Tekniska Högskolan i Lund
Avdelningen för Bärande Konstruktioner

Lund Institute of Technology
Department of Structural Engineering

Lund 1996

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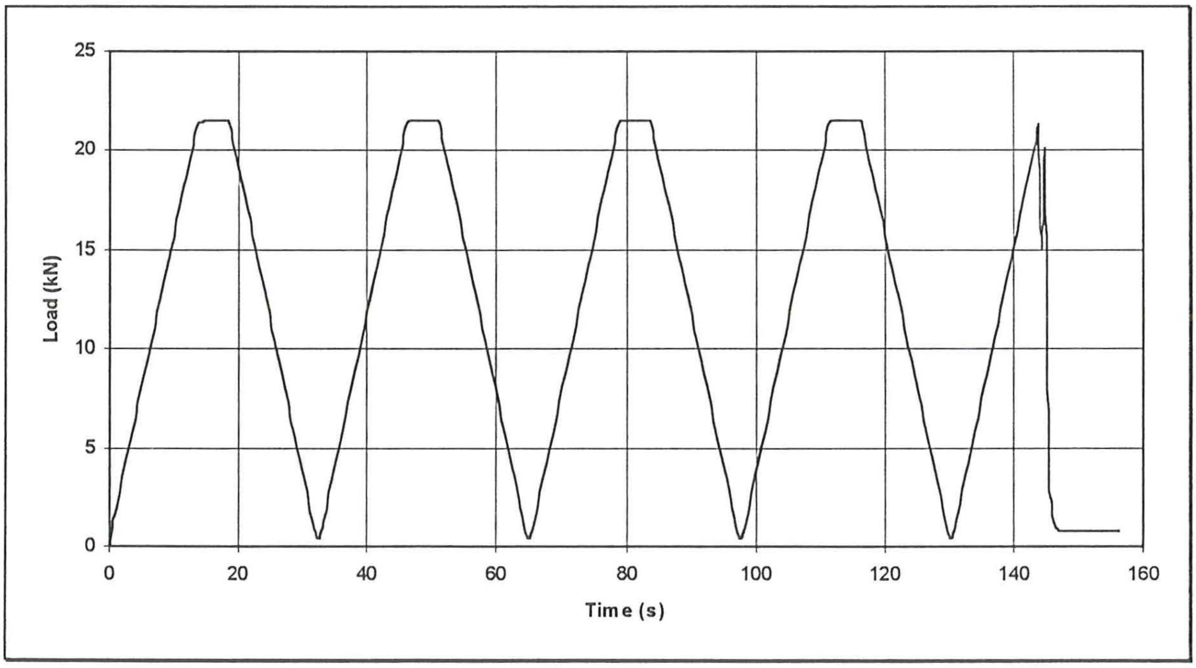

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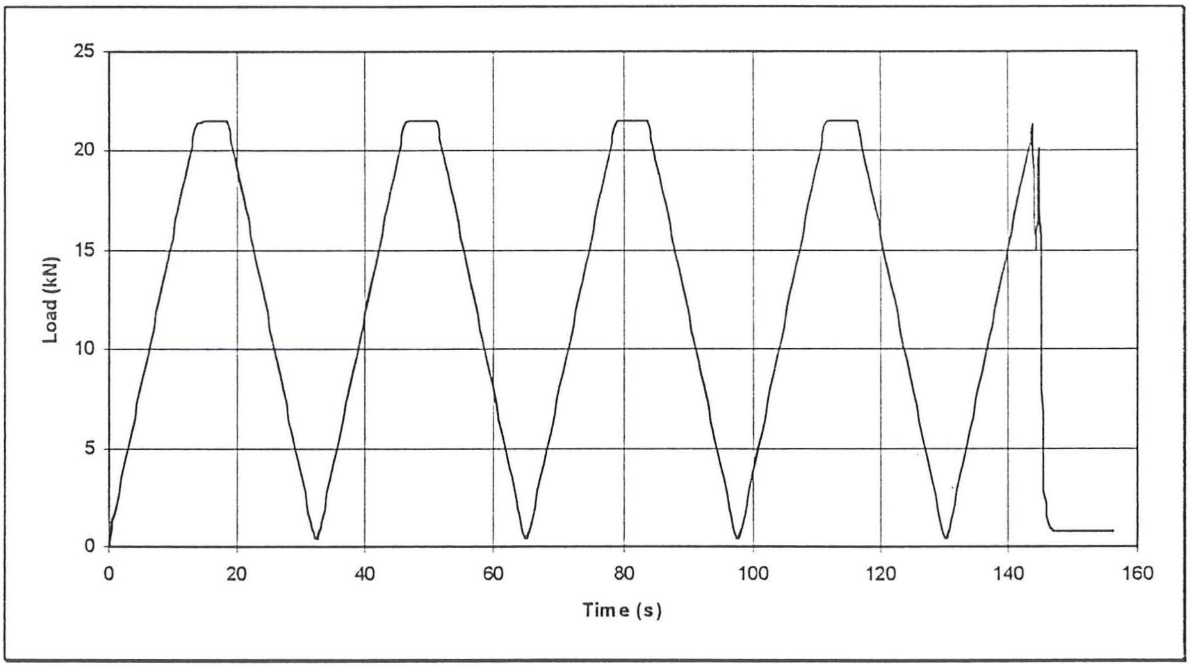

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Handledare: Sven Thelandersson
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Preface

This diploma work by Magnus Norlin has been made to fulfill the requirements for the degree of Civil Engineering at Lund University. The diploma work is formally related to the Division of Structural Engineering of Lund University.

The work has been made at Department of Wood Science of University of British Columbia, Vancouver, Canada during 1996 under supervision of Dr Frank Lam, who also evaluated the thesis. Many thanks are due to Frank Lam for his assistance.

In addition, the thesis has been evaluated at the division of Structural Engineering for fulfilment of the degree.

Lund March 1997

Sven Thelandersson
Professor of Structural Engineering

ABSTRACT

The fatigue behavior of laminated veneer lumber (Douglas-fir) subjected to shear-stress has been studied. The static shear strength of specimens, 37 by 102 by 406 mm was established through a three point bending test over a span of 305 mm. Four series of specimens were subjected to a cyclic load history with peak loads ranging from 95 to 80 percent of the static strength. The duration of each load cycle was approximately 32 seconds. A stress-level verses (log) number of cycles diagram was produced to show the fatigue behavior. The load-level was calculated from the static strength using the assumption of equal rank. A least square regression analysis was made and was found to fit the S-N data well. The lowest load-level tested in this research was approximately 70 percent. At this load-level the specimen survived close to 3000 cycles.

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ACKNOWLEDGMENT

I would like to thank Dr. Frank Lam for his supervision during this research. Dr. Sven Thelandersson is thanked for giving me the opportunity to write my thesis at U.B.C.

Mr. Peter Norlin is acknowledged for sharing his knowledge in the field and further, I would like to thank Mr. Avtar Sidhu and Mr. Bob Myronuk for their help and support during the many hours spent in the laboratory.

1. INTRODUCTION

The volume of high quality raw material for production of solid sawn structural wood components are decreasing. A way of creating a higher yield of the raw material is by using products made from smaller wood elements, such as flakes, strands or veneers. Laminated veneer lumber (LVL) is a product that fulfill the demands of greater yield without any significant decrease in mechanical properties.

Rotary peeled veneers, cut in appropriate size, dried and spread with adhesive are pressed with the grain parallel to the billet under heat to become LVL.

Laminated veneer lumber has been used as construction components for a long time. During the second world war, laminated veneer products were used in the aircraft industry as structural members in fighter-planes with excellent result. However, rapid development in the aircraft industry coupled with advances in material science allow carbon fiber and aluminum to be the material of choice in aircraft replacing laminated wood products. There are, however, many applications that suit laminated veneer products to take advantage of its uniformly and relatively high structural properties. Laminated veneer products are today commonly used as structural components in floor and roof framing members (joists / beams) and as wall or floor sheathing material (panels).

2. REVIEW OF LITERATURE

2.1 Laminated Veneer Lumber

Bohlen (1972) under the USDA FPL Presslam Research Team and Koch (1973) found that butt jointed laminations of thick rotary peeled veneer proved to have higher structural properties than sawn lumber except for longitudinal shear strength.

Bohlen also performed tests on LVL to evaluate the effects of butt joints on shear strength. He tested short beam specimens as joists. In 50 percent of the specimens, there were no joints present in any cross section. The average shear strength in these specimens were the same as that in the other specimens, which had at least one or more butt joints. Bohlen drew the conclusion that the presence of butt joints has no influence on the shear strength of LVL when tested as a joist.

Because of the layered structure of LVL, the strength-reducing defects are distributed throughout the whole volume of material, and the amount of low-strength wood in any cross section are minimized. Hence, high and dependable design strength in LVL can be expected.

One of the major variables when predicting the mechanical properties in LVL is the amount and depth of lathe checks. Lathe checks appear on the veneer face due to the induced stresses during rotary peeling of the raw log (see Fig. 1).

When wood is exposed to shear forces that are high enough to cause failure, it can fail in longitudinal shear or rolling shear. Rolling shear failures occur when the shear forces acting perpendicular to the grain direction are large enough to make the fibers roll on top of each other. Longitudinal shear failures occur when whole fibers slide in the grain direction relatively to each other. Therefore the depth of lathe checks has less effect on the longitudinal shear strength than the rolling shear strength.

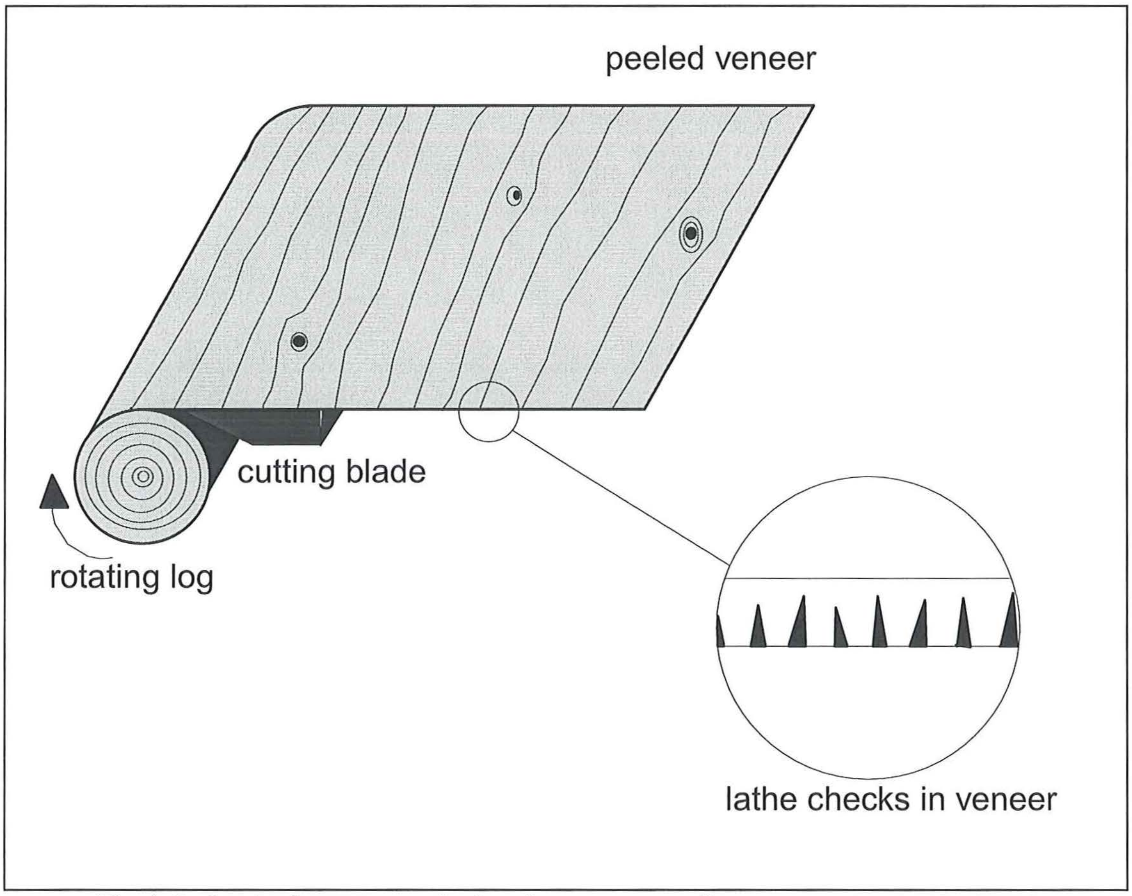

Fig. 1. Lathe checks appear on the face due to rotary peeling.

