	121 197	1.605	2	2.083	.205
024	1	2	2	40.000	8.672	140.007	1.605	2	2.146	.205
025	1	2	2	50.000	8.534	178.240	1.605	2	2.251	.205
026	2	2	2	35.000	8.826	119.900	1.605	2	2.079	.205
027	2	2	2	49.500	8.850	168.987	1.605	2	2.228	.205
028	2	2	2	45.100	8.811	154.832	1.605	2	2.190	.205
029	2	2	2	38.500	8.813	132.136	1.605	2	2.121	.205
030	2	2	2	37.500	8.826	128.464	1.605	2	2.109	.205
031	2	2	1	96.100	7 790	187 155	1.605	2	2.272	.205
1462	2	2	1	71.500	7.870	140.676	1.605	2	2.148	.205
147	2	2	1	76.000	7.885	149.815	1.605	2	2.176	.205
148	2	2	1	86.000	7.958	171.097	1.605	2	2.233	.205
149	2	2	2	38.500	8.910	130.285	1.605	2	2.115	.205
150	2	2	2	49.500	8.862	168.693	1.605	2	2.227	.205
151	2	2	2	42.500	8.920	143.607	1.605	2	2.157	.205
152	1	2	1	75.000	7.682	144.038	1.605	2	2.158	.205
153	1	2	1	68.000	7 759	131.903	1.605	2	2.120	.205
154	1	2	1	75.000	7.657	143.569	1.605	2	2.157	.205
155	1	2	2	51.000	8.735	176.971	1.605	2	2.248	.205
156	1	2	2	30.500	8.710	106.202	1.605	2	2.026	.205
157	1	2	2	49.500	8.410	179.251	1.605	2	2.253	.205
012	1	2	1	72.500	7.642	138.511	1.930	3	2.141	.286
013	1	2	1	65.200	7.200	117.360	1.930	3	2.070	.286
014	1	2	1	70.000	7.700	134.750	1.930	3	2.130	.286
015	1	2	1	75.000	7.680	144.000	1.930	3	2.158	.286
016	1	2	1	80.000	7.620	152.400	1.930	3	2.183	.286
046	2	2	1	70.000	7 757	135.748	1.930	3	2.133	.286
047	2	2	1	100.000	7.800	195.000	1.930	3	2.290	.286
048	2	2	1	87.500	7.771	169.991	1.930	3	2.230	.286
049	2	2	1	90.000	7.770	174.825	1.930	3	2.243	.286
050	2	2	1	77.000	7.710	148.418	1.930	3	2.171	.286
051	1	2	2	40.000	8.231	148.004	1.930	3	2.170	.286
052	1	2	2	57.500	8.770	198.553	1.930	3	2.298	.286
053	1	2	2	31.500	8.680	110.136	1.930	3	2.042	.286
054	1	2	2	47.500	8.335	173.595	1.930	3	2.240	.286
055	1	2	2	43.000	8.700	149.934	1.930	3	2.176	.286
056	2	2	2	41.000	8.818	140.616	1.930	3	2.148	.286
057	2	2	2	50.000	8.762	172.848	1.930	3	2.238	.286
058	2	2	2	48.500	8.250	179.055	1.930	3	2.253	.286
059	2	2	2	38.000	8.880	129.162	1.930	3	2.111	.286
060	2	2	2	47.000	8.820	161 147	1.930	3	2.207	.286
158	2	2	1	71.500	7.858	140.462	1.930	3	2.148	.286
159	2	2	1	75.000	7.881	147 769	1.930	3	2.170	.286
