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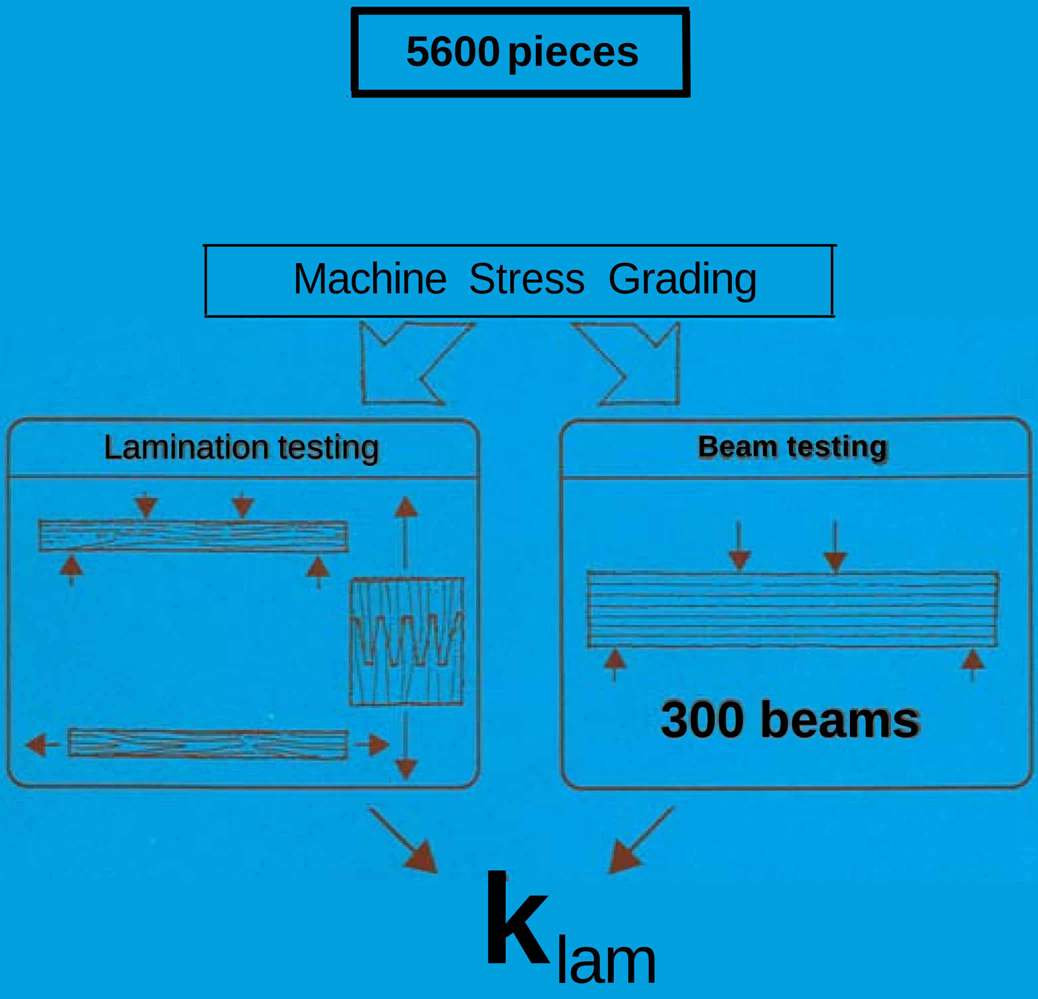

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A report of cooperative research between the Forest Products Laboratory and the Norsk Treteknisk Institutt (Norwegian Institute of Wood Technology), Oslo, Norway performed during September 3, 1990 to September 20, 1991.

ISBN 82-7120-029-1
ISSN 0546-3637

Oslo, September 1992

Falk, Robert H., et al. The performance of glued laminated beams manufactured from machine stress graded Norwegian spruce. (Meddelelse / Norsk Treteknisk Institutt ; no.77). Oslo, Norway : Norsk Treteknisk Institutt, 1992. 60 p. ISBN 82-7120-029-1. ISSN 0546-3637.

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FORORD.

Trevirke har i hundrevis av år vært det dominerende konstruksjonsmaterialet i Norge. Det har høy styrke sammenlignet med egenvekt, og brukt under riktige forhold, er det meget holdbart. Stavkirkene fra middelalderen er bevis godt nok på det siste.

Trevirke har i sin naturlige form imidlertid en stor bruksbegrensing ved at tverrsnittsdimensjon og lengde er gitt av naturen. Konstruktører har opp gjennom tidene forsøkt å løse dette på forskjellige måter. Mindre tverrsnitt har blitt koblet sammen ved hjelp av mekaniske forbindelsesmidler til større tverrsnitt som har kunnet oppta den nødvendige belastningen, eventuelt spenne over tilstrekkelig lengde.

Ved hjelp av nye limtyper som er videreutviklet gjennom de siste tiårene, er det i dag mulig å lime sammen mindre tretverrsnitt (lameller) til tverrsnitt med ønsket størrelse og lengde. Dersom en velger ut de best egnete delemnene og gjennom en godt kontrollert produksjonsprosess limer disse sammen til fullt statisk samvirke, vil det ferdige limtretverrsnittet ha egenskaper som med hensyn til styrke og stivhet på de fleste områder overgår tradisjonelt heltre. I Norge ble det startet med limtreproduksjon rundt 1960 og i dag (1992) er det 7 bedrifter som produserer limtre. Limtre har gang på gang vist seg konkurransedyktig både med hensyn til pris og egenskaper/bruksområde sammenlignet med andre konstruksjonsmaterialer som stål og betong. Som eksempel på store konstruksjoner hvor limtre er gått av med seieren med hensyn til materialvalg, er det nok å nevne at 3 av hovedarenaene for OL-94 er bygget med limtre i hovedbæresystemet.

Konkurransen mellom de forskjellige konstruksjonsmaterialene er imidlertid meget hard, og det skal bare små endringer i konkurranseevnen til før et materiale sakker akterut. Limtreindustrien i Norge så derfor med uro på de signaler som etter hvert kom fra utlandet i forbindelse med det internasjonale standardiseringsarbeidet som har pågått i noen år. Tegn tydet blant annet på at limtre produsert etter norsk praksis, ville komme til å få en drastisk reduksjon i beregningsmessig bæreevne sammenlignet med hva vi i har dag. Konsekvensen av de nye standardene kunne bli meget skjebnesvanger for norsk limtreindustri spesielt, men også for bruk av trevirke i store konstruksjoner generelt.

Norske Limtreprodusenters Forening bestemte seg derfor for å få utført et større prosjekt hvor limtreets egenskaper med hensyn til styrke og stivhet skulle kartlegges. Gjennom en solid dokumentasjon ønsket en å kunne vise hvilke egenskaper limtre produsert etter norske/nordiske metoder virkelig har, samt få aksept for dette hos de som utarbeider de internasjonale standardene (CEN).

Prosjektet ble økonomisk støttet av Norges Teknisk-Naturvitenskapelige Forskningsråd (NTNF), Norsk Treteknisk Institutt (NTI) og av den norske limtreindustrien selv. Arbeidet med prosjektet ble startet i September 1990 og ble delvis utført ved Raumnes Bruk A/S (senere Raumnes Tre A/S) og delvis ved NTI.

Robert H. Falk (Forest Products Laboratory, Wisconsin, USA) som i perioden September 1990 til September 1991 var ansatt ved NTI som gjesteforsker med stipend fra NTNF, har utført en stor del av arbeidet både med hensyn til laboratorietesting, beregningsarbeid og rapportering.

Prosjektet ble styrt gjennom en prosjektgruppe bestående av Åge Holmestad (Moelven Limtre A/S), Arnold Sagen (Raumnes Bruk A/S, senere Raumnes Tre A/S), Robert H. Falk (FPL/NTI), Kjell Helge Solli (NTI) og Erik Aasheim (NTI).

Oslo, september 1992
NORSK TRETEKNISK INSTITUTT

RESYMÉ/SAMMENDRAG.

I samarbeid med Norske Limtreprodusenters Forening har Norsk Treteknisk Institutt (NTI) gjennomført et prosjekt hvor hensikten har vært å dokumentere de styrkemessige egenskapene hos norskprodusert limtre. Prosjektet ble støttet av NTNF.

Til prosjektet ble det skaffet ca. 85 m^3 limtrelameller (totalt 5602 lameller) med dimensjon 40 x 95 mm. I utgangspunktet var det ønskelig å fordele disse styrkemessig i klassene C37-14E, C30-12E, C24-11E og C21-10E, slik at det kunne produseres limtrebjelker med 4 forskjellige tverrsnittsammensetninger. De nevnte klassene var i overenstemmelse med klasser gitt i dokumenter fra CEN TC 124 (1990).

Samtlige lameller ble nummerert før de ble maskinsortert på en Computermatic styrkesorteringsmaskin ved Raumnes Bruk A/S (senere Raumnes Tre A/S). Under sorteringsprosessen var det til maskinen tilkoblet en PC som registrerte samtlige målepunkter i hver lamells hele lengde. Sorteringsdataene ble i ettertid noe modifisert på bakgrunn av en systematisk feil ved sorteringsmaskinen.

De modifiserte stivhetstallene fra styrkesorteringen ble brukt til å sette opp en "rankingliste" over lamellene basert på antatt sammenheng mellom styrke og stivhet. Fra denne listen plukket en deretter ut lamellene som skulle inngå i prosjektets forskjellige delundersøkelser på en slik måte at hver kategori inneholdt lameller fra hele utvalgets styrkespekter. På denne måten var det mulig å laboratorieteste et mindre antall lameller med hensyn til f.eks. bøyefasthet, og likevel kunne anta at fastheter og variasjoner var tilnærmet identisk med hva en ville få ved å teste samtlige 5602 enkeltlameller.

Bruddfasthetene fra laboratorietesten ble statistisk behandlet, hver for seg og i kombinasjon med de korresponderende dataene fra maskinsorteringen. Ved hjelp av disse resultatene kunne en på ny gå inn i den nevnte rankinglisten, og deretter fastsette hvor grensene til de enkelte fasthetsklassen skulle ligge. Det viste seg da at nærmere 100% av materialene befant seg i de 2 øverste fasthetsklassene (C37-14E og C30-12E). Antall lameller i de nederste klassene (C24-11E og C21-10E) var så lavt at det ble valgt å utelate dem fra videre bruk i prosjektet.

Lamellene som var øremerket til limtreproduksjon fra de 2 øverste klassene (ca. halvparten av det totale volum) ble deretter sortert fra hverandre slik at klasse C37-14E og C30-12E lå adskilt. Lamellene ble havlet, fingerskjøtt og deretter limt opp til limtrebjelker med dimensjon 90 x 300 x 6000 (mm). Det ble produsert bjelker med 3 forskjellige oppbygninger, og ca. 100 av hver type. De 3 typene ble betegnet LH35 (C30-12E i samtlige lameller), LH40 (C37-14E i samtlige lameller) og LC38 (C37-14E i de ytterste 2 lamellene på begge sider, C30-12E i de midterste).

Samtlige limtrebjelker ble bøyeprøvet ved NTI's laboratorium. Elastisitetsmoduler, bøybruddfastheter og bruddårsak ble registrert. Den statistiske behandlingen av testdataene viste at limtre produsert av norsk gran oppnår de fastlagte fastheter og elastisitetsmoduler. En forutsetning for dette er imidlertid at en klarer å sortere ut nødvendige fasthetsklasser for dellamellene. En annen konklusjon en kan trekke fra resultatene, er at lamineringsfaktoren, k_{lam}, som benyttes i Norge er noe høy, men at dette kompenseres ved at lamellenes fastheter er høyere enn antatt.

Som hovedkonklusjon for prosjektet kan det sies at limtreets konkurranseevne ikke bør bli svekket på grunn av de kommende europastandardene. Både råstoff og produksjonsteknologi er tilstede for å produsere høykvalitet limtre i henhold til de nye standardene. Produsentenes største utfordring vil være å etablere et sorteringssystem som klarer å skille ut det nødvendige volum av lameller i de høyere fasthetsklassene.

ABSTRACT

This study focuses on the characterization of machine stress graded Norwegian spruce laminating lumber and glued-laminated (glulam) timber beams in comparison to CEN standards. Material property testing indicated that the supplied laminating lumber can be represented by two CEN strength classes, C37-14E and C30-12E, with 48% and 50% yield, respectively. Beams constructed from these established grades exhibited strength and stiffness meeting the requirements of CEN combinations LH35, LH40, and LC38. Computed laminating factors, k_{lam}, were found to be in the range of 1.05 to 1.15 and are in close agreement with the assumed values of the CEN standards.

ACKNOWLEDGEMENTS

Many members of the staff of the Norsk Treteknisk Institutt (Norwegian Institute of Wood Technology) contributed to the success of this study. Erik Aasheim and Jostein Baardsen always assured that necessary funding, equipment and extra help were never far from reach. Kjell H. Solli provided insightful analytical assistance while Asle Tengs helped in the development and debugging of the data acquisition equipment. Kjell Lindrupsen oversaw the seemingly endless series of lumber and beam tests and with the energetic assistance of technical students Dag Molteberg and Dag Gundersen helped keep the project on schedule.