Another factor that influences the mechanical properties of LVL is the thickness of the veneers. Preston[1] (1978) examined veneer-resin systems and found that the strength increases with decreasing veneer thickness. Preston further found that a decrease of veneer thickness results in an increase of specific gravity. Fifty percent of the increase in strength can be related to the increase of specific gravity, the other half of the increase Preston related to the repair of lathe checks by resin. Other investigators have reached the same result, Leicester[2] (1978) observed that using sufficiently thin veneers could result in strength properties approaching those of defect-free wood.

One problem with laminated veneer lumber stems from its reduced shear strength along the grain. This is a result of lathe checks induced by rotary peeling, drying and pressing. In 1972 Peters[3] (1983) found that 12.5 mm southern pine veneer press-Lam® achieved a shear strength perpendicular to the glue-line of 50 percent compared to solid-wood. By a vacuum-pressure soak oven-drying treatment (VPS-OD) of block shear specimens, an increase in shear strength perpendicular to the glue-line was achieved. The shear strength in this case reached 60 percent of solid-wood strength. In the plane perpendicular to the checks, the shear is tested higher than in the earlier case, but still only 60 percent in comparison to solid wood. Due to the thick veneers used in this research, this case describes a worst case scenario because of the depth of lathe checks.

[1] As referred by Kunesh.
[2] As referred by Kunesh.
[3] As referred by Laufenberg.

2.2 Fatigue Performance

When a material is exposed to a continued repetition of stress, it will deteriorate This phenomenon is called fatigue. It is very important to understand the mechanism of fatigue, otherwise mistakes made in extrapolation of data can be devastating. In classical treatment of fatigue data, an endurance limit is defined as the maximum stress to which a specimen can be subjected an infinite number of times. In comparison to fatigue in metals, fatigue in wood is a more time demanding subject to study. Metals commonly demands 10 million cycles to assure that the endurance limit is reached. In high strength steel, testing to approximately 2 million cycles are generally enough to assure that the endurance limit is reached. From fatigue studies in wood and plywood, Kommers (1943) found that testing in excess of 50 million cycles was not enough to give an accurate evaluation of the endurance limit.

In 1944, when wood still was used as a structural member in aircraft, Kommers (1944) investigated the fatigue behavior of Sitka spruce and Douglas-fir subjected to repeated and reversed bending stresses. The research was made in cooperation with the U.S. Army-Navy-Civil-Committee. A reversed stress-cycle superimposed on a constant stress level was used to model the loading resulted from a non accelerating flight. Tests were made at the same mean stress level (20 % of the static modulus of rupture) but with different amplitudes. Hence, the maximum load-level of the different test cycles ranged from 35 % to 80 % of the static modulus of rupture. The endurance strength for solid Sitka spruce and Douglas-fir at 50 million cycles was found to be 38 percent of the static modulus of rupture.

Other studies of fatigue indicate that the number of cycles to failure is not dependent on the load frequency, Cai (1996). In this research, the fatigue behavior in Oriented strain board (OSB) subjected to shear was studied. The OSB consisted of a mixture of different wood species (aspen was the most common species). A five point bending test was used to evaluate the fatigue performance. Tests were executed at three different stress-levels, 90, 80 and 70 percent of the static strength. At the 80 percent level, two groups of specimens were tested with different load frequencies: 1 Hz and 0.5 Hz. The researchers found no statistical difference of the fatigue behavior between the two groups. A straight line was fit to the data by least squares regression. At a stress level of 70 percent, the OSB panels approximately survived 10 000 cycles. Further the researchers drew the conclusion that the endurance limit of OSB subjected to shear stresses is way below 60 percent of the static strength.

Another study of fatigue behavior has been performed by Lam (1991). In this study the aim was to evaluate the performance of laminated wood panels in decking systems. As a part of the study fatigue tests were executed on small size specimens from a prototype decking panel. Cyclic tests were performed at 5 different stress levels: approximately 100%, 90%, 85%, 80% and 75% of the static strength. A full size relationship and a size adjusted relation ship was established between the stress ratio and number of cycles until failure. From the full size relationship, it was found that a applied stress ratio corresponding to 3000 cycles to failure was 0.47. The size adjusted relationship gave the result that the prototype panel survived 3000 cycles at a stress ratio of 0.5.

3. OBJECTIVES

The research objectives were to evaluate the fatigue performance of LVL subjected to shear stresses along the grain for plank wise applications. This research was a part in a larger project where the fatigue performance of members subjected to shear stress perpendicular to grain was also studied.

4. MATERIALS AND METHODS

4.1 General description

All the specimens that were tested in this research were manufactured at U.B.C. Twenty-five panels were pressed. From each panel, five test specimens were taken. The specimens were divided into six different test series, two short term test series and four cyclic test series. The two short term test groups were used as control groups to determine the static strength of the LVL panels. The two short term test series consisted of deflection controlled short term tests and load controlled short term tests. The cyclic tests consisted of tests at 95, 90, 85 and 80 percent of the median static strength. Both the short term specimens and the specimens in the cyclic groups were subjected to a three point bending test. In the fatigue tests, the load-cycle was repeated until the specimen failed and the number of cycles until failure were observed.

The width and thickness for all the specimens were measured before testing. Immediately after testing to failure a sample from each one of the specimens was taken to measure the moisture content. The weight of the sample was measured, then the specimens were dried in an oven for 48 hours and the oven dry weight was measured. The moisture content was calculated from the difference between the specimen weight and the oven dry weight divided by the ovendry weight.

4.2 Panel manufacturing

The LVL panels were made up by 15 layers of 2.54 mm thick Douglas Fir veneer and an additional reinforced layer of fiber-glass at the bottom of the specimen as shown in fig. 2. Where b is the width, t_f the thickness of the fiber-glass and t is the thickness of one veneer. The fiber-glass layer was added to prevent the panels from failing in tension under the bending load and force them to fail in longitudinal shear. The panels were manufactured in two steps. The first step consisted of pressing the panels. The second step consisted of applying the fiber-glass.

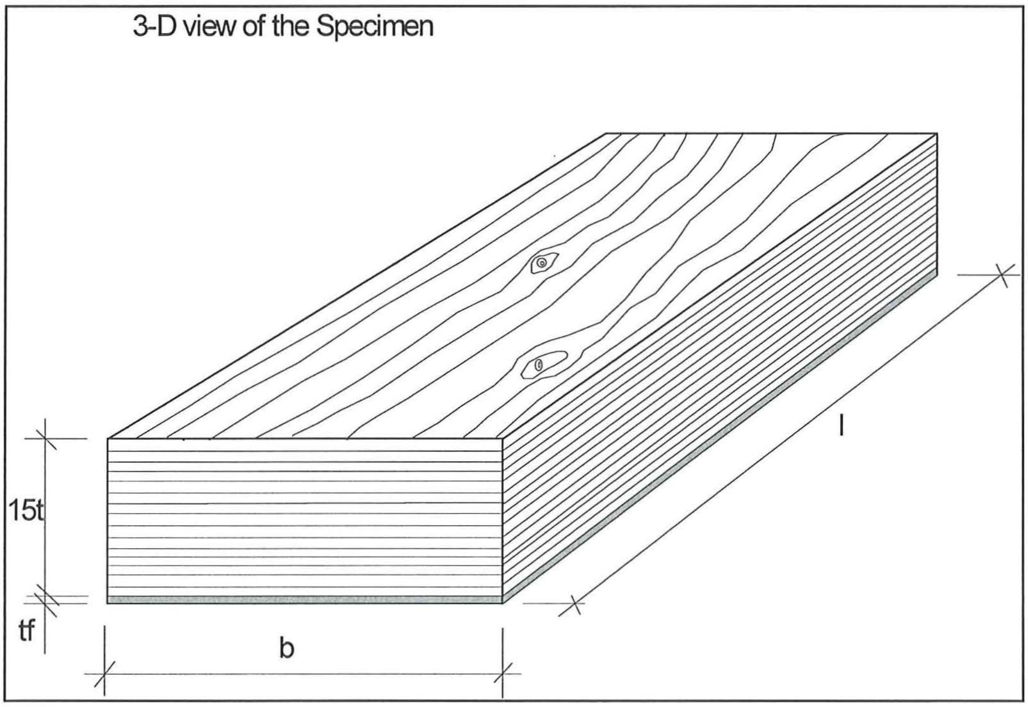

Fig. 2. 3-D view of the specimen

The veneers were donated by Ainsworth Lumber Co. Ltd. and they had been conditioned to a moisture content between 6-8 percent. The veneers were cut to 0.61 by 0.61 m sheets, spread with resin and pressed to LVL panels. An automatic glue spreader was used to apply the resin (see fig. 3). The glue spread on veneers was 194 g/m^2 and the resin used, was a Phenol formaldehyde. After being pressed, the average thickness of the panels was 3.7 cm.

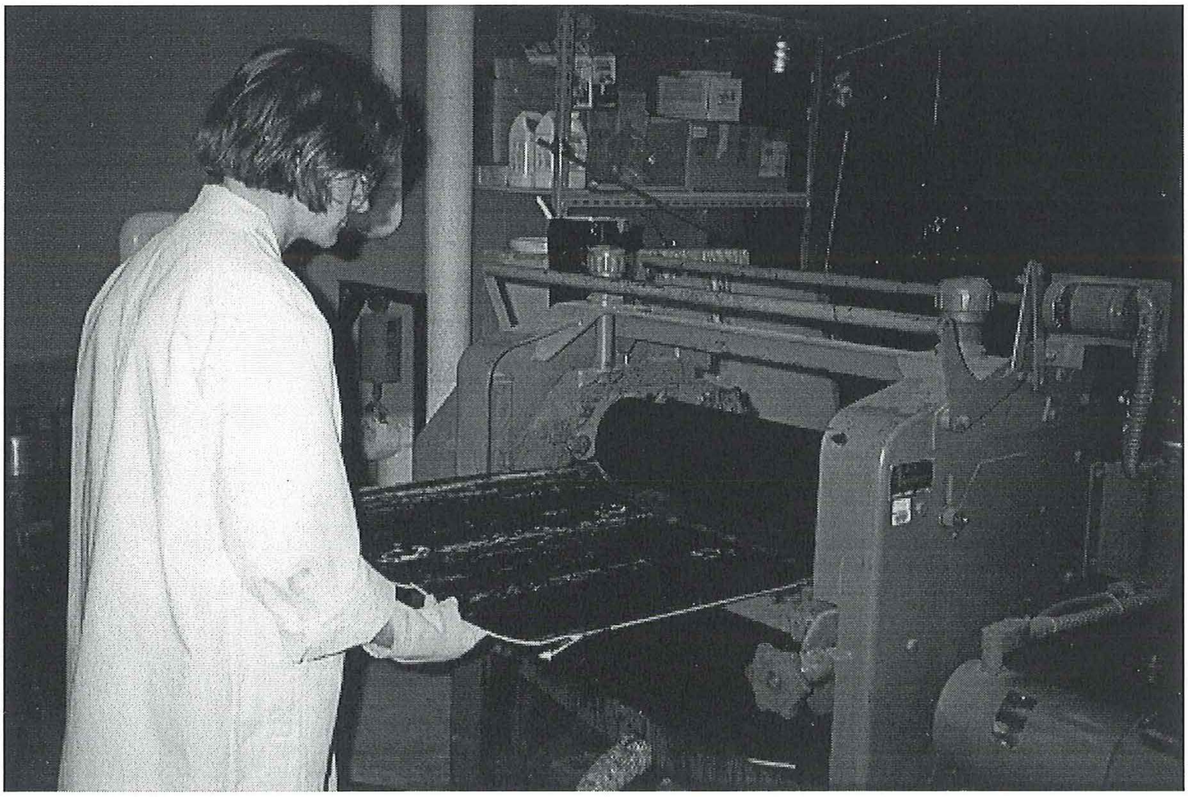

Fig 3. An automatic glue spreader was used to apply the resin.