160	2	2	1	85.500	7.800	166.725	1.930	3	2.222	.286
161	2	2	2	42.500	8.954	142.879	1.930	3	2.155	.286
162	2	2	2	48.500	8.894	164.513	1.930	3	2.216	.286
163	2	2	2	53.000	8.888	179.936	1.930	3	2.255	.286
164	1	2	1	81.000	7.690	155.723	1.930	3	2.192	.286
165	1	2	1	81.000	7 713	156.188	1.930	3	2.194	.286
166	1	2	1	94.000	7.595	178.483	1.930	3	2.252	.286
167	1	2	2	62.500	8.647	219.502	1.930	3	2.341	.286
168	1	2	2	51.000	8.695	177.950	1.930	3	2.250	.286
169	1	2	2	49.500	8.580	175.402	1.930	3	2.244	.286
071	1	2	2	40.500	8.682	141.564	2.234	4	2.151	.349
072	1	2	2	52.000	8.557	184.816	2.234	4	2.267	.349
073	1	2	2	65.000	8.795	223.659	2.234	4	2.350	.349
074	1	2	2	60.500	8.627	213.049	2.234	4	2.328	.349

075	1	2	2	57.500	8.700	200.493	2.234	4	2.302	.349
076	1	2	2	60.500	8.502	216.560	2.234	4	2.336	.349
077	1	2	2	52.500	8.588	185.836	2.234	4	2.269	.349
078	1	2	2	53.000	8.800	182.239	2.234	4	2.261	.349
079	1	2	1	66.000	7.603	125.450	2.234	4	2.098	.349
080	1	2	1	81.000	7.772	157.383	2.234	4	2.197	.349
081	1	2	1	66.500	7.815	129.924	2.234	4	2.114	.349
082	1	2	1	97.000	7.632	185.076	2.234	4	2.267	.349
083	1	2	1	91.000	7.616	173.264	2.234	4	2.239	.349
084	1	2	1	76.500	7 704	147.339	2.234	4	2.168	.349
085	2	2	2	56.000	8.920	189.224	2.234	4	2.277	.349
086	2	2	2	60.000	8.910	203.041	2.234	4	2.308	.349
087	2	2	2	43.500	8.884	147.770	2.234	4	2.170	.349
088	2	2	2	46.500	8.896	157.682	2.234	4	2.198	.349
089	2	2	2	47.500	8.903	160.907	2.234	4	2.207	.349
090	2	2	2	51.500	8.874	175.202	2.234	4	2.244	.349
091	2	2	2	47.500	8.900	160.978	2.234	4	2.207	.349
093	2	2	1	80.500	7.895	158.887	2.234	4	2.201	.349
094	2	2	1	89.000	7.860	174.885	2.234	4	2.243	.349
095	2	2	1	102.500	7.895	202.309	2.234	4	2.306	.349
096	2	2	1	97.500	7.857	191.514	2.234	4	2.282	.349
097	2	2	1	98.000	7.902	193.599	2.234	4	2.287	.349
098	2	2	1	96.500	7.875	189.984	2.234	4	2.279	.349
099	2	2	1	100.500	7 778	195.422	2.234	4	2.291	.349
100	2	2	1	94.000	7.893	185.486	2.234	4	2.268	.349
101	1	2	1	93.000	7.779	180.862	2.234	4	2.257	.349
102	2	2	2	50.000	8.846	170.793	2.234	4	2.232	.349
0841	1	2	1	80.000	7 700	154.000	2.234	4	2.188	.349
103	1	2	1	77.500	7.348	142.368	2.653	5	2.153	.424