The periodic technical suggestions from Age Holmestad of Moelven Limtre A.S., Arnold Sagen of Raumnes Bruk A.S., and Carl Johan Johansson of Statens Provningsanstalt (The Swedish National Testing Institute) were greatly appreciated as was the always helpful hand of the Raumnes Bruk staff.

Roland Hernandez and Dave Green from the Forest Products Laboratory in Madison, Wisconsin also provided insightful and helpful comments, especially regarding lumber properties and statistical methods.

Finally, this study was sponsored by the Norsk Treteknisk Institutt, the Norges Teknisk-Naturvitenskapelige Forskningsråd (Royal Norwegian Council for Scientific and Industrial Research), the Norske Limtreprodusenters Forening (Norwegian Glulam Producers Association), and the U.S. Forest Products Laboratory and would not have been possible without their generous support.

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1. INTRODUCTION

The realization of a unified European Economic Community (EEC) in western Europe will have a significant effect on the commerce and trade of its 300 million people. Besides the obvious economic implications of such a large free trade market, an important aspect of the unification process is the development of common building design and product performance standards. Currently under development are uniform performance standards for eighteen European countries under the auspices of the European Committee for Standardization (CEN).

Because these standards may be quite different than those currently used by individual countries, it will be necessary for nations choosing to compete in the EEC to evaluate the performance of their products relative to the CEN standards. Establishing relative performance levels of various wood products is especially important to the Nordic countries, since their economies depend so heavily on forest products export.

2. OBJECTIVES

The basic objective of this research is to characterize the performance of glued-laminated (glulam) timber beams manufactured from machine stress graded Norwegian spruce relative to CEN standards. This study involves the strength and stiffness testing of Norwegian spruce lumber for the establishment of lamination grades meeting CEN standards, testing of finger joints, and the testing of full size beams in bending.

Specific objectives are to:

1. Characterize the mechanical properties of machine stress graded Norwegian spruce lamination lumber and determine the yield of lamination grades meeting CEN standards.

2. Evaluate the performance of full size glulam beams constructed from the established lamination lumber grades.

3. Quantify the relationship between the bending and tensile strength of the finger joints and lamination lumber (as tested in tension or bending, outside the beam) and the required performance of these elements on the tension side of the beam.

3. BACKGROUND

3.1 Applicable Standards

CEN standards under development describe the methodology by which characteristic strength and stiffness properties are to be established in Europe for structural timber and glulam timber (EN TC 124.203 (Comite European de Normalisation 1990a). EN TC 124.207 (CEN 1990b)). Table 1 from EC TC 124.203 is reproduced in Appendix 1 and indicates the strength and stiffness properties required for acceptable lamination grades. Note that the grade designation (e.g., C30-12E) refers to the required characteristic bending strength (30 MPa (4350 psi)) and the required mean bending modulus of elasticity (12,000 MPa (1.74 x 10^6 psi)). Tables 1-3 of EN TC 124.207 are also reproduced in Appendix 1 and give the classification of glulam produced from lamination grades meeting the requirements as well as the characteristic strength and stiffness properties for glulam beams constructed of homogeneous and combined layups. These tables were applicable at the start of this project in 1990; although the tables will change through the CEN draft standard revision process, they will nonetheless be referred to throughout this report.

3.2 Related Research

Testing of glulam beams by Solli (1987) in Norway has demonstrated that glulam beams of Norwegian manufacture exhibit high performance levels. Beams constructed with T30 outer and T24 inner laminations exhibited a characteristic bending strength of 42.5 MPa (6960 psi) with a mean modulus of elasticity of 12,700 MPa (1.84 x 10^6 psi). A second series of beams, with T40 outer and T30 inner laminations, exhibited a characteristic bending strength of 54.0 MPa (7830 psi) and a mean modulus of elasticity of 14,350 MPa (2.08 x 10^6 psi). See Appendix 2 for the visual requirements of these grades. Despite the excellent strength performance exhibited by these beams, the yield of the T40 grade was estimated to be less than 5% of total lamination production.

These results are in contradiction with those obtained by Johansson (1990) on glulam beams manufactured from Swedish-grown machine stress rated Norwegian spruce. The beams tested by Johansson were constructed of T40 outer and T24 inner laminations. A characteristic bending strength of 37.6 MPa (5450 psi) and a mean modulus of elasticity of 13,700 MPa (1.99 x 10^6 psi) were measured. This bending strength is significantly lower than that found by Solli (1987); however, the yield of the T40 grade from the total population of laminating stock was estimated to be 35%-5.5%.

It is apparent from the above results that the Norwegian-produced beams were of higher strength than those produced in Sweden, but at the cost of a significantly lower yield in high grade laminations.

3.3 Laminating Effect

For glulam timber beams it has been found that the performance of the individual tension laminations tested outside of the beam does not necessarily correspond one-to-one to their performance within the beam. This relationship between the characteristic strength of the laminations and the actual failure stress of these tension elements in the laminated beam is referred to as the "laminating effect" and is accounted for in European design by the factor, k_{lam}. Nordic standards use this factor in conjunction with the strength of laminations to compute a characteristic beam bending strength (NS 3470, 1989). The magnitude of this factor (which serves to increase the design stress), depends on the lamination grade utilized, where lower grades are allowed a greater increase.

The primary physical effects accounted for by the factor k_{lam} are (1) differences in tension performance of single laminations as measured by standard test methods and their actual performance in the beam (where there is more lateral constraint), (2) the stress redistribution around low stiffness areas (knots) through adjacent laminations, and (3) the fact that dispersion of low strength laminations throughout the beam volume decreases the probability that the lowest strength laminate will initiate beam failure. The CEN standard referred to above suggests k_{lam} values from 1.03 (LC38 combination) to 1.39 (LH25 combination). See Table A1.4, Appendix 1.

Research has been performed to help characterize this laminating effect. In Denmark, Larsen (1982) tested 200 glulam beams in bending and individual laminations in tension. A lamination factor, defined as the ratio of the <u>mean</u> ultimate bending stress of the beam series divided by the <u>mean</u> tensile strength of the tension lamination utilized, was determined and ranged from 1.05 to 1.73 depending on the grade of the tension lamination and the quality of the finger joints. The highest values were obtained for beams with higher grade tension laminations containing standard quality finger joints or with lower quality laminations with no finger joints. Lower values resulted from beams with weak finger joints in the tension lamination.

In the United States, limited testing of glulam beams with laminated veneer lumber (LVL) tension laminations indicated a laminating factor of 1.25 (Braun and Moody 1977). This factor includes the effects of differing stress distributions on the LVL tested in tension and the stress in bending of the beam. Also, since the LVL contained no finger joints, their influence could not be quantified. Nonetheless, current U.S. practice incorporates this laminating factor in establishing qualification testing of finger-jointed laminations used in glulam beams (ANSI/AITC A190.1, 1992). Current Norwegian timber design standards allow the use of a laminating factor of 1.20 to 1.40 (NS 3470, 1989), depending on the grade of laminations utilized.

The European standard EN TC 124.207 (1990b) allows the determination of characteristic strength properties of glulam using k_{lam} and the tensile properties of the laminating grade utilizing the following formula:

$$\begin{aligned} f_{b,g} &= (k_{lam})\ f_{t,1} \\ &= (2.7 - 0.04f_{t,1})f_{t,1} \qquad (1) \end{aligned}$$

where

$f_{b,g}$ = characteristic bending strength of the glulam
$f_{t,1}$ = characteristic tensile strength of the lamination grade

Provisions in the above standard also allow the use of the k_{lam} factor to predict beam bending stiffness from the bending stiffness of the laminations.

4. MATERIAL DESCRIPTION AND INITIAL GRADING

The lamination lumber utilized in this study was provided by the largest manufacturer of lumber in Norway (Norske Skog A.S.) and was visually graded by the manufacturer to meet the requirements of Norwegian glulam industry visual grades LT20 and LT30 (See Appendix 2). Though the supplied lumber was from trees grown in Norway, Norway spruce (*Picea abies*) is found throughout Europe and is included in a general classification referred to as European whitewood,

The 5602 lumber pieces were nominally 40 mm x 95 mm (1.6 in. x 3.75 in.) in cross section. Unlike U.S. lumber producers, Norwegian industry typically supplies lamination lumber in random lengths. The material provided for this study varied in length from 2.20 m (7 ft.) to 5.65 m (18 ft.), with an average length of about 4.3 m (14 ft.). The actual distribution of lamination lumber lengths is shown in Figure 1.

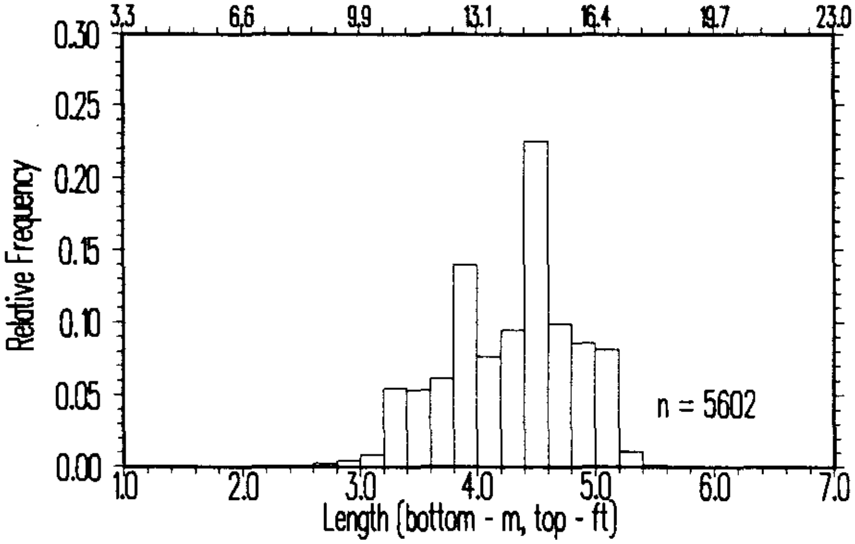

FIGURE 1 - Length Distribution of Supplied Lamination Lumber

Each piece of lumber was run through a Computermatic MK-IV machine stress grader (Plessy Co., Meadowberk, NSWW; Australia), a load controlled machine. The machine was adjusted according to manufacturers specifications and was set to segregate the lumber into four potential lamination grades: C37-14E, C30-12E, C24-11E, and C21-10E. Displacement values (also referred to as bit values) were set as shown in Table 1, where one bit is equal to 0.1905 mm (0.0075 in.) of displacement. Note the resulting grade yield for this first machine stress grading.

TABLE 1
Yields From Machine Stress Grading

CEN GRADE	**LIMITING BIT VALUE**	**Yield (%)**	
		First Grading	Second Grading
C37-14E	**<21**	5	1
C30-12E	**< 27**	55	26
C24-11E	**< 32**	25	42
C21-10E	**< 39**	13	24
< C21-10E	**> 39**	2	7

After marking all lumber pieces with a identifying number, a second machine grading was performed. Calibration settings on the machine stress grader were identical to the first grading described above. Specialized data acquisition equipment developed for this study were used to record and analyze displacement data at 150 mm (6 in.) intervals along each lumber piece. Figure 2 illustrates this mapped displacement. Measurements are not possible over the first 550 mm (22 in.) and the last 750 mm (30 in.) of the lumber piece. From these displacement profiles a continuous modulus of elasticity map could be generated.

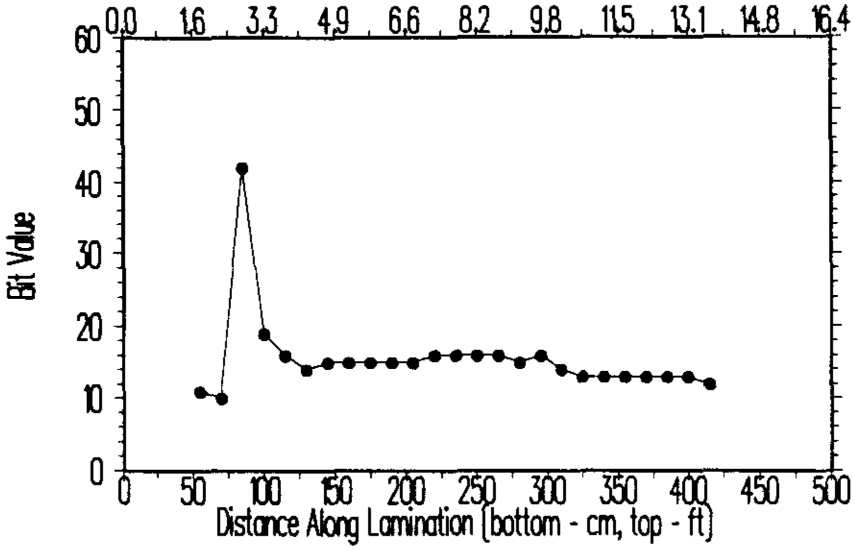

FIGURE 2 - Bit Value Map for Single Lumber Piece

As indicated in Table 1, the yields from these two machine stress gradings of the same lumber pieces were not consistent. It has long been recognized that the Computermatic machine stress grader is very sensitive to vibration generated by the moving lumber as it enters the grader (Galligan 1978). This vibration can affect lumber displacement as the lumber moves through the grader, especially at the first few measurement points. This causes the machine to inconsistently, and very often incorrectly, grade a board. Despite adjustment of the machine stress grader to manufacturers specifications, a large percentage of lumber evaluated in this study were incorrectly graded due to the described vibration.