A standard Hot Plate press was used to press the panels (see fig. 4). Two aluminum plates protected the press plates from the flowing resin. The press time was set to 19 minutes. The curing temperature for the Phenol formaldehyde resin was 93-97 °C and the curing time was 2 minutes. It took 17 minutes to reach the curing temperature in the middle layers. The temperature of the press plates was set to 150 °C and the pressure was 13.79 MPa. The panels were hotstacked after being pressed.

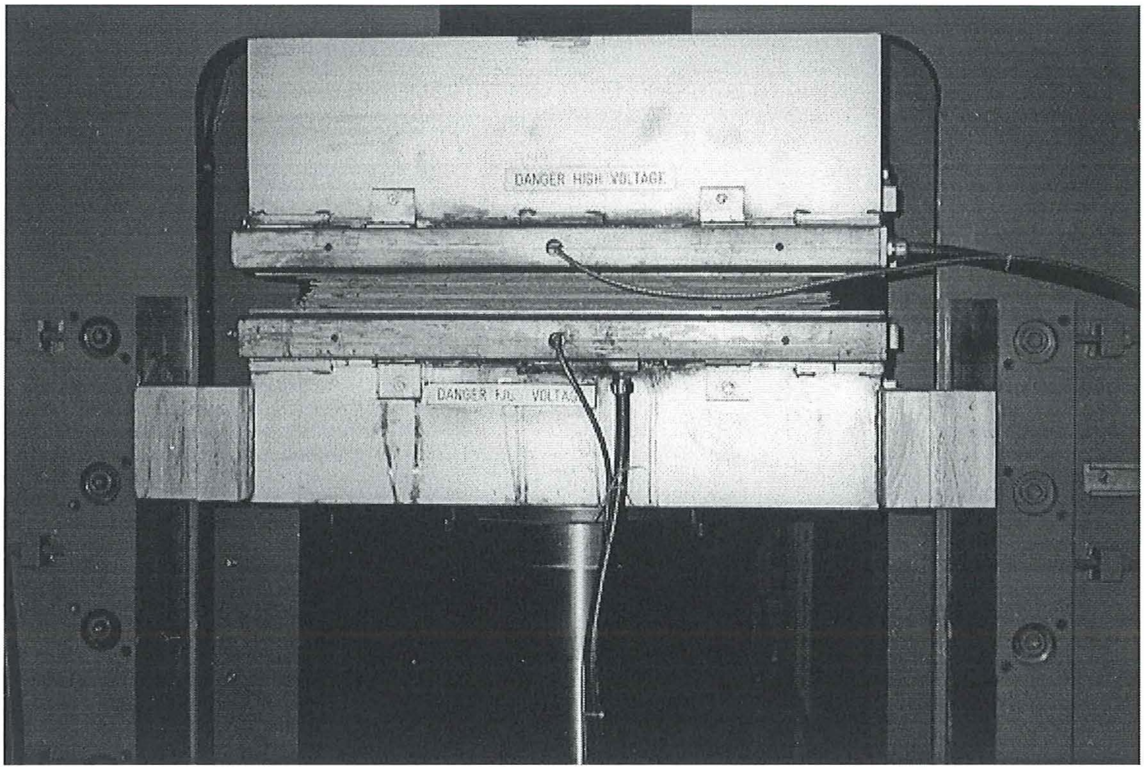

Fig. 4. A standard hotplate press was used to press the panels

Fig. 5 shows a panel where an additional fiber-glass layer has just been pressed to the panel. The fiber-glass was pressed to the bottom side of the specimens in a Standard Hot Plate Press. Fiberite Inc. provided the fiber-glass. The fiber-glass was a prepregnated woven rowing epoxy type e-glass and the thickness was 0.15 mm. Two aluminum plates were used to protect the press plates. A sheet of Teflon was used to prevent the epoxy to stick to the aluminum plates. The press time was 30 minutes and the temperature on the press plate closest to the fiber-glass was 150°C. The pressure was 106.7 MPa. After the fiber-glass layer was pressed to the panels they were again hotstacked.

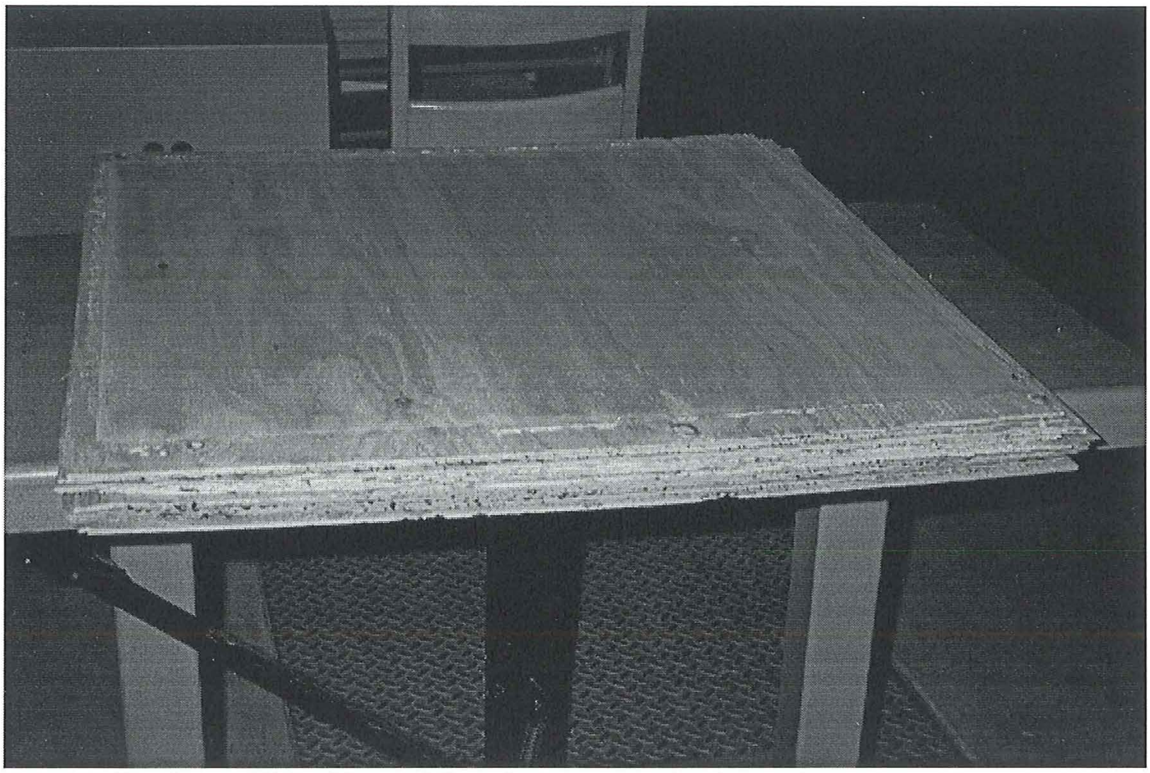

Fig. 5. An additional layer of fiber-glass was pressed to the panels

4.3 Test program

The 25 panels were cut into 102 by 37 by 406 mm specimens. Each panel was cut into five specimens; in total 125 specimens were manufactured. The panels were given numbers 1 to 25 and the specimens cut from each panel were also given numbers 1 to 5 starting from the edge, so the specimen cut from the middle of the panel always had number 3. From the beginning, the idea was to only use three different cyclic series, 95, 90 and 85 percent in addition to the two short term strength series. The specimens were divided into the different test series so that one panel had one specimen in each series. The five specimens from each panel were randomly divided into the five test series.

Ten specimens from each one of the above mentioned groups were initially tested. After looking at the results it was decided that an additional series should be tested at 80 percent to obtain more reliable data at the lower load levels. Since there were 20 specimens from the three cyclic groups that were not selected to be tested, an additional group was created from these specimens.

Twenty-five specimens were tested in the deflection controlled short term test series and another twenty-five in the load controlled short term test series. Twenty specimens were tested at the 95 percent level, twenty at 90, fifteen at 85 and ten at 80.

An MTS model 810 hydraulic control close loop universal testing machine (see fig. 6) was used to perform all the tests. A three point bending test setup was used. The distance between the two supports were 305 mm. The deflection controlled test series was the first series to be executed. The MTS was set to generate a uniform crosshead movement of 1.37 mm per minute until the specimens failed. The deflection controlled test series was executed to be able to calculate the ramp-rate for the load controlled test series. The median of the ultimate failure load was taken and used to calculate the ramp-rate for the load-controlled and the cyclic test series. Since a load-cycle of 30 seconds was preferred in the fatigue tests, a load-rate of 800 N/s was used to test the specimens in the load-controlled mode. This means that the median load for the deflection controlled test series was reached after 15 seconds.

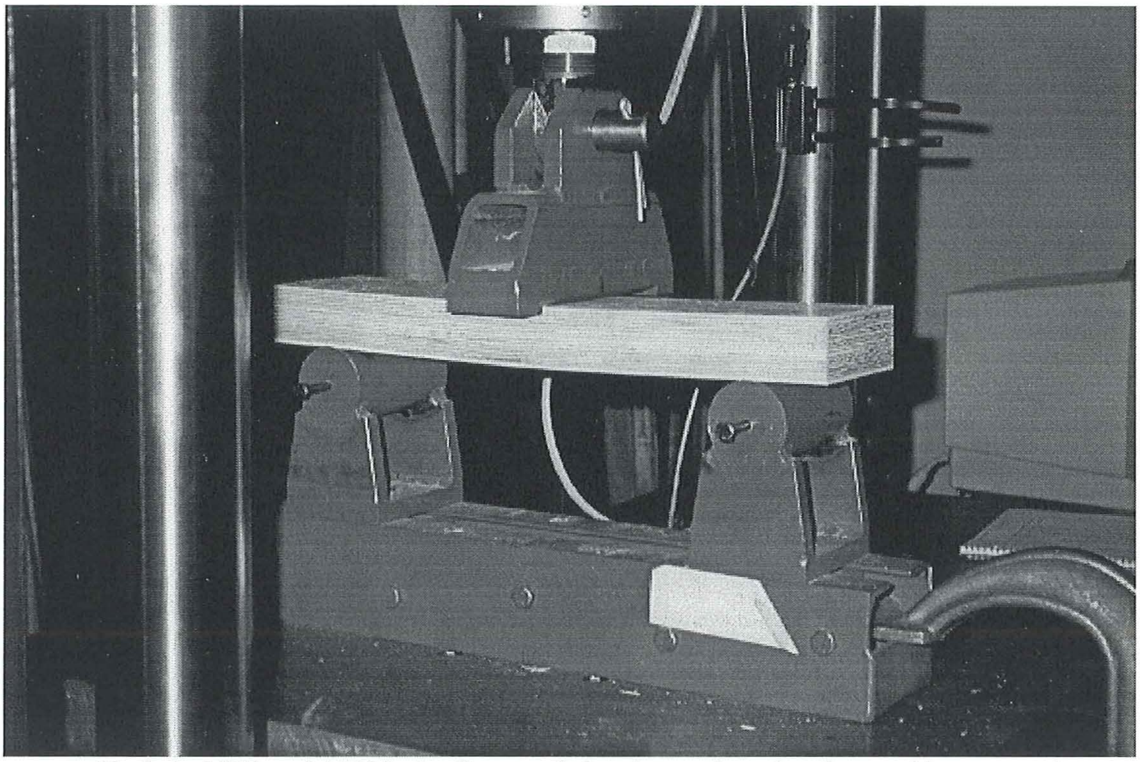

Fig 6. An MTS model 810 hydraulic control close loop universal testing machine was used to perform all the tests.