104	1	2	1	96.000	7.410	177.840	2.653	5	2.250	424
105	1	2	1	86.000	7.552	162.368	2.653	5	2.211	424
106	1	2	1	92.500	7.674	177.461	2.653	5	2.249	.424
107	1	2	1	95.500	7.803	186.297	2.653	5	2.270	.424
108	1	2	1	91.000	7.962	181 136	2.653	5	2.258	.424
109	1	2	1	115.500	7.871	227.275	2.653	5	2.357	424
110	1	2	1	109.000	7 772	211 787	2.653	5	2.326	.424
111	1	2	2	60.000	8.634	211.090	2.653	5	2.324	424
112	1	2	2	61.500	8.645	216.048	2.653	5	2.335	.424
113	1	2	2	56.000	8.574	198.591	2.653	5	2.298	424
114	1	2	2	51.000	8.621	179.739	2.653	5	2.255	.424
115	1	2	2	52.500	8.700	183.058	2.653	5	2.263	.424
116	1	2	2	57.500	8.760	198.832	2.653	5	2.298	.424
117	1	2	2	55.500	8.720	192.987	2.653	5	2.286	.424
118	1	2	2	50.500	8.749	174.895	2.653	5	2.243	.424
119	2	2	1	110.000	7.761	213.428	2.653	5	2.329	424
120	2	2	1	96.000	7.783	186.792	2.653	5	2.271	.424
121	2	2	1	86.000	7.782	167.313	2.653	5	2.224	.424
122	2	2	1	116.000	7.410	214.890	2.653	5	2.332	.424
123	2	2	1	110.000	7 700	211.750	2.653	5	2.326	.424
124	2	2	1	107.500	7 780	209.088	2.653	5	2.320	.424
125	2	2	1	97.000	7.862	190.654	2.653	5	2.280	.424
126	2	2	1	80.000	7.838	156.760	2.653	5	2.195	.424
127	2	2	2	75.000	8.755	259.527	2.653	5	2.414	424
128	2	2	2	65.000	8.830	222.544	2.653	5	2.347	.424
129	2	2	2	64.000	8.828	219.183	2.653	5	2.341	.424
130	2	2	2	72.500	8.752	250.981	2.653	5	2.400	.424
131	2	2	2	78.500	8.720	272.963	2.653	5	2.436	.424
132	2	2	2	61.000	8.863	207.854	2.653	5	2.318	.424
133	2	2	2	62.000	8.890	210.429	2.653	5	2.323	424

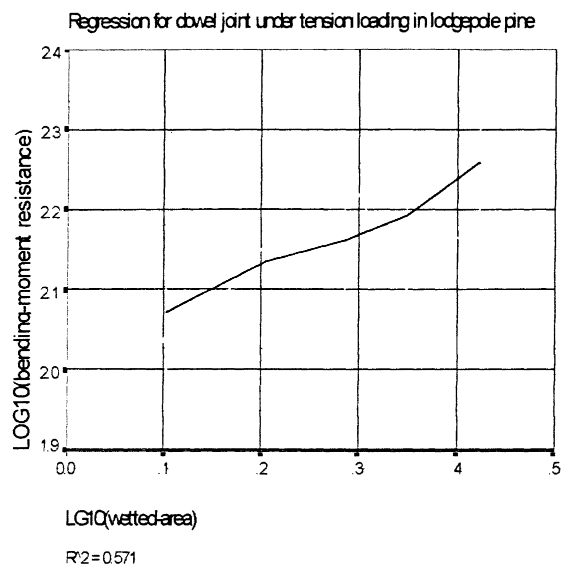
134	2	2	2	77.500	8.743	268.628	2.653	5	2.429	.424
w001	1	1	1	46.500	7.532	87.560	.814	6	1.942	-.089
w002	1	1	1	66.000	7.432	122.628	.814	6	2.089	-.089
w003	1	1	1	45.000	7.610	85.613	.814	6	1.933	-.089
w008	1	1	1	46.500	7.484	87.002	.814	6	1.940	-.089
w007	1	1	1	40.000	7.628	76.280	.814	6	1.882	-.089
w017	1	1	2	38.000	8.500	136.056	.814	6	2.134	-.089
w018	1	1	2	32.500	8.663	113.895	.814	6	2.057	-.089
w019	1	1	2	52.500	8.720	182.555	.814	6	2.261	-.089
w020	1	1	2	32.500	8.682	113.601	.814	6	2.055	-.089
w021	1	1	2	42.700	8.651	149.883	.814	6	2.176	-.089
w022	2	1	2	28.000	8.831	95.851	.814	6	1.982	-.089