The displacement of the single lumber piece is shown in Figure 2 (for the stiffest piece from the population of 5602 pieces) indicates the effect of this excessive vibration. This piece was graded as unacceptable for any grade due to the high bit value (low modulus of elasticity) at the third data point, though the rest of the piece was stiff enough to qualify for the highest (C37-14E) grade (< 21 bits).

All data collected from the machine stress grader was statistically analyzed (where necessary) to eliminate the described effects of vibration. The methodology used is explained in detail in Appendix 3. After correction of the data for the effects of vibration, average modulus of elasticity, MOE_{mac}, and low point modulus of elasticity, $MOE_{lowpoint}$, were calculated for each piece. All modulus of elasticity data were corrected to 12%

moisture content per EN TC 124.202 (1989).

A histogram and fitted distribution of MOE_{mac} for the parent population of lumber (5602 pieces) are shown in Figure 3.

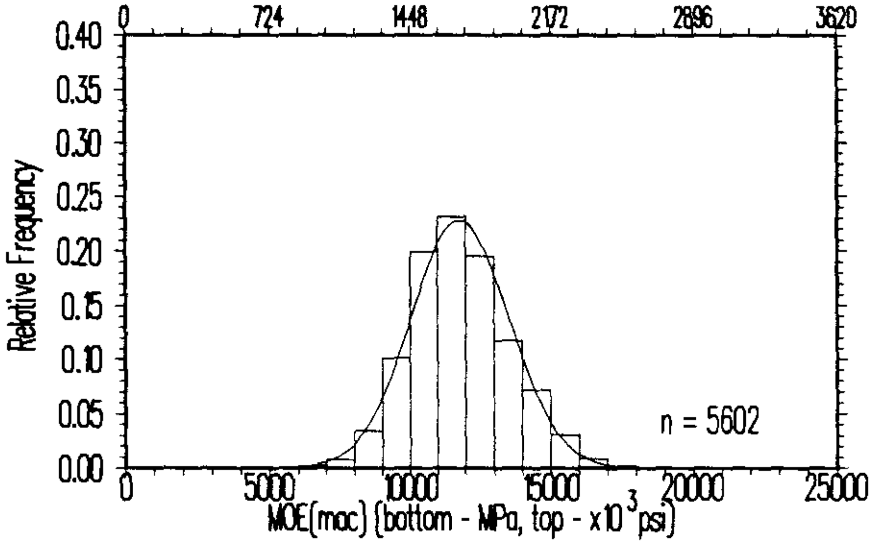

FIGURE 3 - Distribution of MOE_{mac}

5. LAMINATION LUMBER TESTING

Using the corrected machine stress grader data, the parent population of lumber pieces were ranked according to MOE_{mac} and a representative sample from throughout this ranked population was selected for material property testing. These material property tests provided the information necessary to establish lamination grades meeting CEN requirements.

The lamination lumber material property tests performed included (1) bending modulus of elasticity (flatwise and edgewise), (2) bending strength (edgewise), (3) tension strength, and (4) average density. Pieces to be tested were selected in such a way that the MOE_{mac} distribution of each material property test group matched the MOE_{mac} distribution of the parent population of lumber. All tests were performed on specimens 38 mm x 90 mm (1.50 in. x 3.54 in.) in cross section. Specimen length varied depending on the specific test performed and the requirements of the test standard ISO 8375 (1985). All modulus of elasticity test data were corrected to 12% moisture content in accordance with CEN standards.

5.1 Lumber Modulus of Elasticity

Laboratory flatwise bending tests were performed on 412 lumber pieces to confirm that the machine stress grader properly measured flatwise stiffness. These laboratory tests were performed over the same span, 914 mm (36 in.), and at the same load level as is used in the machine stress grader and provided a measure of MOE_{flat}. As indicated in Figure 4 and equation 2, a one-to-one correspondence does not exist between MOE_{flat} and MOE_{mac}; however, the correlation coefficient (r) between these two parameters was found to be 0.88. The regression equation between MOE_{flat} and MOE_{mac} is

$$MOE_{mac} = 0.91 MOE_{flat} - 61 \tag{2}$$

The lack of one-to-one correspondence is likely due to dynamic effects of the machine stress grader affecting the measurement of MOE_{mac} under operating conditions.

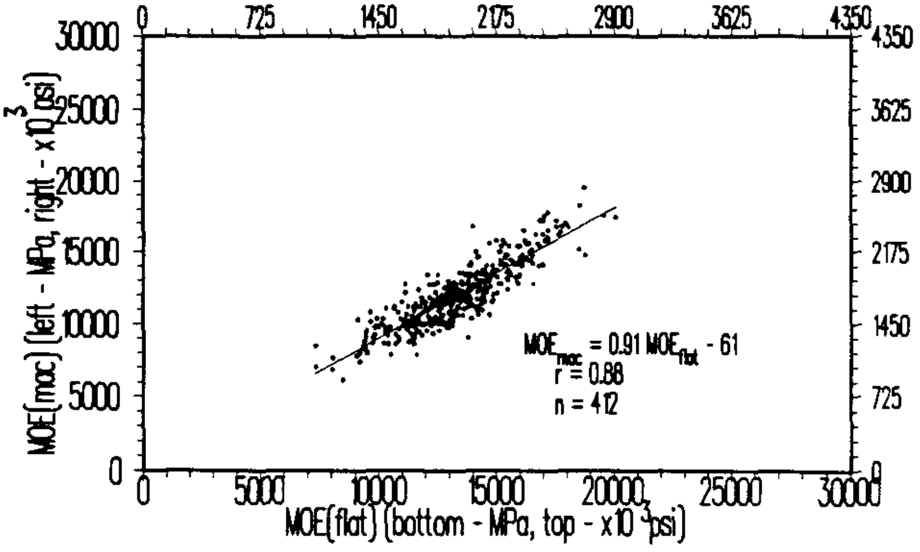

FIGURE 4 - Relationship between MOE_{flat} and MOE_{mac}

Laboratory edgewise modulus of elasticity tests were performed in accordance with ISO 8375 (1985) on the above 412 lumber pieces to develop a correlation between MOE_{edge} and MOE_{mac}. However, due to a faulty displacement measuring device, some data was found to be unreliable and retesting was performed on a second data set. From this data set, the regression equation between MOE_{mac} and MOE_{edge} was found to be

$$MOE_{edge} = 1.00 MOE_{mac} + 1694 \tag{3}$$

The correlation coefficient (r) for this regression was also found to be 0.87. The distribution of edgewise bending stiffness is shown in Figure 5.

Table 2 (at the end of this section) summarizes the distribution estimates of MOE_{mac} and MOE_{edge} for the parent population of lumber pieces.

5.2 Lumber Bending Strength

All lumber pieces slated for edgewise bending tests were visually graded according to the Norwegian standard NS 3080 (1988) and the most severe visual defect identified (see Appendix 2). The maximum defect was randomly located regarding its position with respect to the tension or compression side and these tests were performed in accordance with ISO 8375 (1985).

Because the specimens were tested on edge with a member depth of 90 mm (3.54 in.) and the reference depth is 200 mm (7.87 in.) according to EN TC 124.202 (1989), the following equation was used to adjust the bending strength data to the reference depth:

$$k_b = (200/d)^{0.20} \tag{4}$$

where d = depth of the member (90 mm).

All lumber test data, unless otherwise noted, were adjusted to the reference depth of 200 mm (7.8 in.) using equation 4. This also applies to the presented regression equations.

Figure 6 shows the distribution of lumber bending strength, $f_{b,1}$, for the tested lumber pieces. The regression equation between MOE_{edge} and $f_{b,1}$ was found to be

$$f_{b,1} = 0.00413 MOE_{edge} - 1.24 \tag{5}$$

where the correlation coefficient is r = 0.75 (Figure 7).

Table 2 indicates that the average bending strength of the total population of lumber pieces (after adjustment for depth using equation 4) is 48.5 MPa (7030 psi). This is consistent with the findings of Foslie and Moen (1968) who evaluated 2x4 Norwegian Spruce lumber from several districts of Norway.

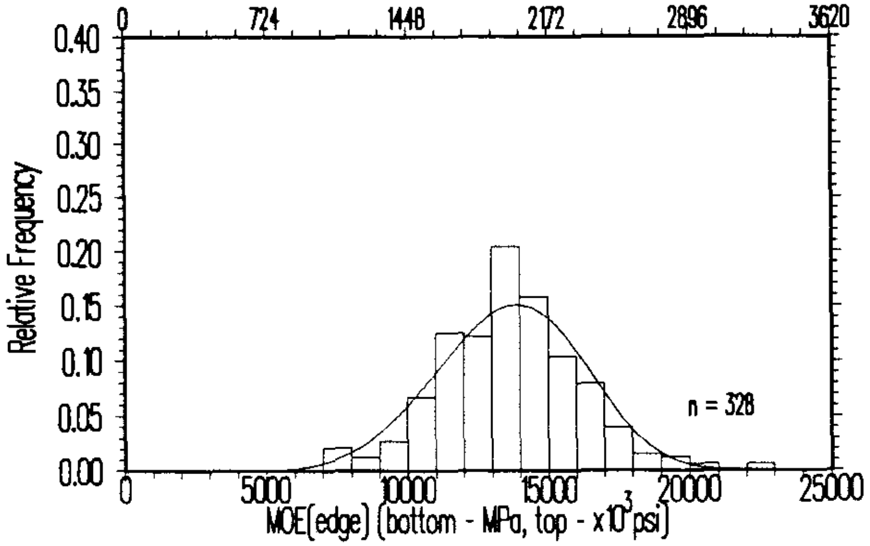

FIGURE 5 - Distribution of Modulus of Elasticity, MOE_{edge}

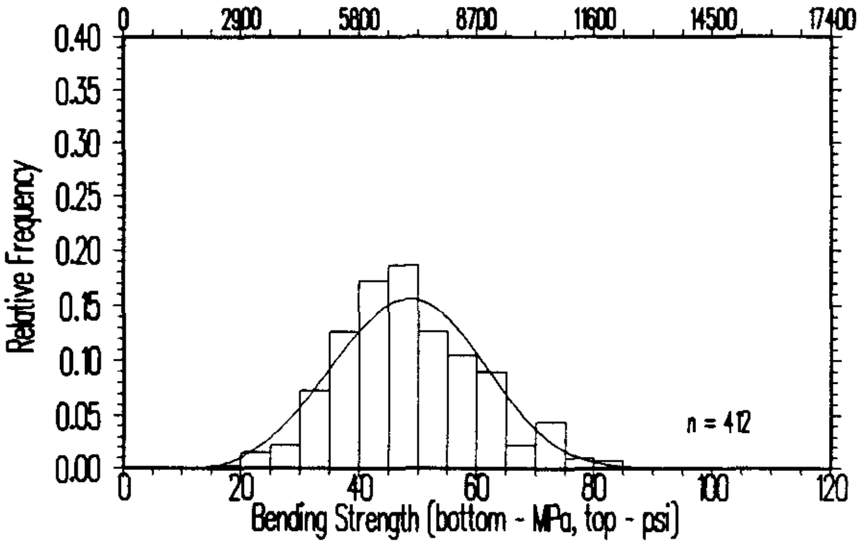

FIGURE 6 - Distribution of Bending Strengths, $f_{b,1}$

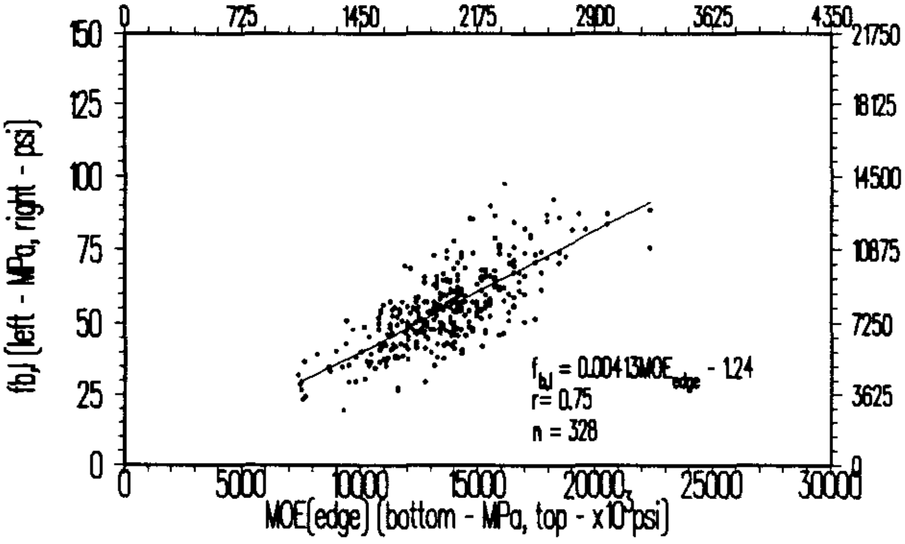

FIGURE 7 - Relationship Between MOE_{edge} and $f_{b,1}$

5.3 Lumber Tensile Strength

Tensile tests were performed on 414 lumber pieces in accordance with ISO 8375 (1985). These specimens were also visually graded according to the Norwegian standard NS 3080 (1988). The specimens were fabricated such that the maximum defect was located in the unsupported region of the lamination between the grips of the tension machine. The unrestrained distance between the grips was 1.00 m (39 in.). For tension testing, ISO 8375 stipulates a specimen length between the grips of at least nine times the nominal width. Though the specimen length between the grips was somewhat greater than the stated requirement, no length effect correction was applied to the tension strength results. However, the tensile strength of each specimen was adjusted to the reference width of 200 mm (7.8 in.) using equation 4.