All the cyclic test series were executed in the load control mode. The load-rate was the same as in the short term load-controlled test series, 800 N per second. The specimens were tested in repeated loading fatigue. This means that the ratio, R, (the maximum applied stress divided by the minimum applied stress) is between 0 and 1. Figure 7 shows the load-cycle that was used for the cyclic tests. The load-cycle followed a trapezoid form. If the specimens were tested close to 100 % of their strength, the load verses time curve would have resembled a triangle, uploaded to 100 % and downloaded to 0 again with the same ramp-rate. The four different load-cycle curves were constructed by "cutting off" the tops of the triangles at different load-levels. When the load reached the level the specimen was tested on (level X) it was kept constant for a time corresponding to the time it would take to continue the uploading from level X to 100 % and than downloading again to level X. The load cycles were repeated until the specimen failed.

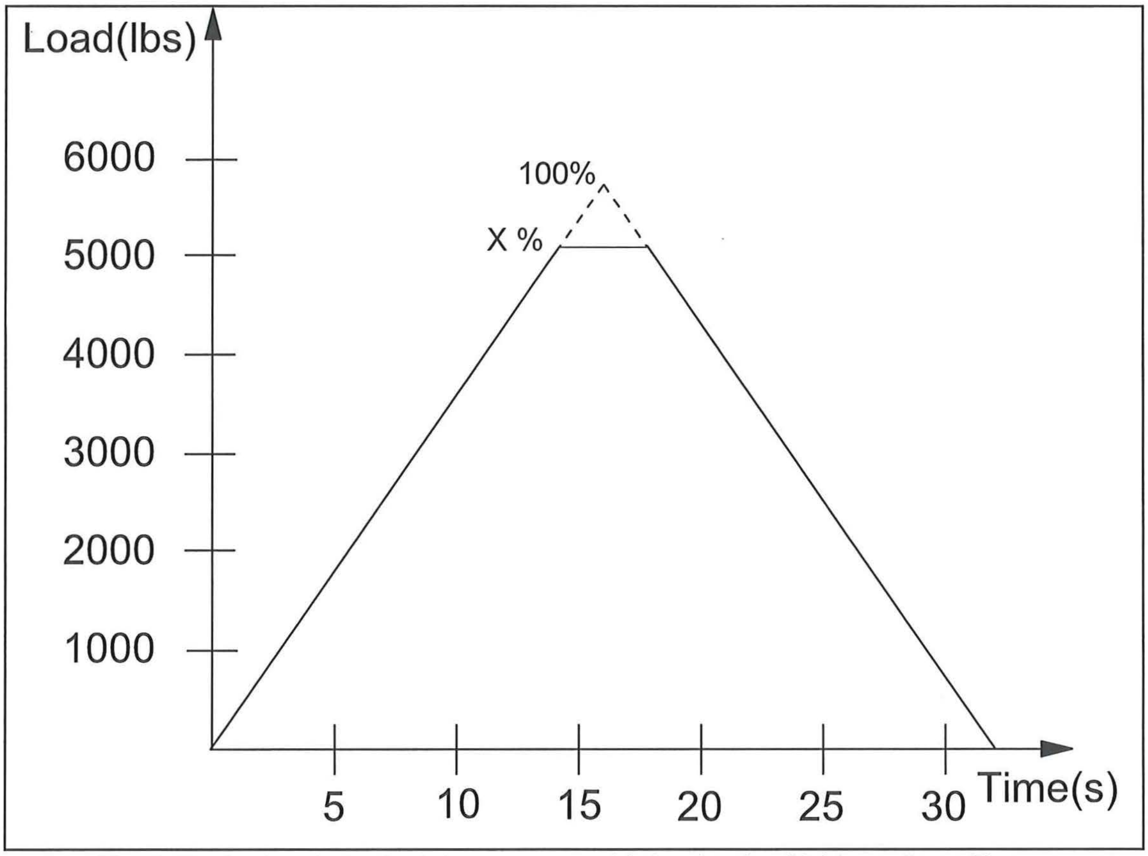

Fig. 7. The load cycle for the fatigue tests resembled a triangle with it's top "cut off'.

5. ANALYSIS

5.1 Short term tests

The median and the average for the ultimate load were calculated for both the deflection controlled and the load controlled tests series. Both elementary beam theory and finite element analysis were used to calculate the maximum shear-stress in the specimens. The purpose with the finite element calculations was to evaluate if the conditions for the elementary beam theory were fulfilled. The material properties of the Douglas-fir and the fiber-glass were taken from the literature Lam (1991) and Berthelot (1992) respectively. The following values were used throughout the analysis:

Douglas-fir veneers	Fiber-glass
$E_L = 13.581$ GPa	$E_L = E_T = 72.4$ GPa
$E_T = 0.428$ GPa	$G_{LT} = 7.30$ GPa
$G_{LT} = 0.830$ GPa	

where E and G is the modulus of elasticity and shear modulus respectively. The subscripts indicate the fiber direction.

5.1.1 Elementary beam theory:

In the elementary beam theory calculations, the neutral axis was calculated with the following formula:

$$15t \cdot b \cdot \frac{15t}{2} + t_f \cdot \frac{E_f}{E_w} \cdot b \cdot \left(15t + \frac{t_f}{2}\right) = \left(15t \cdot b + t_f \cdot \frac{E_f}{E_w} \cdot b\right) \cdot \bar{y} \tag{1}$$

Where t is the thickness of the veneers, t_f the thickness of the fiber-glass, E_f the MOE for the fiber-glass, E_w the MOE for the veneers, $\bar{y}$ is the distance from the top-side of the specimen to the neutral axis and b the width of the specimen (see fig 2 and fig 8). In fig. 8 the fiber-glass is transformed to wood. The specimen consisted of two materials with different MOE's. Thus, in order to use elementary beam theory, the cross section of the specimen had to be transformed during the calculations to consist of only one material. The fiber-glass was transformed to wood by multiplying the cross sectional width of the fiber-glass by a factor n (see fig. 8):

$$n = \frac{E_f}{E_w} \tag{2}$$

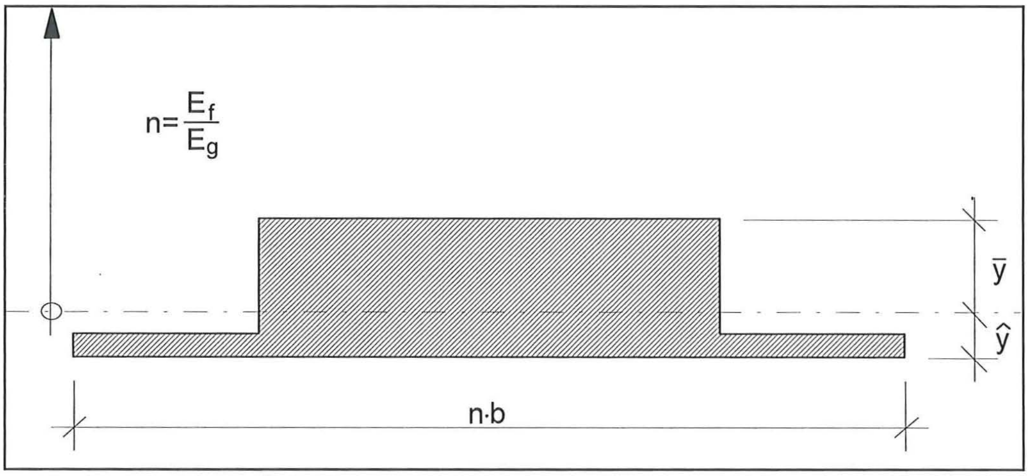

Fig. 8. Cross section of the specimen when the fiber-glass is transformed to wood

The strength of the "new" fiber-glass area with properties of wood corresponds to the strength of the original area with properties of fiber-glass. Solving for $\bar{y}$:

$$\bar{y} = \frac{225t^2 \cdot E_w + 30 \cdot t \cdot t_f \cdot Ef + t_f^{\ 2} \cdot E_f}{2 \cdot \left(15t \cdot E_w + t_f \cdot E_f\right)} \tag{3}$$

The Moment of Inertia is calculated as:

$$Ic = \frac{b \cdot (15t)^3}{12} + b \cdot 15t \cdot \left(\frac{15t}{2} - \bar{y}\right)^2 + \frac{\frac{E_f}{E_w} b \cdot t_f^{\ 3}}{12} + \frac{E_f}{E_w} \cdot b \cdot t \cdot t_f \cdot \left(15t + \frac{t_f}{2} - \bar{y}\right)^2 \tag{4}$$

The shear stresses are distributed as a function of the variables x and y. The equation for the distribution of shear-stresses in the specimen is:

$$\tau(x, y) = \frac{V(x) \cdot S(y)}{I_c \cdot b} \tag{5}$$

Where S(y) is the first moment and V(x) is the shear force. The first moment can be expressed as:

$$S(y) = (\bar{y} - y) \cdot b \cdot \left(y + (\bar{y} - y)\right) = \frac{b}{2} \cdot (\bar{y} - y)^2 \tag{6}$$

The maximum shear-stress is wanted. Since the maximum shear-stress is found in the neutral axis, the equation can be written:

$$S(y) = \frac{b \cdot \bar{y}^2}{2}, when\ y = 0 \tag{7}$$

V(x) is the shear force at a distance, x, from the edge in the specimen. The maximum shear force in the specimen for this specific load case is:

$$V = \frac{P}{2} \left(see\ fig\ 9\right) \tag{8}$$

The maximum shear stress in the neutral axis can now be written as:

$$\tau_{\max} = \frac{P \cdot \bar{y}^2}{4 \cdot I_c} \tag{9}$$

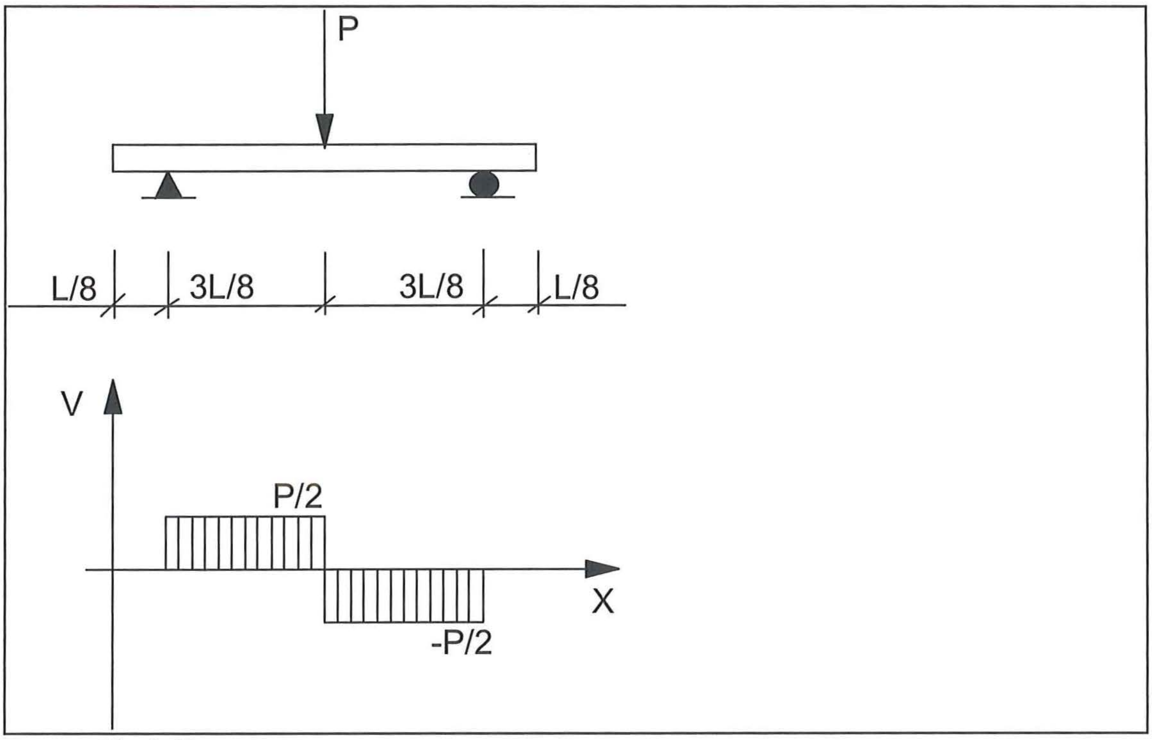

Fig. 9. Test setup

5.1.2 Finite element method

A two dimensional finite element program made by Dr. Foschi was used to make the finite element calculation. Since the stress distribution in the specimen is symmetrical, only one half of the specimen was modeled. Fig. 10 shows how the specimen was divided into elements. The width, thickness and length had been measured for all the specimens before testing. The average measurements were used to model the specimen with a width of 101.6 mm, a thickness of 37.44 mm and a length of 406.4 mm. The elements were numbered upwards from left to right starting from the lower left corner. The nodes were given numbers in the same way. The program uses isoparametric elements each containing eight nodes, the total number of elements were 117 and the total amount of nodes were 396. The support was modeled as shown in fig. 10. Nodes 78 and 107 were restricted to move in the X direction. Node number 88 was restricted to move in both the X and Y direction. The load on one half of the specimen is one half of the total load, 2.54 kN. Since the top veneer is being compressed during the test, the contact surface is approximately 5 mm. The load from the cross-head was modeled as a distributed load on element 117. The influence from the other half of the specimen were considered by making node number 378 to 396 restricted to move in the X direction.

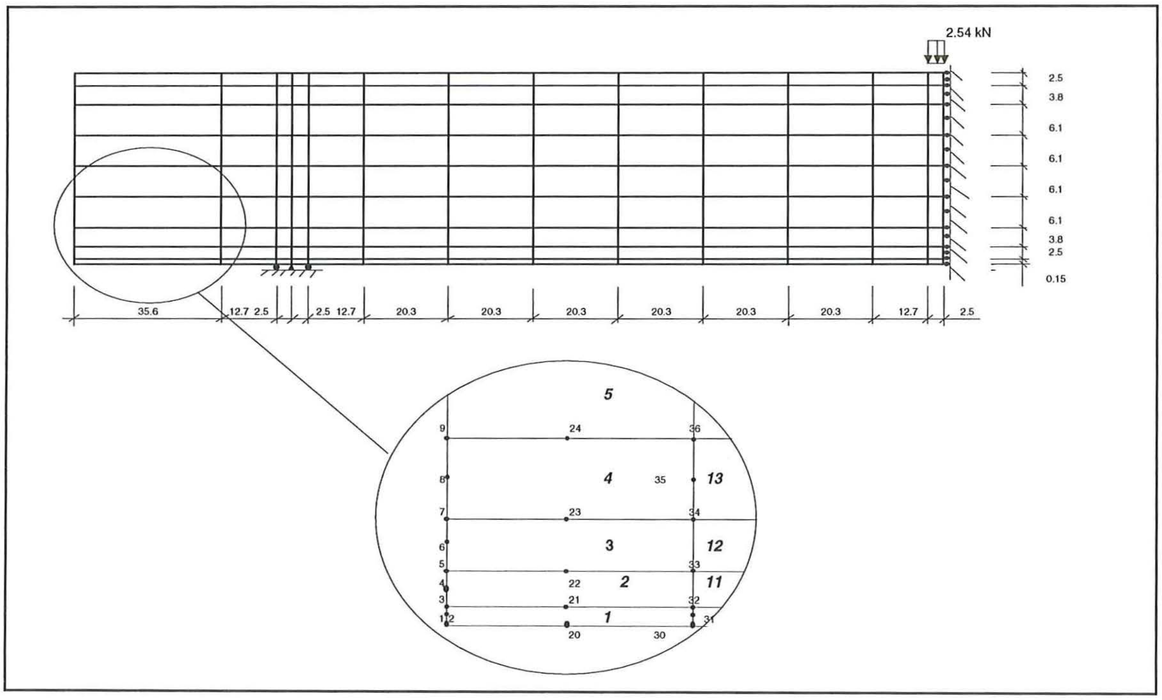

Fig. 10. The Finite Element Analysis mesh.

5.2 Fatigue tests

The short term test specimens were ranked after their ultimate load and the test results were fit to a 3P-Weibull distribution in a Curve fit program made by Dr Foschi. The program gave an output plot file (see fig 12 and fig 13), it also calculated the scale, shape and location parameters for the 3P-Weibull formula (see equation 11). The 3P-Weibull formula was used to calculate the load-levels for the cyclic tests.

When evaluating the results from the cyclic tests, the assumption of equal rank was used. This may be considered valid, since a specimen that fail at high number of cycles is likely to have a higher short term strength than a specimen that fails after a few load cycles. The number of cycles to failure of the specimens were ranked in ascending order and given a corresponding probability level:

$$p_i = \frac{i}{n+1} \tag{10}$$

where p_i is the probability level and n is the total number of tested specimens within the series. A predicted short term strength, τ_i, was calculated based on the 3P-Weibull distribution as:

$$\tau_i = m\left[-\ln(1-p_i)^{1/k}\right] + l \tag{11}$$

where m= the scale parameter, k= the shape parameter and l= the location parameter. Thus, the load level for specimen i, L_i, could be calculated as:

$$L_i = \frac{\hat{\tau}}{\tau_i} \tag{12}$$

where $\hat{\tau}$ is the peak load in the load cycles for the particular test level.

5.3 Regression analysis

A straight line was fit to the test points in the load-level verses (log) number of cycles diagram by a least square fit regression. The equation for a straight line is $y_i=b_0+b_1(x_i)$. In this case, since the X-axis was logarithmic, the equation was written as $y_i^*=b_0+b_1\log(x_i)$. The b_0 and the b_1 values are calculated with the following formuli:

$$b_1 = \frac{SPyx_1}{SSx_1} \, and \, b_0 = \bar{y} - b_1 \cdot \bar{x}_1 \tag{13}$$

where $\bar{y}$ *and* $\bar{x}_1$ are the mean for the y_i and the x_{1i} values, $x_1=\log(x_i)$

$SPyx_1$ = Sums of products $x \cdot y$

SSx = Sums of squares x

$SPyx_1$ is defined as:

$$SPyx_1 = \sum y_i \cdot x_{1i} - \frac{\left(\sum y_i \cdot \sum x_{1i}\right)}{n} \tag{14}$$

and

SSx is defined as:

$$SSx_1 = \sum x_{1i}{}^2 - \frac{\left(\sum x_{1i}\right)^2}{n} \tag{15}$$

A correlation coefficient, R^2, was calculated to determine how good the regression line fit was. The R^2 value is defined as:

$$R^2 = \frac{SS^* REG}{SSy} \tag{16}$$

SSy = Sums of squares y and defined as:

$$SSy = \sum y_i^{\ 2} - \frac{(\sum y_i)^2}{n} \tag{17}$$

SS*REG = Sums of squares regression and defined as:

$$SS^* REG = SSy - (\sum \Delta y), where\, \Delta y = y_i - y_i^{\ *} \tag{18}$$

y_i is the value of the load-level from the test and y_i^* is the predicted load-level based on the regression equation. The R^2 value should be close to one if the fit is good. Another way to evaluate the fit is to check the value of the standard deviation against the residuals. Two times the standard deviation should be larger than any residual. The sum of squares residuals are written $SS^* RES$ and:

$$SS^* RES = \sum \Delta y \tag{19}$$

The results of the regression analyze are shown in fig. 17 and fig. 18.

6. RESULTS AND DISCUSSIONS

6.1 General discussions

The results from the cyclic tests are shown in fig. 16 to fig. 20. The diagrams show the relation between how many number of cycles the specimens survived and their load-levels. The specimens in this research failed rather abruptly so there were no problems deciding how many cycles they survived. A typical displacement verses number of cycles diagram is shown in fig 11. When the displacement abruptly increased by approximately 5 mm over one cycle, the specimen was considered to have failed. This increase in displacement often took place within one cycle, thus the number of cycles the specimen in the figure survived was 13.

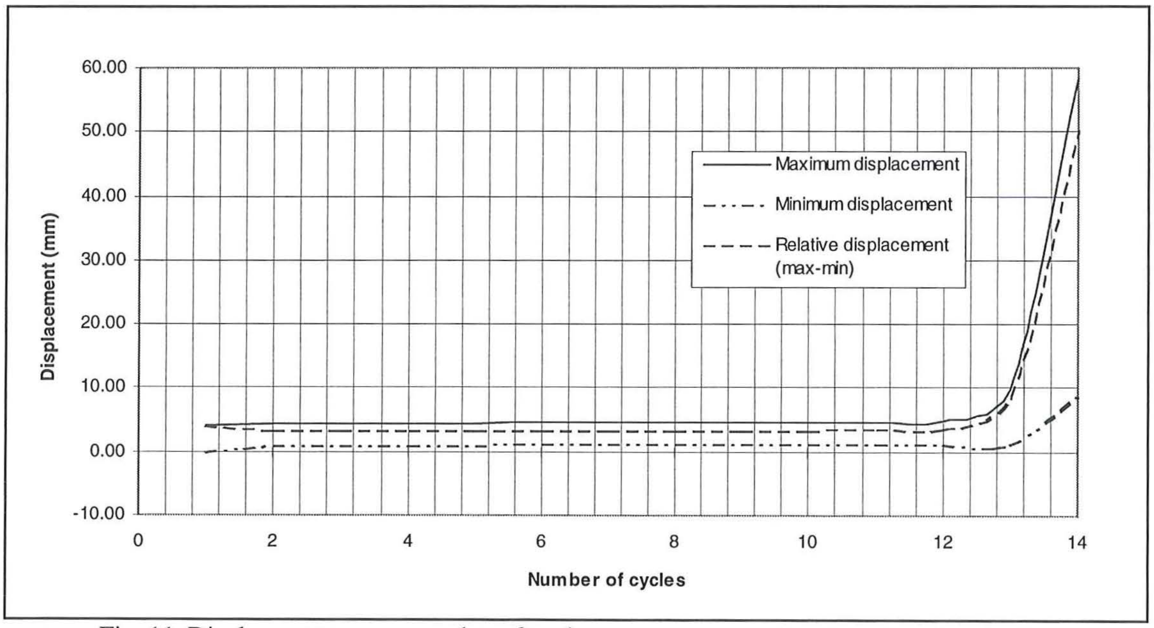

Fig. 11. Displacement verses number of cycles

There were four specimens out of 115 that failed in bending. That is 3.5 percent of the total amount of specimens. Without the fiber-glass reinforcements, the number would likely have been considerably higher. Of the four specimens that failed in bending, two failed in deflection control and two at the 95 percent test level. At the 90, 85 and 80 percent test levels all the specimens failed in longitudinal shear. It seems that bending failure only occurred at the higher test-levels. When a specimen failed in bending, it was considered as an unsuccessful test and the result was excluded from the analyses.