w023	2	1	2	30.000	8.791	103.286	.814	6	2.014	-.089
w024	2	1	2	28.000	8.826	95.920	.814	6	1.982	-.089
w025	2	1	2	31.500	8.765	108.849	.814	6	2.037	-.089
w026	2	1	2	31.500	8.796	108.373	.814	6	2.035	-.089
w011	2	1	1	47.500	7 732	91.818	.814	6	1.963	-.089
w012	2	1	1	52.600	7 732	101.676	.814	6	2.007	-.089
w013	2	1	1	41.000	7 724	79.171	.814	6	1.899	-.089
w014	2	1	1	51.500	7 726	99.472	.814	6	1.998	-.089
w015	2	1	1	50.000	7 783	97.288	.814	6	1.988	-.089
w097	1	1	2	46.500	8.374	169.136	.814	6	2.228	-.089
w098	1	1	2	41.000	8.402	148.618	.814	6	2.172	-.089
w099	1	1	2	30.000	8.759	103.753	.814	6	2.016	-.089
w100	1	1	1	71.000	7.528	133.622	.814	6	2.126	-.089
w101	1	1	1	62.500	7.577	118.391	.814	6	2.073	-.089
w102	1	1	1	72.000	7.610	136.980	.814	6	2.137	-.089
w104	2	1	1	62.500	7.830	122.344	.814	6	2.088	-.089
w105	2	1	1	60.000	7.810	117 150	.814	6	2.069	-.089
w106	2	1	1	50.000	7.814	97.675	.814	6	1.990	-.089
w107	2	1	2	30.000	8.835	102.639	.814	6	2.011	-.089
w108	2	1	2	32.500	8.850	110.951	.814	6	2.045	-.089
w109	2	1	2	22.500	8.827	77.068	.814	6	1.887	-.089
w027	1	1	1	70.500	7.566	133.351	1 182	7	2.125	.073
w028	1	1	1	50.500	7.411	93.564	1 182	7	1.971	.073
w029	1	1	1	82.500	7.466	153.986	1 182	7	2.187	.073
w030	1	1	1	67.500	7.567	127.693	1 182	7	2.106	.073
w031	1	1	1	66.500	7.600	126.350	1 182	7	2.102	.073
w032	1	1	2	42.500	8.438	153.366	1 182	7	2.186	.073
w033	1	1	2	52.500	8.656	184.158	1.182	7	2.265	.073
w034	1	1	2	36.000	8.665	126.126	1 182	7	2.101	.073
w035	1	1	2	38.500	8.695	134.335	1 182	7	2.128	.073
w036	1	1	2	48.000	8.566	170.399	1 182	7	2.231	.073
w037	2	1	1	70.000	7 761	135.818	1 182	7	2.133	.073
w038	2	1	1	66.500	7 789	129.492	1 182	7	2.112	.073
w039	2	1	1	73.000	7 730	141.073	1 182	7	2.149	.073
w040	2	1	1	69.000	7.719	133.153	1.182	7	2.124	.073
w041	2	1	1	77.500	7.721	149.594	1 182	7	2.175	.073
w042	2	1	2	37.600	8.803	129.231	1 182	7	2.111	.073
w043	2	1	2	40.000	8.762	138.279	1 182	7	2.141	.073
w044	2	1	2	43.000	8.800	147.854	1 182	7	2.170	.073
w045	2	1	2	42.500	8.826	145.593	1 182	7	2.163	.073
w046	2	1	2	42.600	8.808	146.312	1.182	7	2.165	.073
w081	1	1	2	52.250	8.668	182.984	1 182	7	2.262	.073