Figure 8 shows the distribution of tensile strength for the tested lumber. The regression equation between MOE_{mac} and $f_{t,1}$ was found to be

$$f_{t,1} = 0.0021MOE_{mac} + 7.38 \qquad (6)$$

where the correlation coefficient is r = 0.51 (Figure 9). Table 2 summarizes the average tensile strength of the total population of lumber pieces.

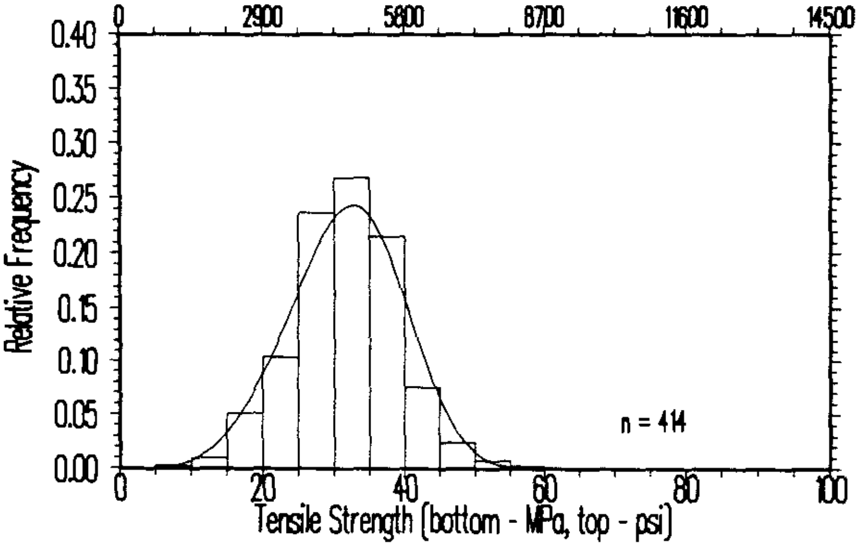

FIGURE 8 - Distribution of Tensile Strength, $f_{t,1}$

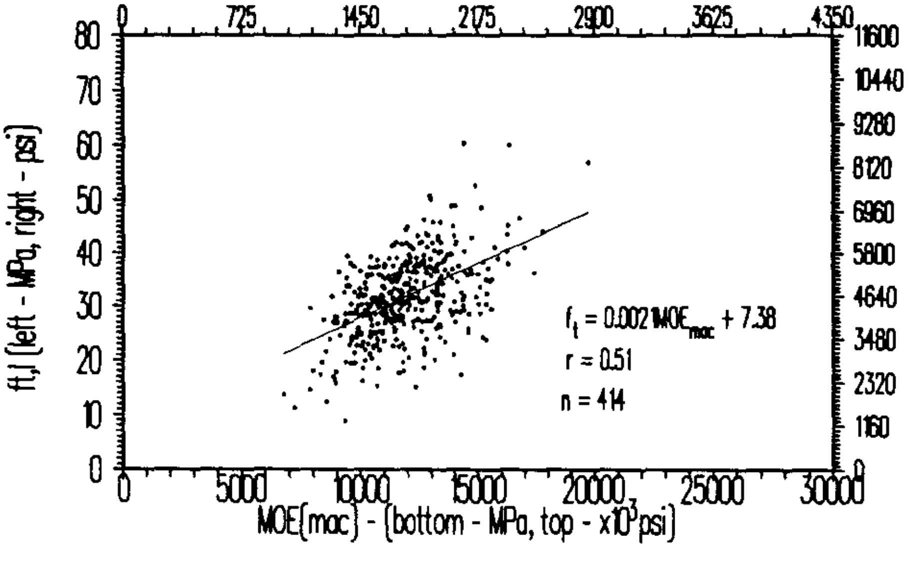

FIGURE 9 - Relationship Between MOE_{mac} and $f_{t,1}$

5.4 Lumber Density

Average density was computed by weighing 838 pieces selected from throughout the parent population of supplied lumber. All data was corrected to 12% moisture content according to EN TC124.202 (1989). Figure 10 shows the distribution of density for these specimens. The average density is found to be about 482 kg/m^3 (30.1 lb/ft^3). This is agreeable with the findings of Foslie and Moen (1968). In 1968, the average density for 2x4 lumber from several districts of Norway was found to be 491 kg/m^3 (30.7 lb/ft^3).

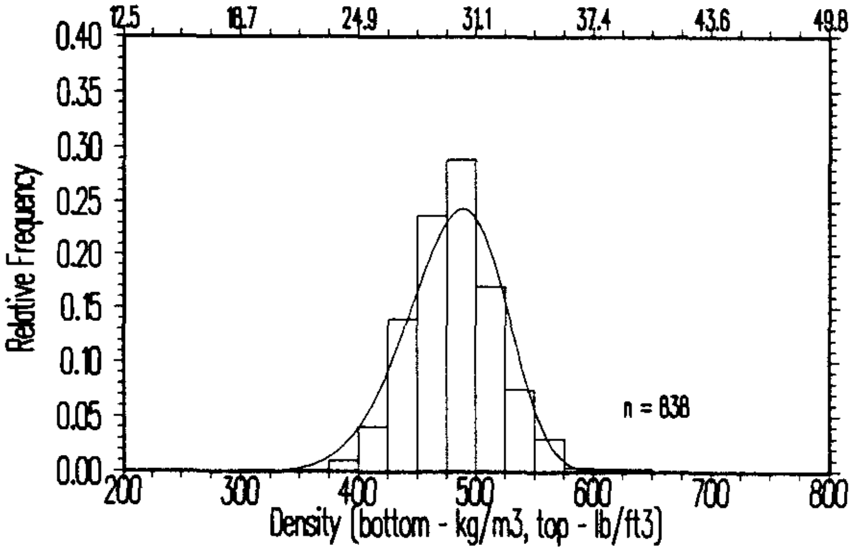

FIGURE 10 - Distribution of Density

TABLE 2

Statistical Estimates of Properties for the Parent Population of Lumber

PROPERTY	***n***	**PERCENTILE ESTIMATES**[1] MPa[2] (x10^{3}psi)		**COV**[3] (%)
		50th	**5th**	
MOE$_{mac}$[4]	5602	11,772 (1710)	8891 (1290)	14.9
MOE$_{edge}$	328	13,614 (1970)	9225 (1340)	18.9
$f_{b,1}$[5]	412	48.5 (7.030)	27.4 (3.970)	25.3
$f_{t,1}$[5]	414	31.7 (4.590)	18.1 (2.620)	25.2
Density	838	482 (30.1)	424 (26.5)	7.6

[1] See Appendix 4 for distribution parameters
[2] Density is in kg/m^3 (lb/ft^3)
[3] COV is coefficient of variation
[4] Average MOE of lumber piece
[5] Adjusted to reference size of 200 mm (7.8 in.)

6. DETERMINATION OF LAMINATING GRADES

To determine the grades contained in the parent population of supplied lumber, the results of the machine stress grading, bending stiffness and strength testing, and tension tests were statistically analyzed. Laminating grades meeting the requirements of EN TC 124.203, including C37-14E, C30-12E, C24-11E, and C21-10E, were targeted. To determine which of the 5602 lumber pieces fell into these grades, it was necessary to employ the developed relationships between MOE$_{mac}$ and MOE$_{edge}$ (equation 3), and MOE$_{edge}$ and $f_{b,1}$ (equation 5).

MOE$_{mac}$ is known for each piece in the parent population from the machine stress grading and the correlations between MOE$_{mac}$ and MOE$_{edge}$, and MOE$_{edge}$ and $f_{b,1}$ have been established. These relationships can be used to predict a modulus of elasticity and characteristic edgewise bending strength for each piece in the parent population. The predicted values will be referred to as MOE$_{edge,pred}$ and $f_{b,pred}$. The predicted value for each lumber piece can then be compared to the requirements of the grades of EN TC 124.203

to determine which grade the piece qualifies for.

Figure 11 displays the methodology used. Since $f_{b,pred}$ is used to determine the delineation between the various grades, the relative position of the characteristic regression line of Figure 11 will directly affect the number of lumber pieces meeting the grade requirements. How the location of this characteristic regression line is calculated is therefore significant and will be discussed next.

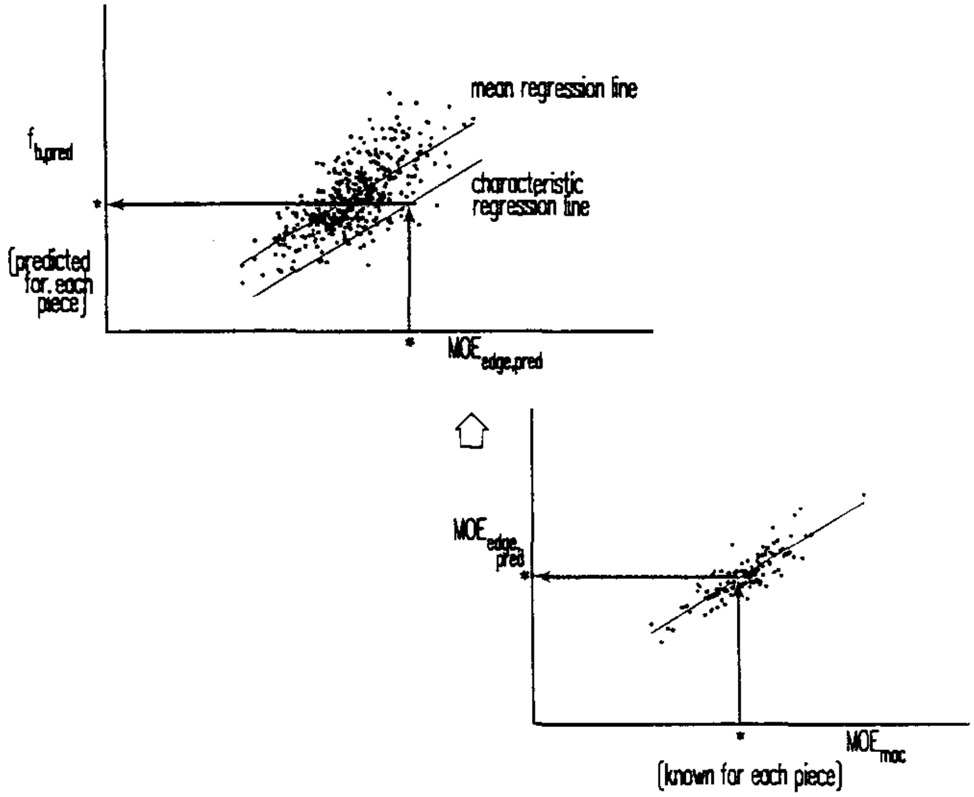

FIGURE 11 - Methodology to Determine Grade Delineation

6.1 Nonparametric Analysis

Since EN TC 124.203 suggests the use of a nonparametric estimate of the characteristic laminating properties, the characteristic regression line shown in Figure 11 represents the 75% tolerance limit of the nonparametric 5th percentile for a sample size of 328. For this sample size and tolerance, the 14th order statistic provides an estimate of the 5% percentile (ASTM D2915 1984). As was shown in Figure 7, the mean regression line is characterized by equation 5. An estimate of the characteristic regression was made by establishing a line of the same slope as the mean regression line such that fourteen data points lie below it. This results in the following equation for the characteristic regression line:

$$f_{b,pred} = 0.00413\ MOE_{edge,pred} - 16.50 \qquad (7)$$

See Figure 12 for a plot of this characteristic regression line. Combining equations 3 and 7.

$$f_{b,pred} = 0.00413\ MOE_{mac} - 9.50 \qquad (8)$$

A survey of the parent population indicated that 2696 of the 5602 lumber pieces (48%) met the requirements of the C37-14E grade based upon $f_{b,pred}$ and $MOE_{edge,pred}$. Similarly, 2771 of the 5602 pieces (50%) qualified for the C30-12E grade. The balance of the supplied lumber (135 pieces, or 2%) fell into the C24-11E grade.