6.2 Short term tests

The results from the short term tests are shown in table 1 and table 2. (and in fig. 12 and fig.13). The median failure load in the deflection controlled tests was 23.1 kN compared to a median value of 25.4 kN for the series tested in load control mode. The difference between the results is about 10 percent. It can be explained by the higher ramp-rate used in the load controlled mode in comparison to the ramp-rate used in the deflection controlled mode. The Coefficient of variation (COV) was 11 % in the deflection controlled mode. In the load controlled mode the COV was 13 %. Wood have a natural variance and the COV for the two series correspond rather well to results from other tests of LVL. Bohlen had a COV of 14 % when he was testing the ultimate tensile strength in PLV (Parallel laminated veneer) and Kunesh had almost the same variance among his specimens, 12 %, when he evaluated the same property, Laufenberg (1983).

eflection control	Failure-load	Shear-strength	Moisture-content
Mean	23551	2914	7,62
St. Dev.	2652	332	0,23
C.O.V	0,1126	0,1139	0,0298
Min	15803	1939	7,09
Max	27325	3429	7,98
Median	23035	2861	7,62

Table 1. Results from the deflection controlled tests

Load control	Failure-load	Shear-strength	Moisture-content
Mean	25036	3095	7,73
St. Dev.	3133	391	0,71
C.O.V	0,1251	0,1263	0,020
Min	18941	2315	7,23
Max	29152	3591	10,91
Median	25387	3159	7,63

Table 2. Results from the load controlled tests

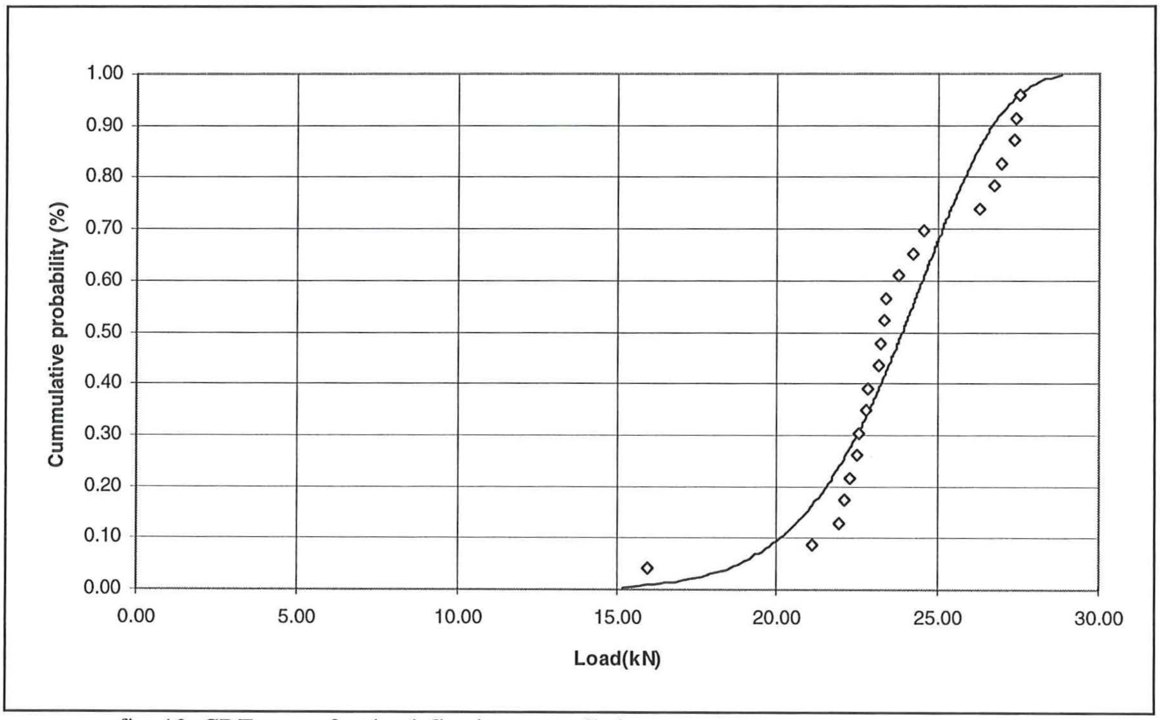

fig. 12. CDF-curve for the deflection controlled tests

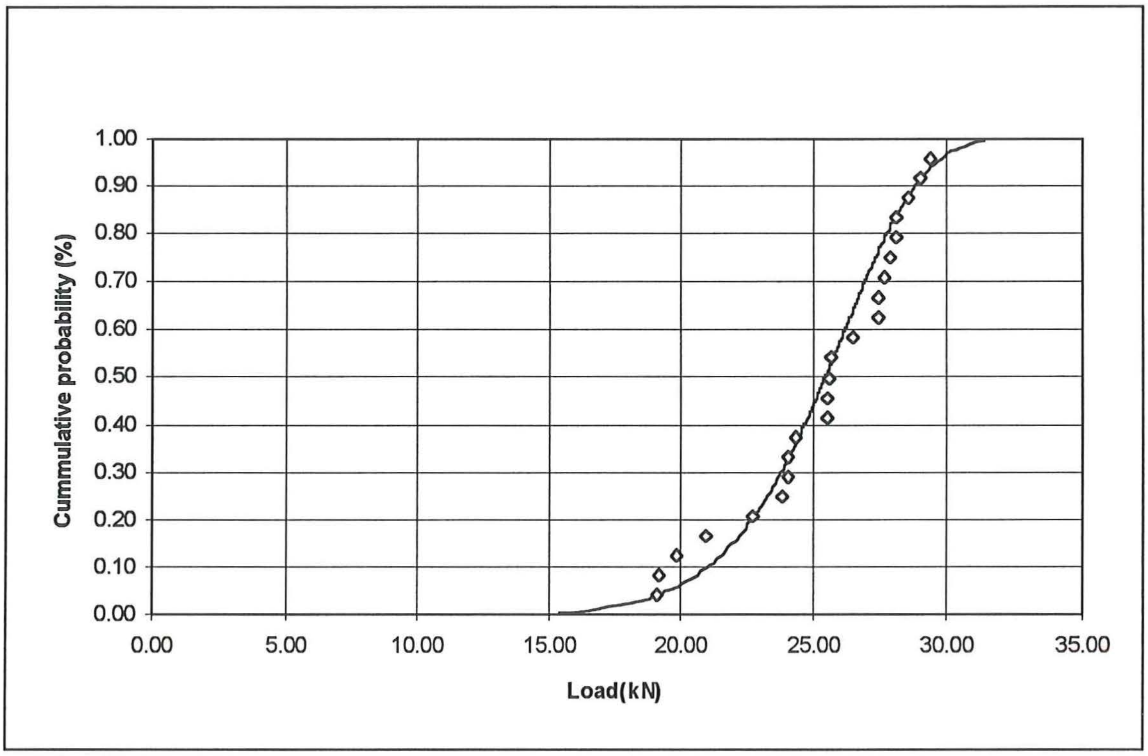

Fig. 13. CDF-curve for the load-controlled tests

The failure-load of 25.4 kN corresponds to a shear-stress of 4.86 MPa calculated with elementary beam theory. The finite element calculations gave the result that the maximum shear-stress in the specimen was 4.88 MPa when the specimen was exposed to a load of 25.4 kN. This shows that the conditions for using the elementary beam theory were fulfilled. The 3D-graph for the distribution of shear-stresses in the specimen calculated with the finite element method is shown in fig 14. The vertical-axis is numbered from 0 to 36.87 mm starting from node number 1 and upwards to node number 19 (see fig. 10). The horizontal-axis ranges from 0 to 201.23 mm for node 19 to node 366. Theoretically the shear stresses should have been zero outside the supports; i.e., the shear stresses between x=0 mm and x=25 mm should have been zero. Also theoretically there should have been an abrupt change of the stress at the middle of the specimen (around 200 mm on the horizontal-axis) The size of the support and the load plate cause stress concentrations which influence the distribution of the shear stresses. The highly concentrated stresses from the load (the right front corner) were not included in the figure to get a better picture of the shape of shear stress distribution. In fig. 15, all the stresses are shown except for the stresses in the fiber-glass. The stresses induced by the support and by the load were extremely high and during the tests the wood was crushed in these areas. Since the stresses were concentrated to a relatively small area, it was considered that they didn't have any influence on the failure mechanism

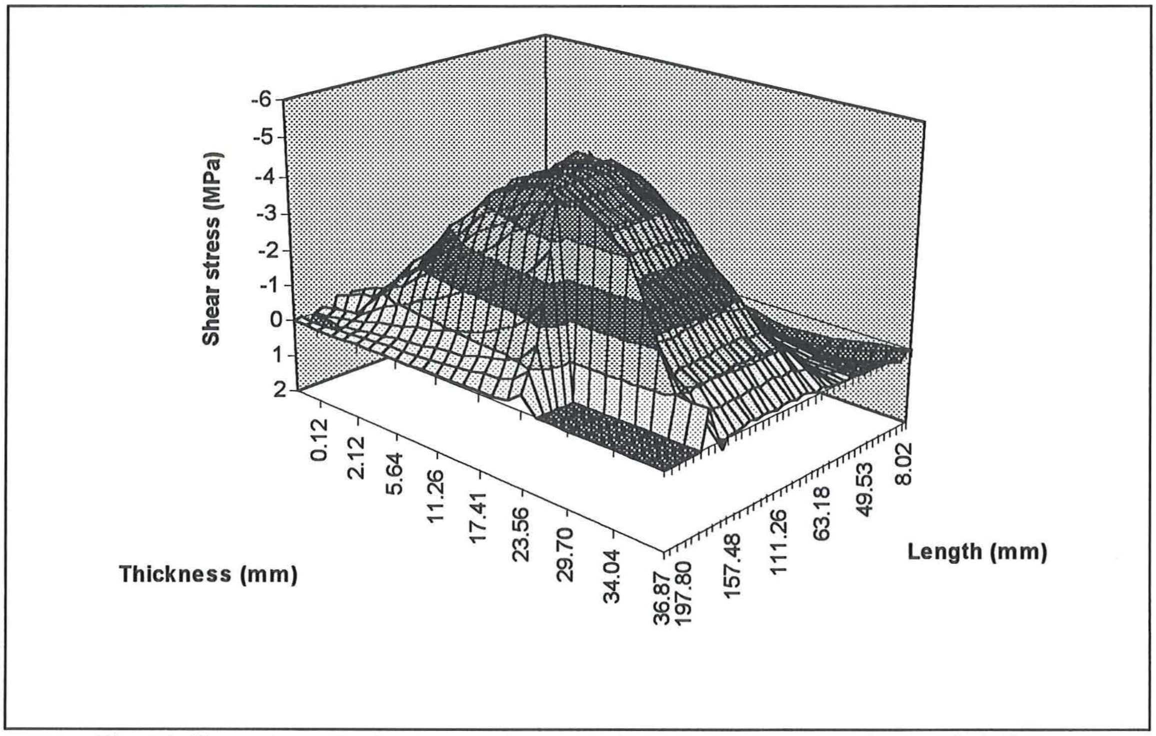

Fig. 14. Shear stress distribution within the specimen (stress concentrations excluded).