w082	1	1	2	52.250	8.664	183.083	1.182	7	2.263	.073
w085	1	1	2	50.000	8.625	176.120	1 182	7	2.246	.073
w086	1	1	1	80.000	7.631	152.620	1 182	7	2.184	.073
w087	1	1	1	85.000	7.726	164.178	1 182	7	2.215	.073
w088	1	1	1	82.000	7.712	158.096	1.182	7	2.199	.073

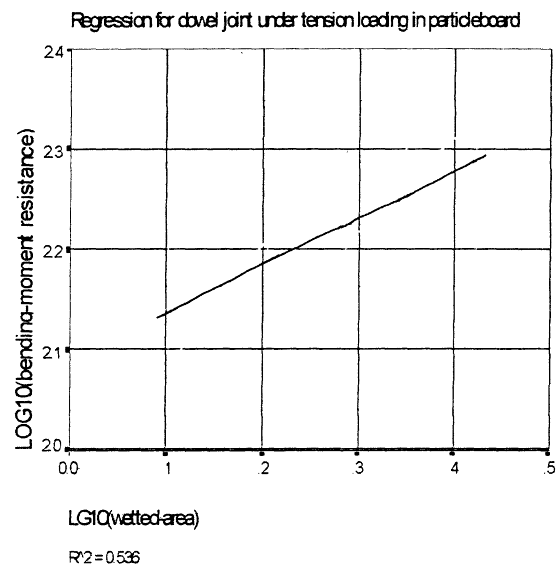
w091	2	1	2	40.000	8.820	137 147	1 182	7	2.137	.073
w092	2	1	2	37.500	8.836	128.280	1 182	7	2.108	.073
w093	2	1	2	38.000	8.855	129.633	1.182	7	2.113	.073
w094	2	1	1	80.000	7.806	156.120	1 182	7	2.193	.073
w095	2	1	1	69.500	7.829	136.029	1 182	7	2.134	.073
w096	2	1	1	69.000	7 770	134.033	1 182	7	2.127	.073
w004	1	1	1	89.500	7.563	169.222	1.628	8	2.228	.212
w005	1	1	1	80.000	7.637	152.740	1.628	8	2.184	.212
w006	1	1	1	72.500	7 766	140.759	1.628	8	2.148	.212
w009	1	1	1	75.200	7 764	145.963	1.628	8	2.164	.212
w010	1	1	1	72.500	7.692	139.418	1.628	8	2.144	.212
w016	1	1	2	45.500	8.720	158.214	1.628	8	2.199	.212
w067	1	1	2	43.300	8.716	150.648	1.628	8	2.178	.212
w068	1	1	2	40.000	8.784	137.851	1.628	8	2.139	.212
w069	1	1	2	61.000	8.658	213.916	1.628	8	2.330	.212
w070	1	1	2	52.500	8.484	188.356	1.628	8	2.275	.212
w071	2	1	1	73.000	7.733	141 127	1.628	8	2.150	.212
w072	2	1	1	73.700	7.776	143.273	1.628	8	2.156	.212
w073	2	1	1	76.500	7 777	148.735	1.628	8	2.172	.212
w074	2	1	1	75.000	7 737	145.069	1.628	8	2.162	.212
w075	2	1	1	90.100	7 737	174.276	1.628	8	2.241	.212
w076	2	1	2	45.000	8.803	154.665	1.628	8	2.189	.212
w077	2	1	2	57.500	8.785	198.133	1.628	8	2.297	.212
w078	2	1	2	50.000	8.801	171.899	1.628	8	2.235	.212
w079	2	1	2	57.600	8.815	197.632	1.628	8	2.296	.212
w080	2	1	2	60.000	8.819	205.749	1.628	8	2.313	.212
w110	1	1	1	102.000	7.473	190.562	1.628	8	2.280	.212
w112	1	1	1	103.400	7.632	197.287	1.628	8	2.295	.212
w113	1	1	1	87.500	7.544	165.025	1.628	8	2.218	.212
w114	1	1	2	57.000	8.550	202.772	1.628	8	2.307	.212
w115	1	1	2	67.500	8.521	241.028	1.628	8	2.382	.212
w116	1	1	2	62.500	8.752	216.363	1.628	8	2.335	.212
w117	2	1	1	88.600	7.821	173.235	1.628	8	2.239	.212
w118	2	1	1	78.500	7.800	153.075	1.628	8	2.185	.212
w119	2	1	1	75.000	7.819	146.606	1.628	8	2.166	.212
w120	2	1	2	47.500	8.857	161.995	1.628	8	2.210	.212