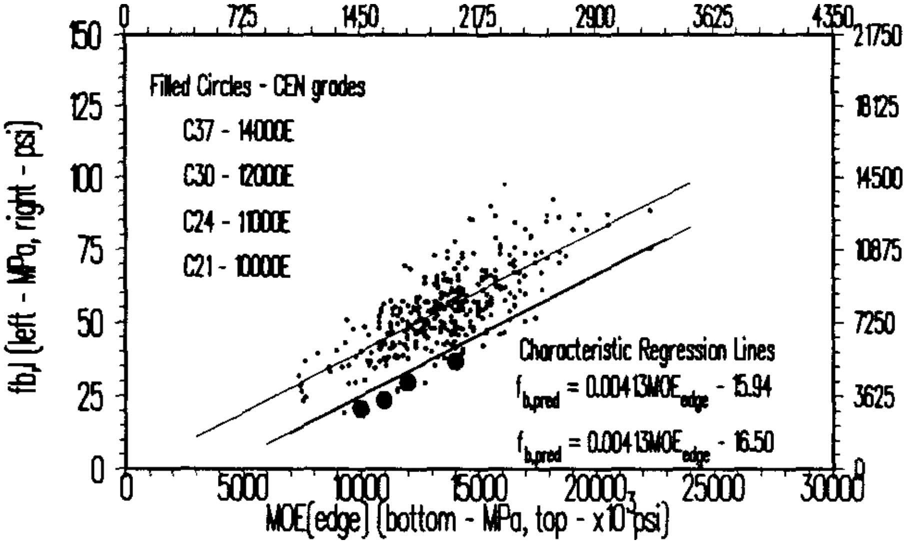

FIGURE 12 - Relationship between MOE_{edge} and $f_{b,1}$ and the corresponding characteristic regression line used to compute $f_{b,pred}$

From equation 8, the minimum MOE_{mac} of lumber from the parent population which fall into the C37-14E grade can be determined. Assuming a characteristic bending strength of 37 MPa (5362 psi), adjusting to a 90 mm (7.8 in.) depth using equation 4, equation 8 suggests a minimum MOE_{mac} of 12,810 MPa (1.86 x 10^6 psi). A similar calculation for the C30-12E lamination grade indicates a minimum MOE_{mac} of 10,350 MPa (1.50 x 10^6 psi) is required. These values are necessary for manufacturers in adjusting the machine stress grader to produce these yields.

6.2 Standard Error of Estimate Analysis

To verify that the nonparametric approach described above provided a reasonable estimate of the characteristic regression line, a second analysis was performed utilizing a calculation of the confidence interval for a mean regression line using the following standard error of estimate formula:

$$f_{b,l} = A + B \times MOE_{edge} - t \times S \times \sqrt{1 + \frac{1}{n} + \frac{(\overline{MOE}_{edge} - MOE_{edge})^2}{S_{xx}}} \qquad (9)$$

where

$\boldsymbol{A, B}$ = constants from regression fit
$\boldsymbol{t}$ = t-statistic (1.645 in this case)
$\boldsymbol{S}$ = standard error
$\boldsymbol{S_{xx}}$ = sum of squares of the error
$\boldsymbol{n}$ = number of observations
$\boldsymbol{MOE_{edge}}$ = mean modulus of elasticity of *n* lumber pieces
$\boldsymbol{MOE_{edge}}$ = average modulus of elasticity of an individual lumber piece

The use of this formula results in the following equation for the characteristic regression line:

$$f_{b,pred} = 0.00413 \ MOE_{edge,pred} - 15.94 \qquad (10)$$

Because the number of specimens is quite high (n = 328), the resulting expression for the characteristic regression line (from equation 9) is nearly linear. See Figure 12 for a plot of this characteristic regression line. Combining equations 3 and 10,

$$f_{b.pred} = 0.00413 \ MOE_{mac} - 8.94 \qquad (11)$$

As seen in Figure 12, the two methods result in estimates of the characteristic regression line that are nearly the same.

As before, surveying the parent population indicated that 2981 of the 5602 lumber pieces (53%) met the requirements of the C37-14E grade, 2528 of the 5602 pieces (45%) qualified for the C30-12E grade, and the balance of the supplied lumber (93 pieces, or 2%) fell into the C24-11E grade.

It is evident that both the nonparametric and the standard error of estimate analyses result in similar yields for the two laminating grades. Most importantly, in either case the yields are significantly higher than that produced by existing machine stress grading practices (see Table 1). Table 3 summarizes the yield of the established grades and the corresponding MOE_{mac} required to obtain these grades (based upon the nonparametric analysis).

TABLE 3
Yields of Established Grades and Required
MOE_{mac} Limits

GRADE	**YIELD** (%)	**Required** **$MOE_{mac}^{1,2}$** **MPa** ($x10^3$ psi)
C37-14E	48	12,810 (1860)
C30-12E	50	10,350 (1500)
< C30-12E	2	-

[1] Values given are at 12% moisture content
[2] Applicable for 90 mm (7.8 in.) depth only

7. PROPERTIES OF ESTABLISHED LAMINATING GRADES

While the above methods utilizing the regressions between strength and stiffness were necessary to determine the delineation between potential laminating grades, it must be determined if the mechanical properties of these grades meet the requirements specified in EN TC 124.207. The measured $f_{b,1}$, MOE_{edge}, $f_{t,1}$, and density data described in the materials testing section were statistically analyzed and distributional and nonparametric estimates of characteristic values were made. All comparisons assume a standard depth (or width) lamination (i.e., 200 mm (7.8 in.)). The required material properties for the C30-12E and C37-14E grades are reproduced in Table 4.

TABLE 4
Material Property Requirements for C30-12E and
C37-14E Grades per EN TC 124.207

MATERIAL PROPERTY	**Percentile**	**MATERIAL PROPERTY REQUIREMENTS** (x10^3 psi)	
		C30-12E	**C37-14E**
$f_{b,1}$	**5th**	30 (4.350)	37 (5.360)
MOE_{edge}	**50th**	12,000 (1740)	14,000 (2030)
	5th	8500 (1230)	10,000 (1450)
$f_{t,1}$	**5th**	18 (2.610)	22 (3.190)
Density	**5th**	410 (25.6)	450 (28.1)

[1] Density is in kg/m^3 (lb/ft^3)

7.1 Lumber Bending Strength

Figures 13 and 14 show the distribution of lumber bending strength, $f_{b,1}$, for the established C30-12E and C37-14E grades. Statistical estimates of the bending strength are summarized in Table 5.

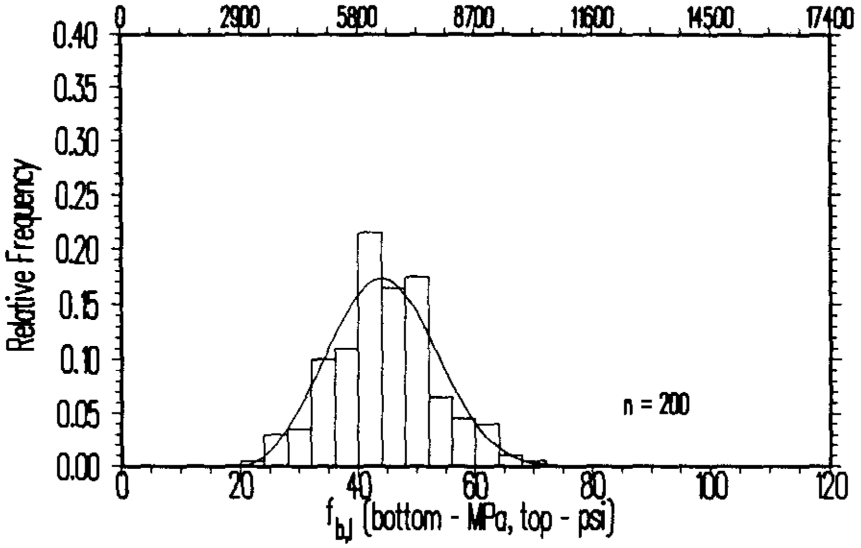

FIGURE 13 - Distribution of Bending Strength, $f_{b,1}$, for the C30-12E Grade

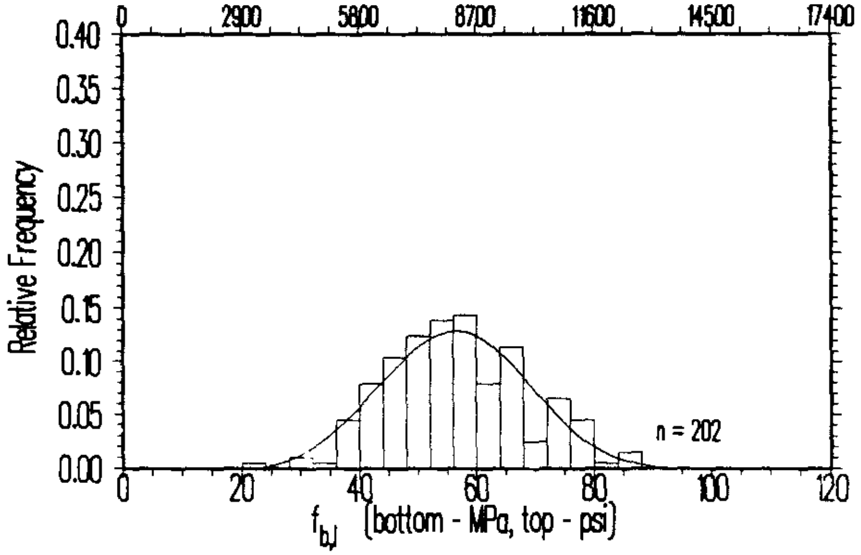

FIGURE 14 - Distribution of Bending Strength, $f_{b,1}$, for the C37-14E Grade

TABLE 5
Statistical Estimates of Lumber Bending Strength, $f_{b,1}$
for the Established Grades

GRADE	**Statistic**	**PERCENTILE ESTIMATES**[1,2] MPa (x10^3 psi)			**COV**[3] (%)
		50th	**5th** (50% Tol.)	**5th** (75% Tol.)	
C30-12E	**Nonparametric**	44.2 (6.400)	30.4 (4.400)	28.2 (4.090)	-
	Distributional[4]	44.5 (6.450)	29.7 (4.310)	28.9 (4.190)	20.0
C37-14E	**Nonparametric**	55.9 (8.100)	38.4 (5.560)	37.4 (5.420)	-
	Distributional[4]	56.3 (8.160)	36.9 (5.350)	35.7 (5.180)	20.9

[1] Adjusted to reference depth of 200 mm (7.8 in.)
[2] Tol. is tolerance limit
[3] COV is coefficient of variation
[4] See Appendix 4 for distribution parameters

These data were adjusted to the reference depth of 200 mm (7.8 in.). Estimates provided are 50% tolerance limits of the 50th and 5th percentiles and a 75% tolerance limit of the 5th percentile. Note that the characteristic bending strength for both grades is quite close to that required by the CEN standard (see Table 4).

Figure 15 compares the bending strengths of the two grades. As expected, most of the C37-14E grade has a bending strength significantly higher than the C30-12E grade; however, the weakest lumber pieces of the higher grade are no stronger than the weakest of the lower grade. This is expected, since the grades were sorted by MOE_{mac}, and MOE_{mac} and $f_{b,1}$ are not correlated strongly enough to insure that all lumber in a higher stiffness grade will necessarily have a bending strength greater than that in a lower stiffness grade.

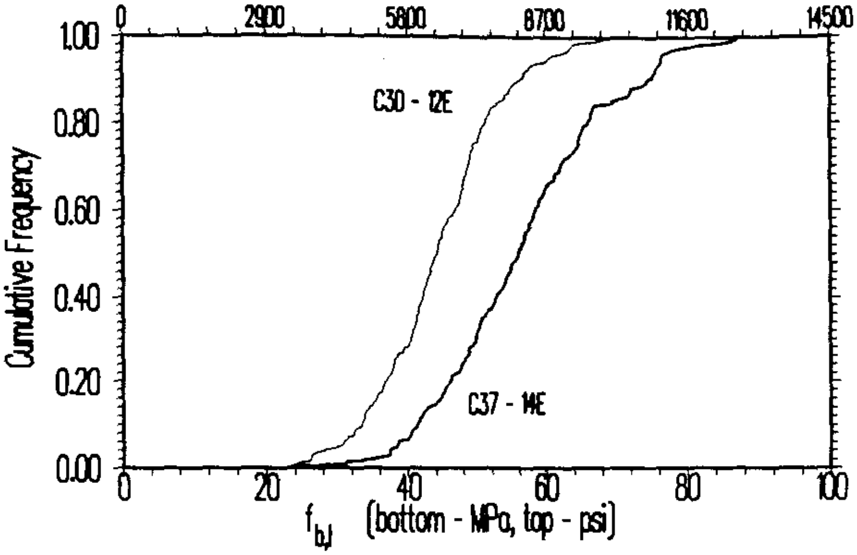

FIGURE 15 - Bending Strength Distributions for the C30-12E and C37-14E Grades

7.2 Lumber Modulus of Elasticity

Distributions of modulus of elasticity for the C30-12E and C37-14E grades are shown in Figures 16 and 17, respectively, and the two grades are compared in Figure 18. Table 6 summarizes statistical estimates of these. data. Comparing the estimates given in Table 6 and the requirements given in Table 4, it can be seen that the established grades exceed the MOE_{edge} requirements at both the mean and 5th percentile levels.