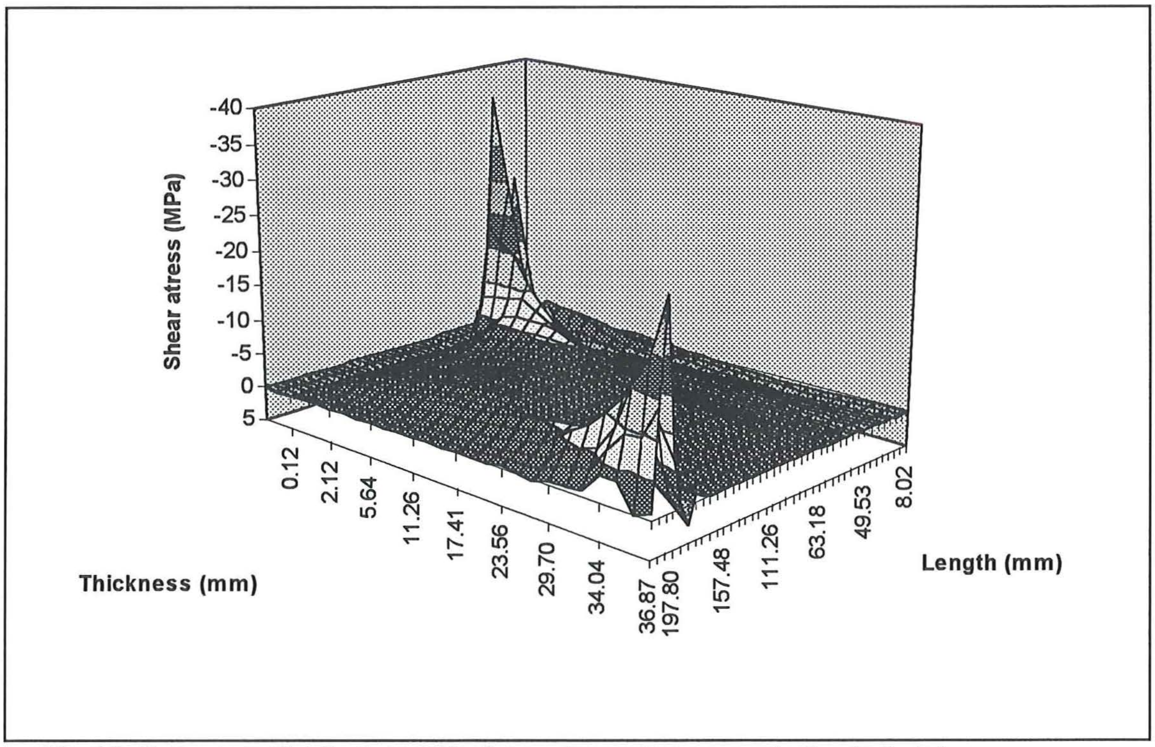

Fig. 15. Shear stress distribution within the specimen, stress concentration included (the stress in the fiber-glass is excluded)

6.3 Fatigue tests

The results from the four different cyclic test series are shown below. Figure 16 shows how many cycles the specimens survived at different load-levels. It also shows at what test level the specimens were tested. In figure 17, the relationship between load level and (log) number of cycles is shown. The regression analysis results are shown in form of a straight line in fig. 18 and fig. 19. The equation for the regression line in fig. 18 is:

$$S = -4.18 \cdot \ln(x) + 100.69, \quad R^2 = 0.806$$

S = stress level defined as a percentage of applied stress to the predicted static strength

x = number of cycles to failure

R^2 is the correlation coefficient.

The standard deviation was checked against the residuals and it was found to be larger than 50 percent of any residual. The equation for the line when points with load-levels above 110 percent are excluded is:

$$S = -3.611\ln(x) + 98.35, \quad R^2 = 0.921$$

The R^2 value of 0.921 shows a very strong regression relation. In fig. 19 the regression line for points with load-levels below 110 percent is shown. This line is not as steep as the one that included all points.

The maximum number of cycles survived by the specimens was almost 3000 cycles at 80 % test-level. The load-level for this specimen was calculated using equal rank assumption as 71 %. This specimen survived almost twice as many cycles as the second strongest specimen, which survived close to 2000 cycles.