w121	2	1	2	46.000	8.844	157 175	1.628	8	2.196	.212
w121b	2	1	2	37.500	8.834	128.317	1.628	8	2.108	.212
w047	2	1	1	95.200	7 755	184.569	2.770	9	2.266	.442
w048	2	1	1	100.100	7 792	194.995	2.770	9	2.290	.442
w049	2	1	1	108.000	7 780	210.060	2.770	9	2.322	.442
w050	2	1	1	95.000	7.804	185.345	2.770	9	2.268	.442
w051	2	1	1	122.500	7.774	238.079	2.770	9	2.377	.442
w052	2	1	2	60.500	8.817	207.523	2.770	9	2.317	442
w053	2	1	2	83.000	8.811	284.946	2.770	9	2.455	.442
w054	2	1	2	65.000	8.832	222.480	2.770	9	2.347	.442
w055	2	1	2	76.000	8.816	260.728	2.770	9	2.416	.442
w056	2	1	2	82.500	8.801	283.633	2.770	9	2.453	.442
w057	1	1	1	88.000	7.442	163.724	2.770	9	2.214	.442
w058	1	1	1	90.000	7 738	174.105	2.770	9	2.241	.442
w059	1	1	1	97.500	7.688	187.395	2.770	9	2.273	.442
w060	1	1	1	68.000	7.688	130.696	2.770	9	2.116	442
w061	1	1	1	72.500	7.708	139.708	2.770	9	2.145	.442
w062	1	1	2	45.000	8.650	157.977	2.770	9	2.199	.442
w063	1	1	2	59.000	8.675	206.426	2.770	9	2.315	.442
w064	1	1	2	61.000	8.612	215.239	2.770	9	2.333	.442
w065	1	1	2	57.500	8.600	203.213	2.770	9	2.308	.442
w066	1	1	2	46.000	8.558	163.470	2.770	9	2.213	442
w132	1	1	1	89.000	7.582	168.700	2.770	9	2.227	442

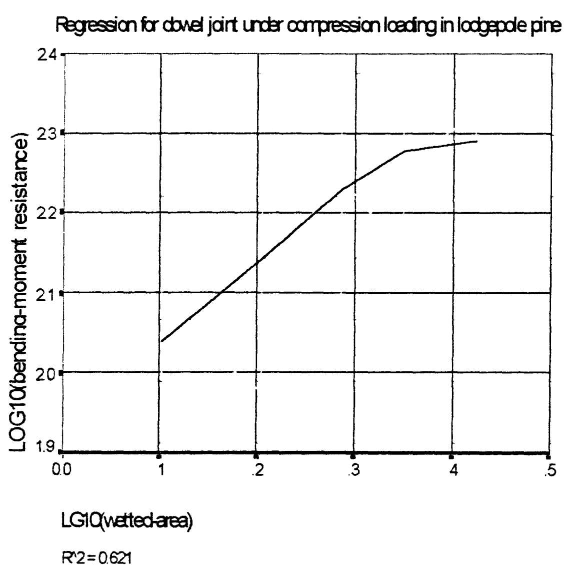
w133	1	1	1	107.500	7.528	202.315	2.770	9	2.306	442
w134	1	1	1	100.000	7.752	193.800	2.770	9	2.287	442
w135	1	1	2	63.000	8.617	222.148	2.770	9	2.347	.442
w136	1	1	2	71.500	8.602	252.624	2.770	9	2.402	.442
w137	1	1	2	62.500	8.520	223.203	2.770	9	2.349	.442
w138	2	1	1	76.500	7.825	149.653	2.770	9	2.175	.442
w139	2	1	1	75.500	7.790	147.036	2.770	9	2.167	442
w140	2	1	1	101.500	7.810	198.179	2.770	9	2.297	.442
w141	2	1	2	75.000	8.827	256.892	2.770	9	2.410	442
w142	2	1	2	66.000	8.880	224.334	2.770	9	2.351	.442
w143	2	1	2	70.500	8.848	240.748	2.770	9	2.382	.442

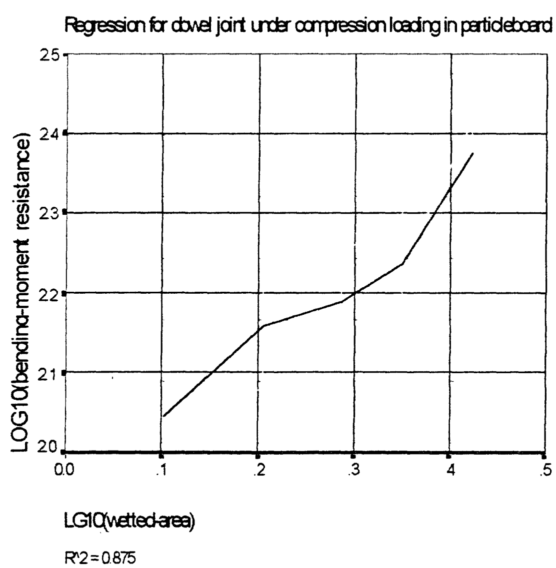
Appendix B-1.

Line charts of regression analysis results for dowel joints under tension and compression loading in lodgepole pine and particleboard









Appendix B-2.
Line charts of regression analysis results for wood-plate joints under tension and compression loading in lodgepole pine and particleboard