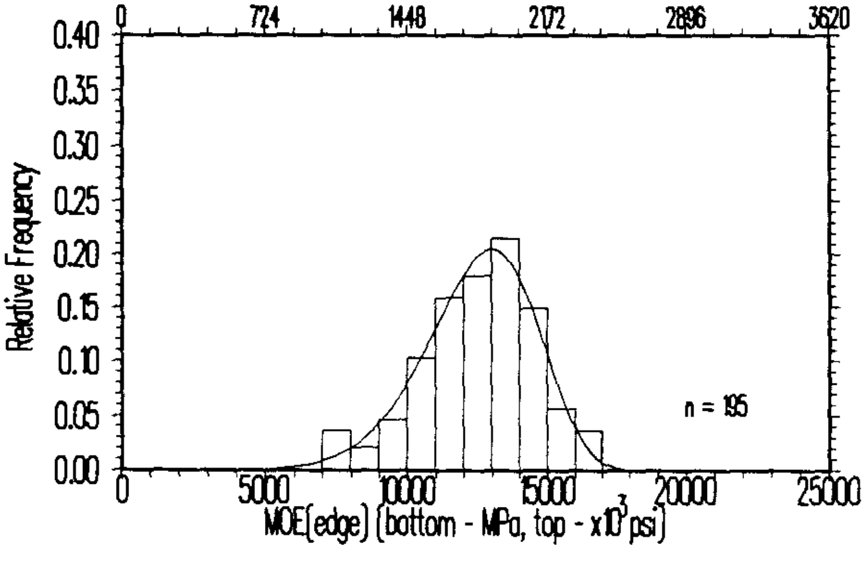

FIGURE 16 - Distribution of Lamination Modulus of Elasticity, MOE_{edge}, for the C30-12E Grade

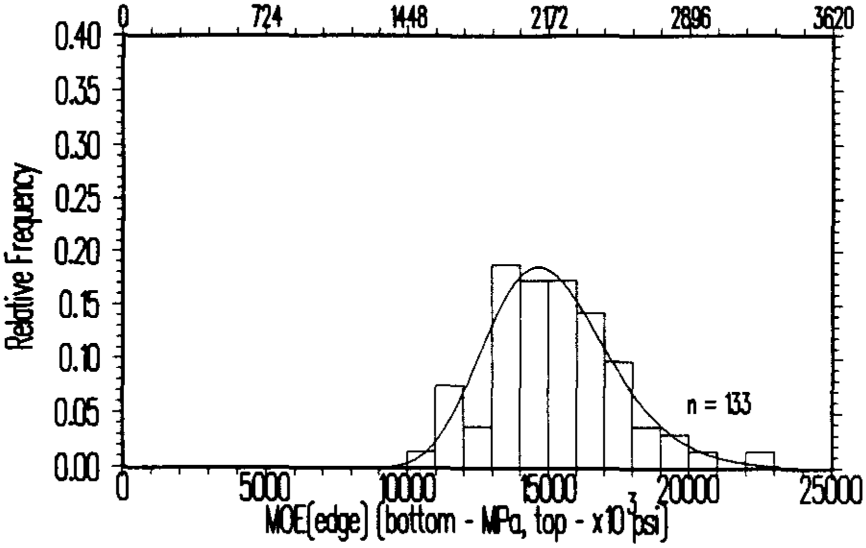

FIGURE 17 - Distribution of Lamination Modulus of Elasticity, MOE$_{edge}$, for the C37-14E Grade

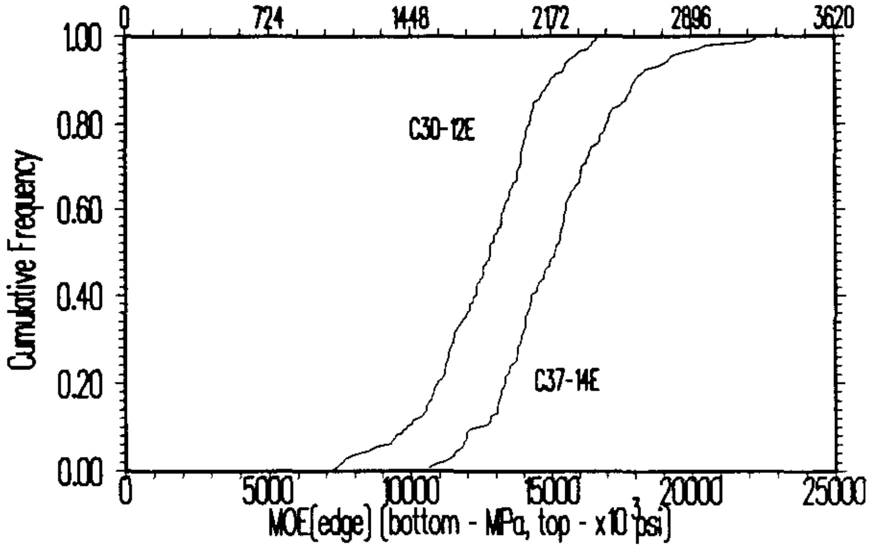

FIGURE 18 - Modulus of Elasticity Distributions for the C30-12E and C37-14E Grades

TABLE 6
Statistical Estimates of Lumber Modulus of Elasticity, MOE_{edge}, for the Established Grades

GRADE	Statistic	PERCENTILE ESTIMATES[1] MPa (x10^{3}psi)			COV[2] (%)
		50th	**5th** (50% Tol.)	**5th** (75% Tol.)	
C30-12E	**Nonparametric**	12,802 (1860)	8522 (1240)	8288 (1200)	-
	Distributional[3]	12,505 (1810)	8965 (1300)	8705 (1260)	15.9
C37-14E	**Nonparametric**	15,102 (2190)	11,550 (1670)	11,533 (1670)	-
	Distributional[3]	15,180 (2200)	11,865 (1720)	11,662 (1690)	14.7

[1] Tol. is tolerance limit
[2] COV is coefficient of variation
[3] See Appendix 4 for distribution parameters

7.3 Lamination Tensile Strength

Figures 19 and 20 show the distribution of lumber tensile strength, $f_{t,1}$, for the C30-12E and C37-14E grades and Table 7 summarizes statistical estimates of these data. Note that the tensile strength values have been adjusted to the reference width of 200 mm (7.8 in.). Figure 21 compares distributions of tensile strength for the two grades. A comparison to Table 4 indicates that both grades of lumber exhibit tensile properties quite close to the CEN requirements.

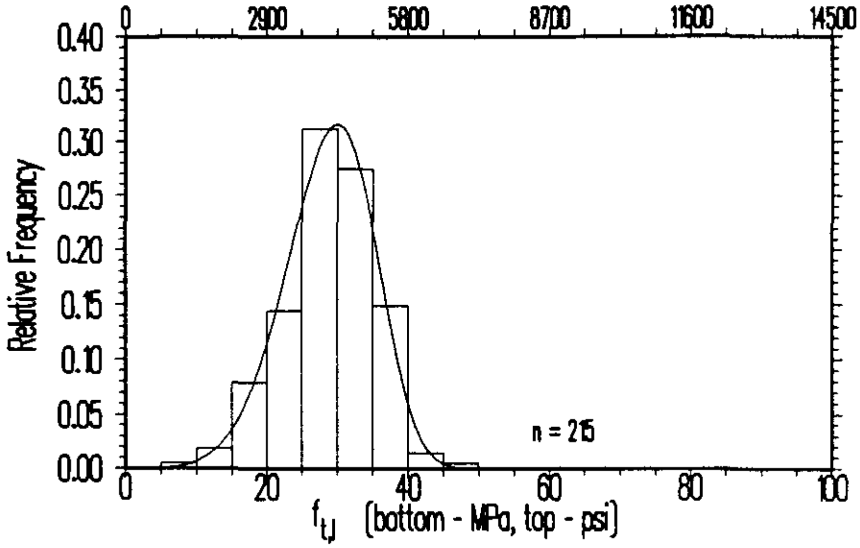

FIGURE 19 - Distribution of Tensile Strength, $f_{t,1}$, for the C30-12E Grade

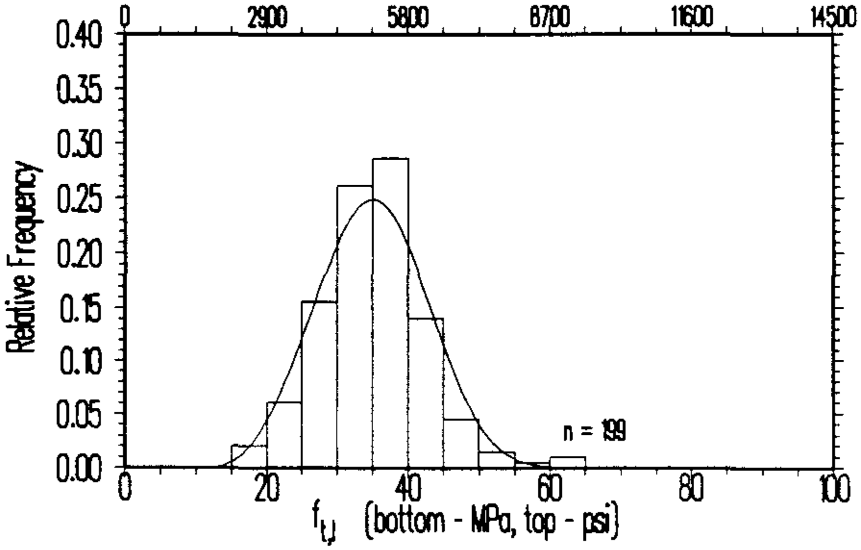

FIGURE 20 - Distribution of Tensile Strength, $f_{t,1}$, for the C37-14E Grade

TABLE 7

Statistical Estimates of Lumber Tensile Strength

$f_{t,l}$ for the Established Grades

GRADE	Statistic	PERCENTILE ESTIMATES[1,2] MPa ($x10^3$ psi)			COV[3] (%)
		50th	**5th** (50% Tol.)	**5th** (75% Tol.)	
C30-12E	**Nonparametric**	28.8 (4.180)	16.8 (2.440)	16.3 (2.360)	-
	Distributional[4]	28.7 (4.160)	17.7 (2.560)	17.0 (2.460)	21.8
C37-14E	**Nonparametric**	34.9 (5.060)	21.5 (3.120)	21.1 (3.060)	-
	Distributional[4]	34.9 (5.060)	22.3 (3.230)	21.6 (3.130)	22.0

[1] Adjusted to a reference width of 200 mm (7.8 in.)

[2] Tol. is tolerance limit

[3] COV is coefficient of variation

[4] See Appendix 4 for distribution parameters

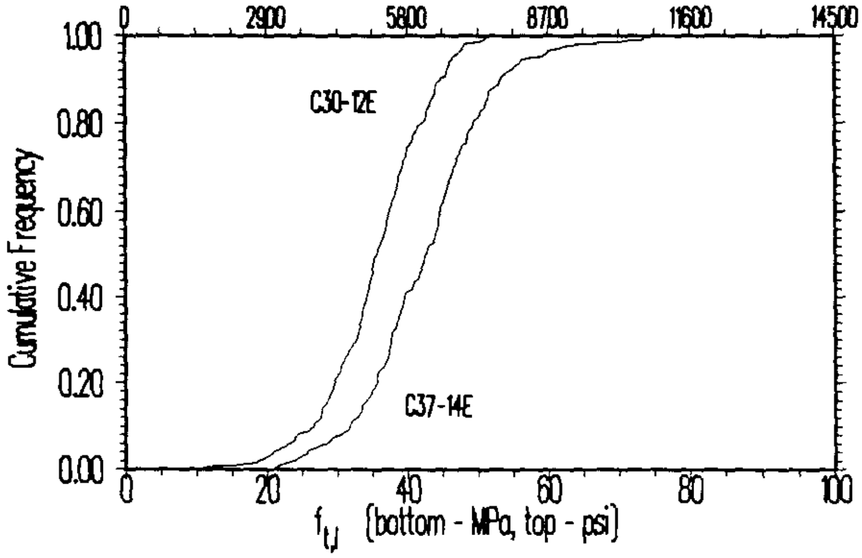

FIGURE 21 - Distribution of Tensile Strength for the C30-12E and C37-14E Grades

7.4 Lumber Density

Figures 22 and 23 show the distribution of lumber density for the established grades. Summarized in Table 8, statistical estimates indicate that the densities for the grades are slightly higher than the characteristic requirements of the CEN standard. Figure 24 compares the densities of the two grades.