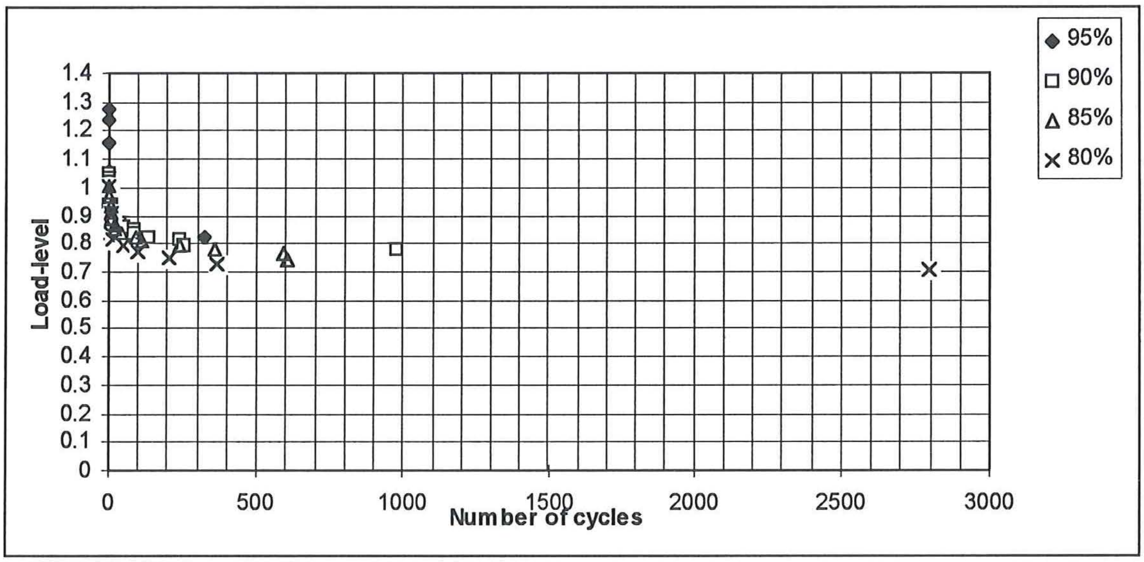

Fig. 16. Number of cycles verses load-level

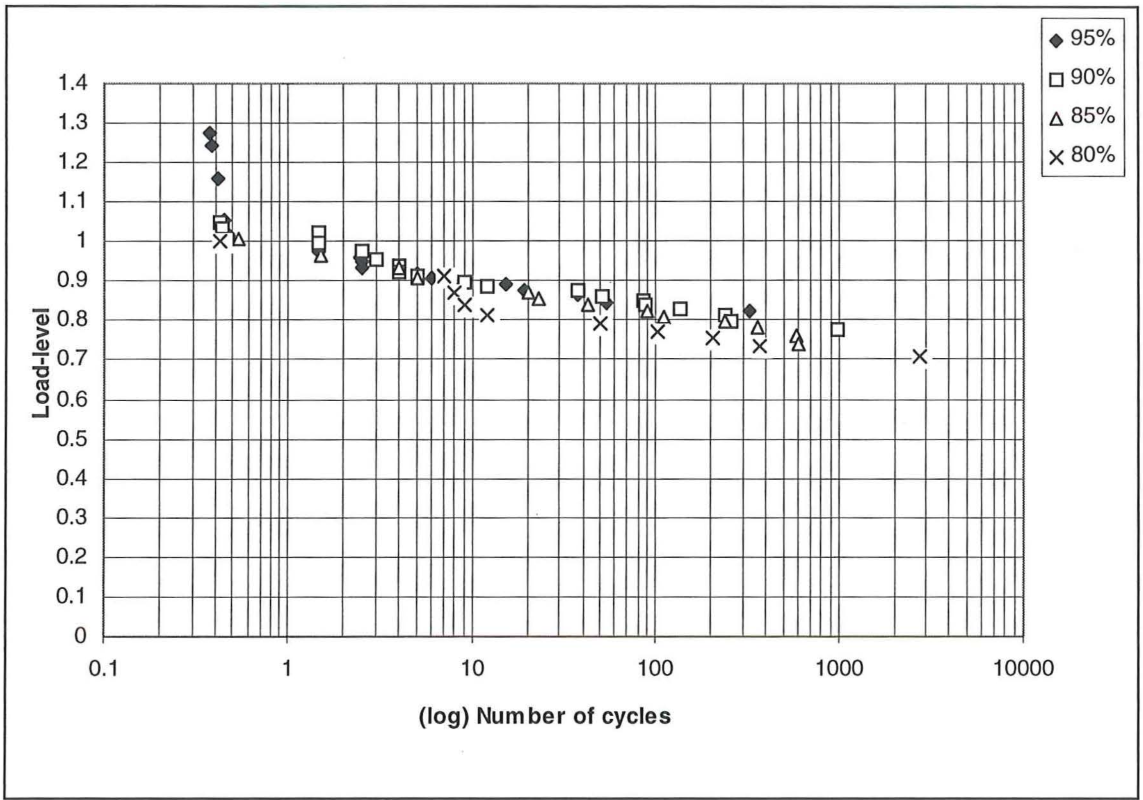

Fig. 17. (log) Number of cycles verses load-level

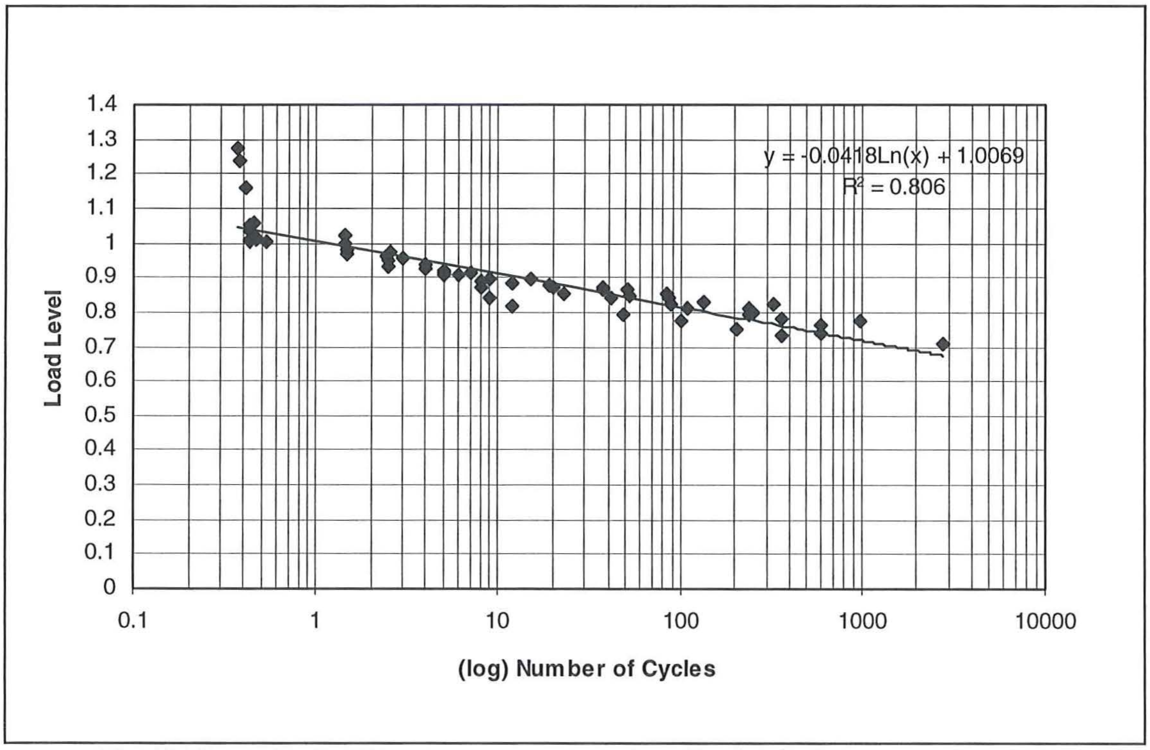

Fig. 18. Regression line fit by least square regression, all points included

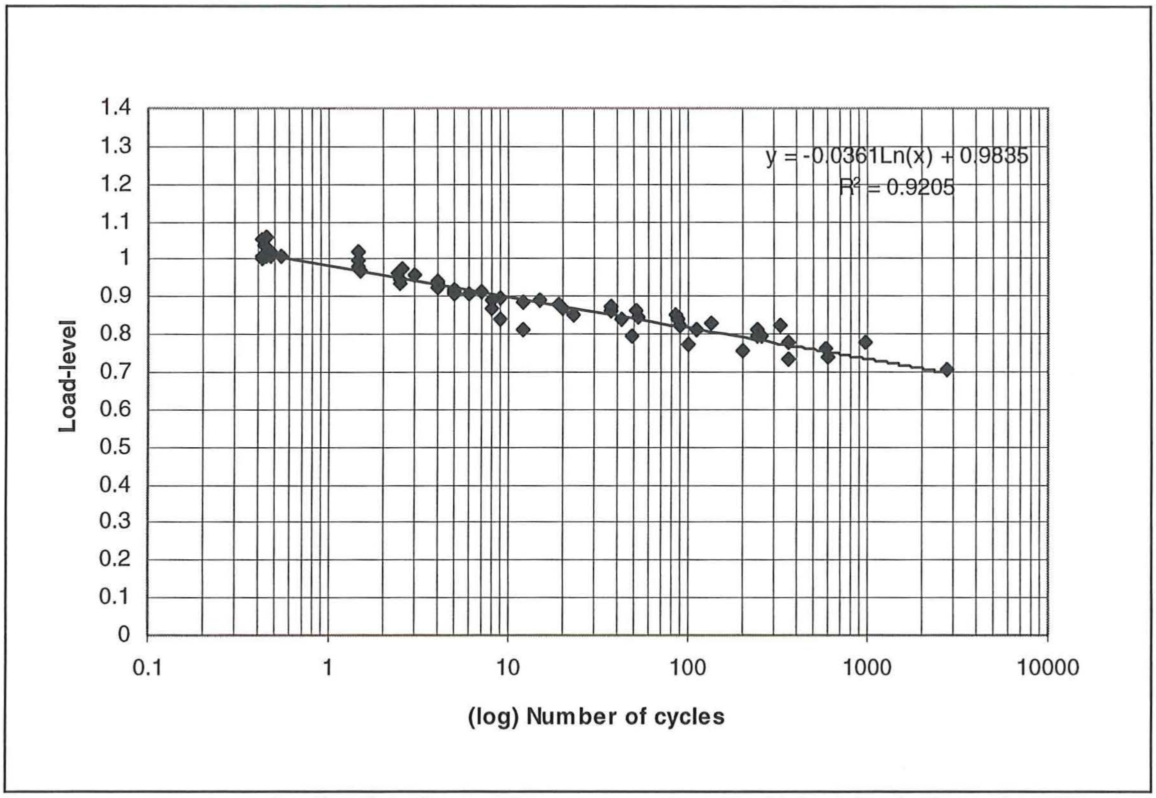

Fig. 19. Regression line fit by least square regression, points with load-levels above 110 percent excluded

There are several data points with load-levels above 100 % which correspond with the specimens that failed during the first cycle. There are six specimens from the 95 % test-level, three from 90 %, one from 85 % and one from 80 % that have load-levels above 100 %. Three of these have load-levels around 120 %. These specimen had extremely low strength and they failed during uploading at between 75-82 % of the median short term strength. The load-level verses number of cycle diagrams (se fig. 18 and fig. 19) are shown in two versions, one including these three test points and one excluding them. Estimations based on the short term strength series gave the result that 6.4 specimens should fail during the first cycle in the 95 % tests series, 4 at 90 %, 2.4 at 85 % and 1.2 at 80 %. These values correspond rather well to the results from the tests

In fig. 20. the cumulative distributions (CDF) curves for the four different test-levels are shown. The reason for the overlaps is that the difference between the various tests-levels is smaller than the natural variation in wood. It is interesting to notice that overlaps only occur between the 85 and 80 percent test-levels.

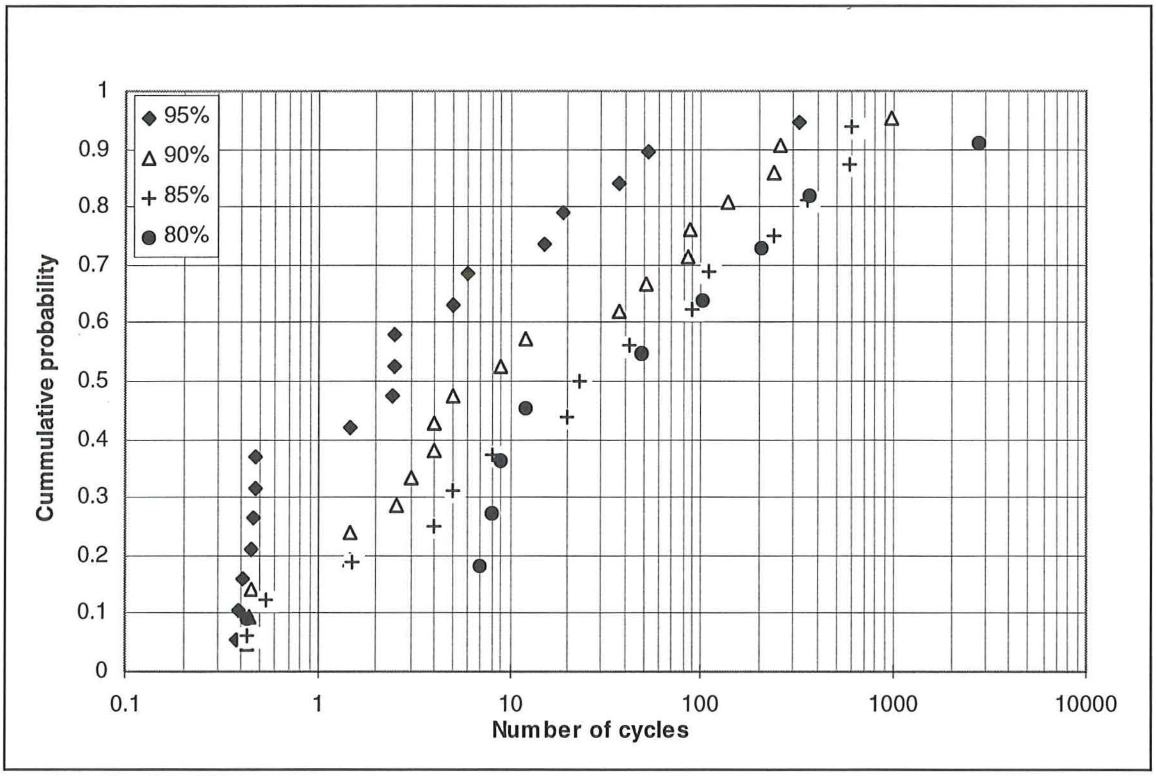

Fig. 20. CDF-curves for the four different test levels

The specimens were examined after being tested. The majority of the specimen failures occurred in more than one layer. Failure would start in one layer and spread to the surrounding layers following the weakest veneers out to the edge. Table 3 shows how many of the specimens that had failure in the 15 different layers. Layer number 1 is the top layer and layer number 15 is the layer next to the fiber-glass. There were four layers where the specimens failed more frequently: layer number 9, 10, 11 and 12. The neutral axis was calculated to be in the lower part of layer 8. There was no sign of glue failure, as all the specimens failed in the wood.

Layer #:	95%	Percentage	90%	Percentage	85%	Percentage	80%	Percentage	total:	Percentage
1	0	0	0	0	0	0	0		0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	0.0666667	1	0.1	2	3.0769231
4	1	0.05	0	0	0	0	2	0.2	3	4.6153846
5	2	0.1	0	0	0	0	0	0	2	3.0769231
6	3	0.15	4	0.2	3	0.2	0	0	10	15.384615
7	3	0.15	4	0.2	5	0.3333333	2	0.2	14	21.538462
8	3	0.15	6	0.3	9	0.6	2	0.2	20	30.769231
9	3	0.15	9	0.45	9	0.6	4	0.4	25	38
10	8	0.4	7	0.35	9	0.6	3	0.3	27	41.538462
11	9	0.45	6	0.3	7	0.4666667	2	0.2	24	36.923077
12	10	0.5	8	0.4	6	0.4	2	0.2	26	40
13	6	0.3	7	0.35	3	0.2	2	0.2	18	27.692308
14	3	0.15	3	0.15	1	0.0666667	1	0.1	8	12.307692
15	1	0.05	4	0.2	1	0.0666667	0	0	6	9.2307692

Table 3. Failure distribution

When the specimens fail, the failure begins with a crack in the section with the highest stress. The crack propagates to the edge and the specimen is not considered to have failed until the crack reached the edge. The three point bending test setup used in this research forced the crack to penetrate into the overhangs (see fig. 9). The specimen overhangs the supports with 25.4 mm at both edges. Since the shear force is zero or close to zero in the overhangs, it can be considered as “locked in” between the overhangs. This setup allows the specimen to take higher loads than what should have been the case in a setup with smaller or no overhangs. This means that the short term strength could be overestimated. When it comes to the cyclic tests, however, the overhang has no influence on the results since stress levels or load levels are studied in relation to the short term results obtained with similar test set up.

7. CONCLUSIONS

The fatigue life is 1500 cycles when the load level is approximately 70 percent of the static ultimate strength. A straight line ($S = -4.18 \cdot \ln(x) + 100.69$) describes the relation between number of cycles verses load-level for LVL boards tested in shear as planks. The specimens in this research were tested at rather high test-levels, 95 to 80 percent of the static strength. The steep slope of the regression line and the tendency of the data, however, indicate that the endurance limit lies far below 70 %.

APPENDIX

Pressing quality variables

When panels are pressed in a hot press, heat is transferred from the plates towards the center of the panel. It is the central layers that are controlling the press time and the temperature settings. The press time and temperature must be set so that the adhesive in the middle layers reaches its curing temperature. If the press-time is set to be too long, the wood will dry out, check and cause the resin to over-cure.

Another important factor is the moisture content of the veneer. Six to eight percent moisture content is desirable. Higher moisture content can cause blow-outs to occur upon release of pressure. It can also result in poor glue penetration and weak joints.

It is also significant that the veneer thickness is fairly uniform; otherwise, air bubbles in the adhesive between the veneers can't be squeezed out during pressing which results in poor bonding. Further, the remaining air bubbles will also cause stress concentrations when the panel is under load.

When a panel is removed from the press, it will pick up moisture from the air and expand. Since the veneers have different density and modulus of elasticity, they will individually expand differently and the panel will have a tendency to cup, especially if the layup is unbalanced. A way to avoid cupping is to make panels with a balanced construction and hotstack the panels when they are cooling down. Hot-stacking allows a longer cooling down period and it puts pressure on the panels.

Due to the stresses caused by the rotary peeling process during manufacturing of the veneers, veneers have lathe checks along the grain. The side with lathe checks is referred to as the open side and the side with no lathe checks is referred to as the closed side. In regard to this when manufacturing LVL, half of the veneers are put with the open face downwards and half with the open face upward, so that both of the faces on the panel have veneers with their closed face outwards. The side without lath-checks is more dense and by arranging the veneers in this way the permeability of the panel decreases.

LITERATURE CITED

Berthelot, J-M. (1992): Matériaux composites, comportement mécanique et analyse des structures.

Bohlen, J.C. (1974): Shear Strength of Douglas-Fir Laminated-Veneer Lumber. Forest Products Journal. 25(2).

Cai, Z. [Bradtmueller. J.P, Hunt. M.O, Fridley. K.J, Rosowsky. D.V]. (1996): Fatigue behavior of OSB in shear. Forest Products Journal. 46(10).

Kommers, W.J. (1943): The Fatigue Behavior of wood and plywood Subjected to Repeated and Reversed Bending Stresses. United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison Wisconsin. 1327.

Kommers, W.J. (1944) : The fatigue Behavior of Douglas-fir and Sitka spruce Subjected to Reversed Stresses Superimposed on Steady Stresses. United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin. 1327-A.

Kunesh, R.H. (1976): Structural Laminated Veneer Lumber. Forest Products Research Society.

Lam, F. (1992): Performance of laminated wood plates in decking systems. The University of British Columbia. Faculty of Forestry. Department of Wood Science.

Laufenberg, T.L. (1982): Parallel-laminated veener: processing and performance, research review. Forest Products Journal. 33(9).