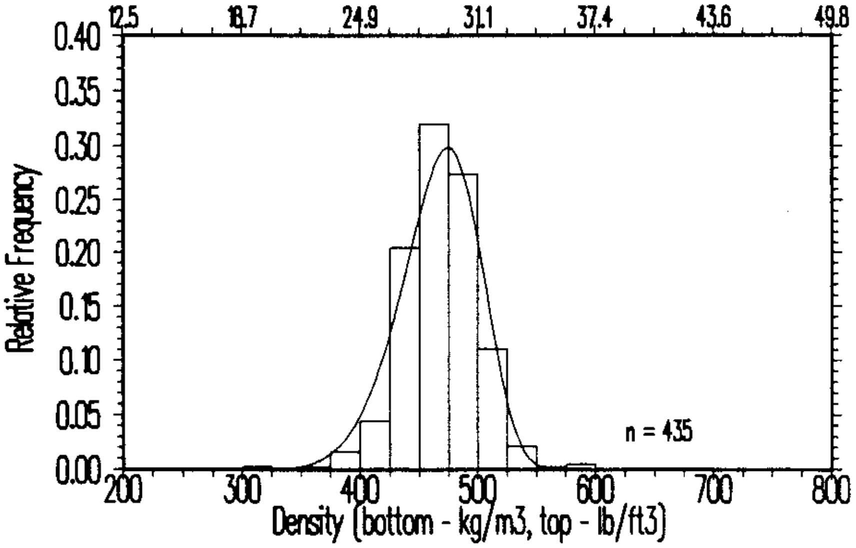

FIGURE 22 - Distribution of Lumber Density for the C30-12E Grade

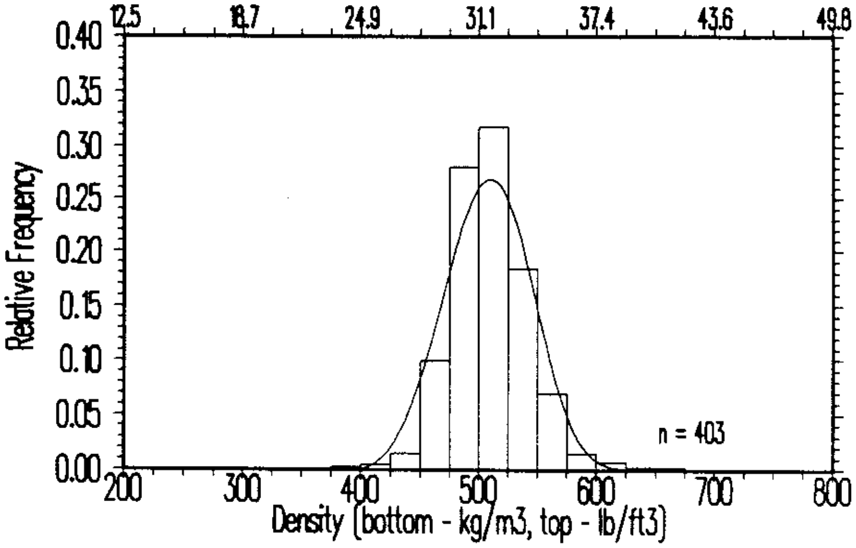

FIGURE 23 - Distribution of Lumber Density for the C37-14E Grade

TABLE 8
Statistical Estimates of Lumber Density for the Established Grades

GRADE	Statistic	PERCENTILE ESTIMATES[1,2] kg/m^3 (lb/ft^3)			COV[3]
		50th	5th (50% Tol.)	5th (75% Tol.)	
C30-12E	Nonparametric	476 (29.7)	423 (26.4)	420 (26.6)	-
	Distributional[4]	478 (29.8)	422 (26.3)	420 (26.6)	7.7
C37-14E	Nonparametric	519 (32.4)	466 (29.1)	459 (28.7)	-
	Distributional[4]	523 (32.6)	460 (28.7)	457 (28.5)	7.9

[1] Corrected to 12% moisture content
[2] Tol. is tolerance limit
[3] COV is coefficient of variation
[4] See Appendix 4 for distribution parameters

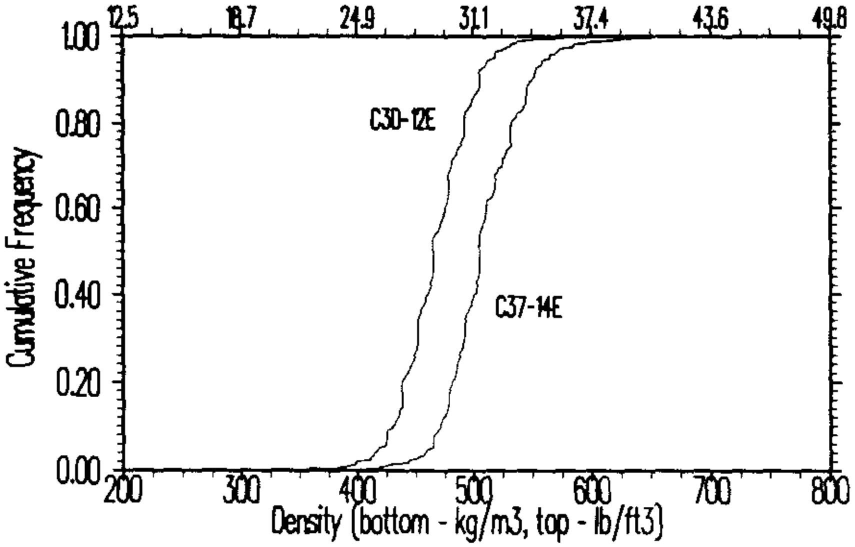

FIGURE 24 - Density Distributions for the C30-12E and C37-14E Grades

8. FINGER-JOINT TESTING

After establishing the two laminating grades, finger-joint specimens were selected from the parent population of lumber for testing. Like the previously described material property tests, the specimens chosen for finger-joint testing were selected such that their MOE_{mac} distribution matched the MOE_{mac} distribution of the parent population of lumber. Both finger-joint tension and finger-joint bending tests were performed. All finger-joint tension test data were adjusted to the reference width of 200 mm (7.8 in.), however finger-joint bending data was not adjusted for depth.

All finger-joint specimens were fabricated on a Cook Bolinder finger-jointing machine at Raumnes Bruk A.S. in Årnes, Norway and were vertically cut to the dimensions shown in Figure 25. To assure the finger-joint test results were representative of the tested glulam beams (to be described), the finger-joint specimens were fabricated at the Same time as the lumber used in beam construction was finger jointed.

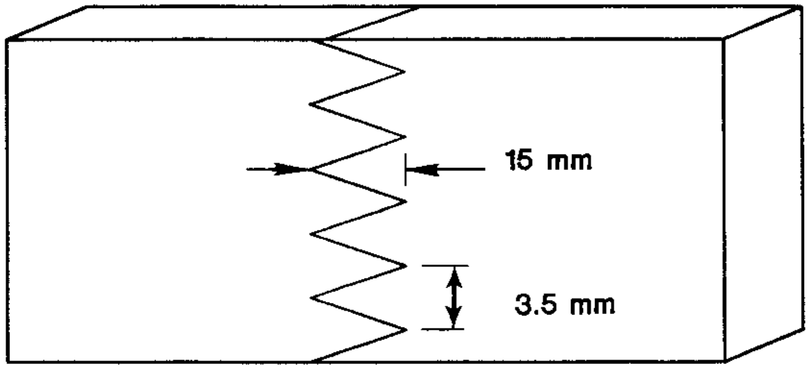

FIGURE 25 - Finger Joint Profile
15 mm (0.59 in.), 3.5 mm (0.14 in.)

8.1 Finger-joint Tensile Strength

The finger-joint tension tests were carried out in the Same manner as the lumber tension tests. However, the specimens were tested with only 300 mm (12 in.) between the tension machine grips. The finger joint was positioned in the middle of the unrestrained span. This short unrestrained test length was necessary to avoid failure at locations other than at the finger joint. We conducted 199 finger-joint tensile strength tests.

Figures 26 and 27 show the distribution of finger-joint tension strengths for the C30-12E and C37-14E laminating grades, respectively, and Table 9 summarizes the statistical estimates for this test data. Figure 28 compares the finger-joint tension strength of the two grades.

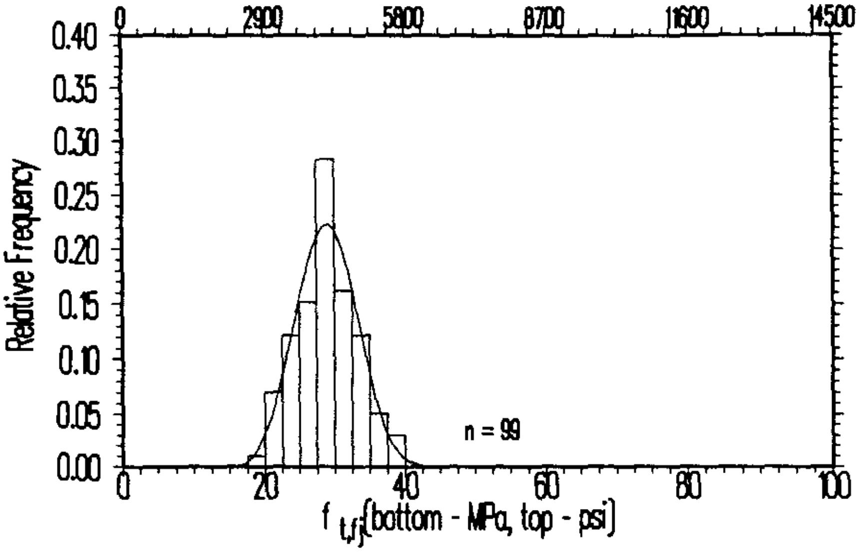

FIGURE 26 - Distribution of Finger-joint Tensile Strength, $f_{t,fj}$, for the C30-12E Grade

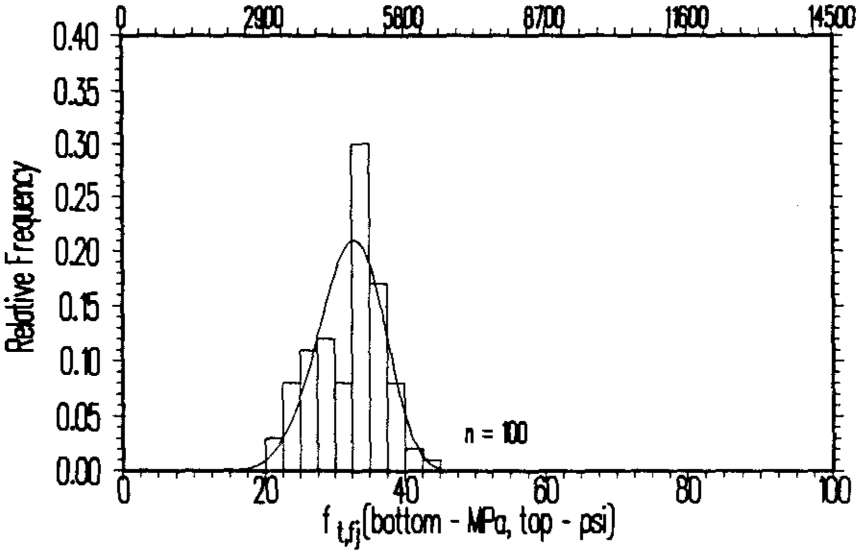

FIGURE 27 - Distribution of Finger-joint Tensile Strength, $f_{t,fj}$, for the C37-14E Grade

TABLE 9
Statistical Estimates of Finger-joint Tensile Strength, $f_{t,fj}$,
for the Established Grades

GRADE	Statistic	PERCENTILE ESTIMATES[1,2] MPa (x10³ psi) 50th	5th (50% Tol.)	5th (75% Tol.)	COV[3] (%)
C30-12E	**Nonparametric**	28.8 (4.180)	21.1 (3.060)	21.1 (3.060)	-
	Distributional[4]	28.8 (4.180)	21.7 (3.150)	21.2 (3.070)	14.9
C37-14E	**Nonparametric**	33.4 (4.840)	23.7 (3.440)	22.0 (3.190)	-
	Distributional[4]	32.1 (4.650)	24.0 (3.480)	23.4 (3.390)	14.5

[1] Adjusted to reference width of 200 mm (7.8 in.)
[2] Tol. is tolerance limit
[3] COV is coefficient of variation
[4] See Appendix 4 for distribution parameters

A comparison of finger-joint tension strength and lumber tension strength distributions, as shown in Figures 29 and 30, reveal some interesting results. First, the variability of the finger-joint tensile strength varies less than the lumber tensile strength (i.e., COVs of 15% vs. 21%). The finger-joint strength is lower than the lumber strength over most of the strength distribution range. Note also that the finger-joint and lumber tensile strength distributions cross, and at the lower end of the strength distribution range lumber strength governs. This is expected, since at the lower end of the lumber tensile strength distribution, the defects in the lumber are more critical than the finger joints. This is especially true for the lower grade lumber pieces (Figure 29).

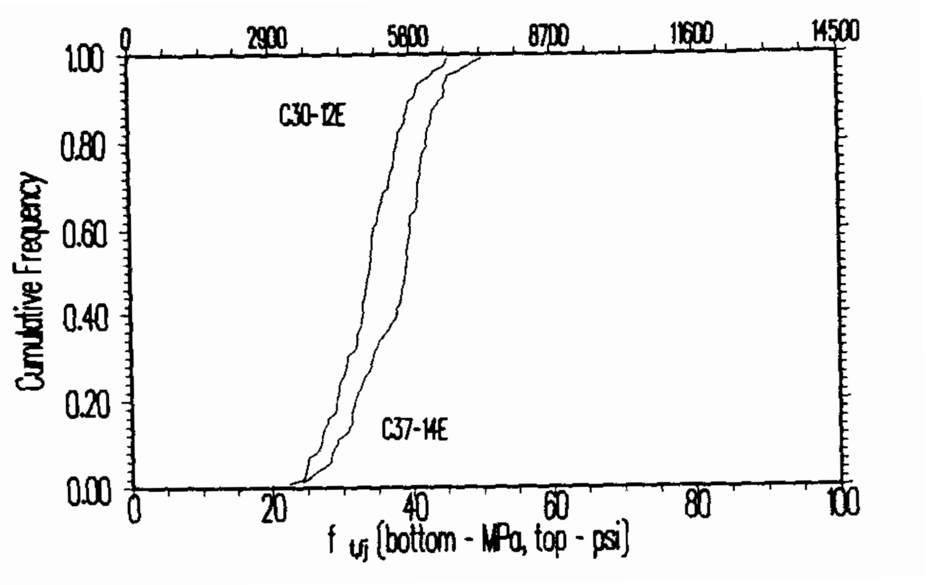

FIGURE 28 - Finger-joint Tensile Strength Distributions for the C30-12E and C37-14E Grades

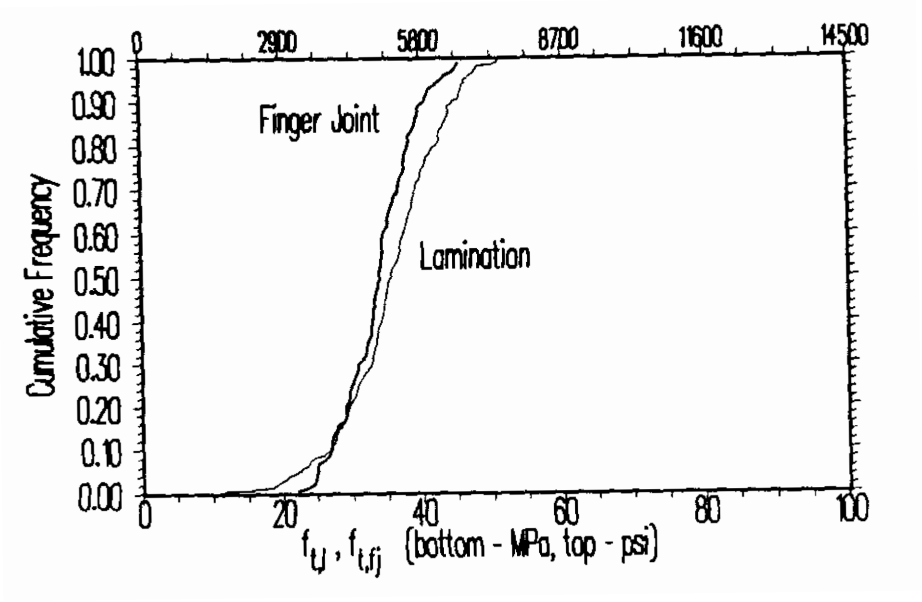

FIGURE 29 - Lumber and Finger-joint Tensile Strength Distributions for the C30-12E Grade

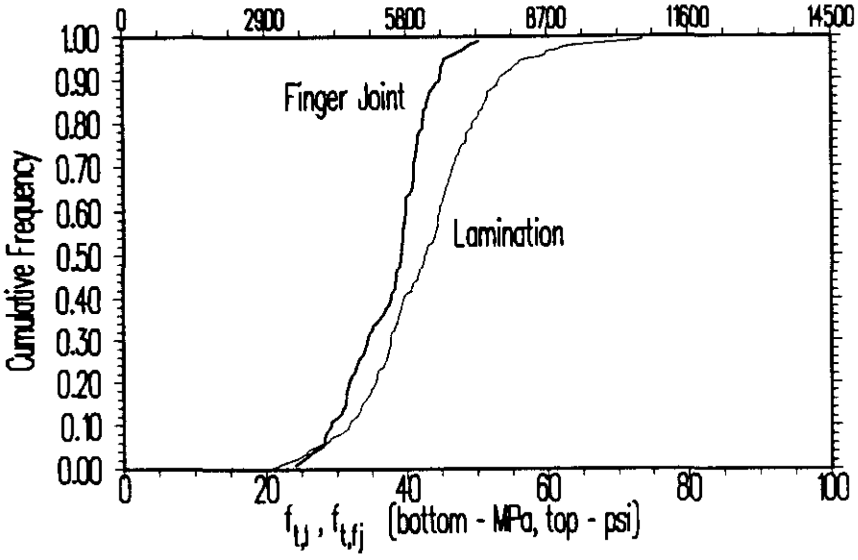

FIGURE 30 - Lumber and Finger-joint Tensile Strength Distributions for the C37-14E Grade

8.2 Finger-joint Bending Strength

In Europe, the flatwise bending strength of finger joints is used as a measure of production quality control for glulam beams. This is in contrast to the United States, where tensile strength is used as measure of finger-joint quality control (ANSI/AITC A190.1, 1992).

Flatwise finger-joint bending strength tests were performed on 196 specimens loaded at two points in a manner similar to that of ISO 8375 (1985); however, the specimens were tested over a span of 24 times the depth (33 mm (1.3 in.)). This configuration is typically used in Norway for finger-joint quality control.

The finger-joint bending strength distributions for the C30-12E and C37-14E grades are shown in Figures 31 and 32, respectively, and statistical estimates are summarized in Table 10. Finger-joint bending strength distributions for the two grades are compared in Figure 33.

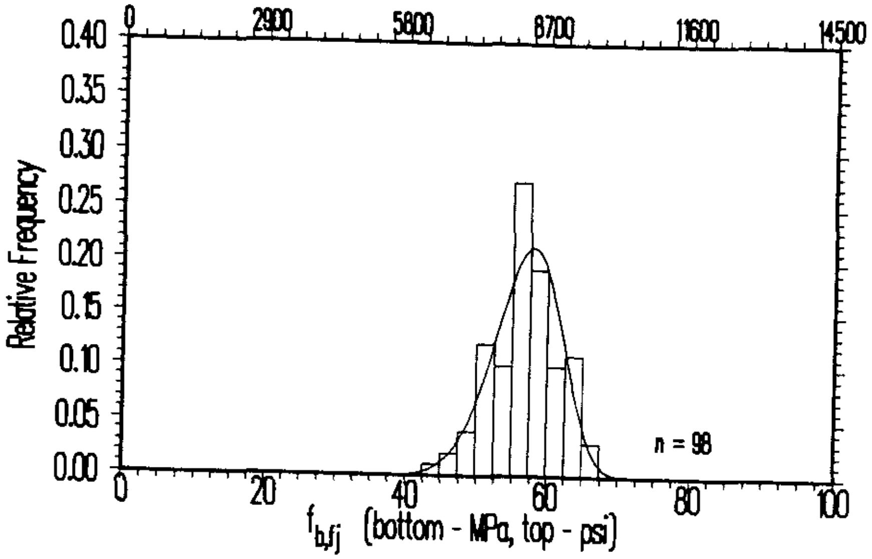

FIGURE 31 - Distribution of Finger-joint Bending Strength, $f_{b,fj}$, for the C30-12E Grade

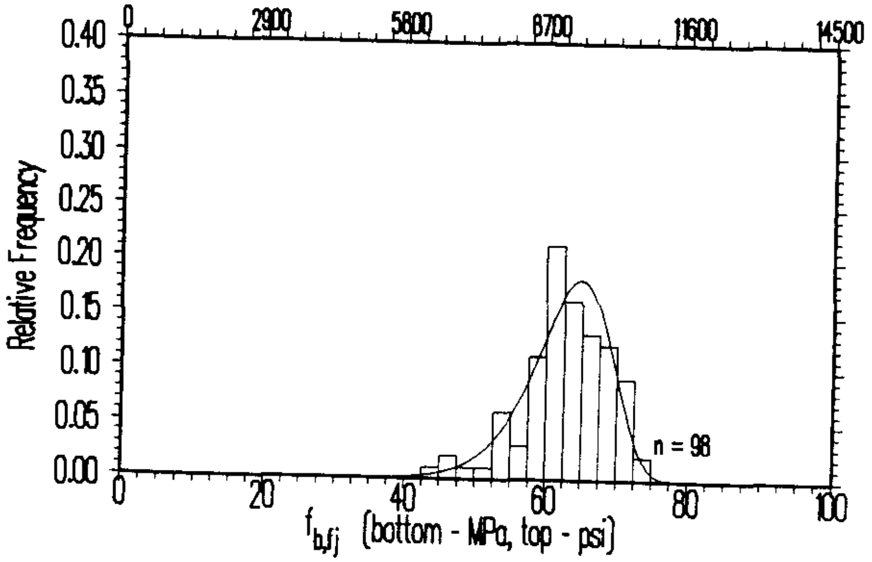

FIGURE 32 - Distribution of Fingerjoint Bending Strength, $f_{b,fj}$, for the C37-14E Grade

TABLE 10
Statistical Estimates of Finger-joint Bending Strength, $f_{b,fj}$, for the Established Grades

GRADE	Statistic	PERCENTILE ESTIMATES[1,2] MPa (x10^3 psi) 50th	5th (50% Tol.)	5th (75% Tol.)	COV[3] (%)
C30-12E	**Nonparametric**	57.0 (8.260)	49.5 (7.170)	46.5 (6.740)	-
	Distributional[4]	56.9 (8.250)	48.7 (7.060)	48.0 (6.960)	8.2
C37-14E	**Nonparametric**	63.2 (9.160)	52.2 (7.570)	46.7 (6.770)	-
	Distributional[4]	62.7 (9.090)	51.9 (7.520)	50.6 (7.330)	9.4

[1] Data unadjusted for depth
[2] Tol. is tolerance limit
[3] COV is coefficient of variation
[4] See Appendix 4 for distribution parameters

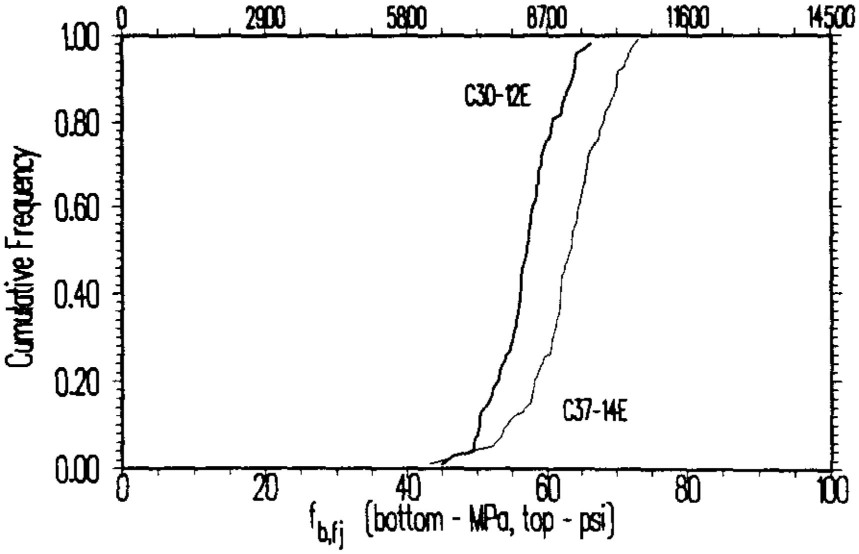

FIGURE 33 - Finger-joint Bending Strength Distributions for the C30-12E and C37-14E Grades

A ratio of finger-joint tension to bending strength can be computed From the test data. If the finger-joint tension data is adjusted to a 90 mm (3.5 in.) width (using equation 4) and the finger-joint bending data is not adjusted, at the characteristic value it is found that $f_{t,fj}/f_{b,fj}$ = 0.52 for the C30-12E grade and 0.54 For the C37-14E grade. These values are about 10% lower than the findings of Larsen (1980). If the ratio is computed using the finger-joint tension data adjusted to a 200 mm (7.8 in.) width (Table 9 values) the ratios are correspondingly lower; 0.45 for the C30-12E grade and 0.46 for the C37-14E grade.

9. FULL SIZE BEAM TESTS

9.1 Materials and Manufacture

The balance of the lumber not utilized in the material property and finger-joint testing were sorted into the established C30-12E and C37-14E grades. Three beam combinations were manufactured from this lumber, two homogeneous (LH35 and LH40) and one combined combination (LC38) (see Appendix 1).

Since the combined combination LC38 utilized C37-14E/C30-12E and not the C37-14E/C24-11E combination specified in the CEN standard, this layup will be referred to as LC38*. Pertinent material property requirements for these beam combinations are presented in Table 11.

TABLE 11

Requirements of Beam Combinations per EN TC 124.207

Material Property	**Percentile**	**CEN Requirements** MPa[1] (x10^3 psi)		
		Beam Combination		
		LH35	**LC38**	**LH40**
$f_{b,g}$	5th	35 (5.070)	38 (5.510)	40 (5.800)
MOE	50th	12,500 (1810)	13,000 (1840)	13,000 (1840)
Density	5th	410 (25.6)	380 (23.7)	450 (28.1)

[1] Density is kg/m^3 (lb/ft^3)

All beams were constructed of nine laminations 33 mm (1.3 in.) in thickness and 90 mm (3.5 in.) in width, resulting in test beams 300 mm (12 in.) in depth. The beams were manufactured by a commercial laminator (Raumnes Bruk A.S., Årnes, Norway) in 24 m (78 ft.) lengths over a four day period. Phenol-resorcinol resin was used for both the finger joints and for face bonding of the laminations. Temperature and humidity conditions were monitored and met Norwegian manufacturing standards.

The lumber pieces were first finger-jointed, allowed to cure overnight, and then face planed immediately before beam gluing and clamping. Four test beams, 6 m (19 ft. 6 in.) in length, were cut from each 24 m (78 ft.) beam. Figure 34 indicates the beam combinations tested. Note that all beam combinations are symmetrical and no special tension laminations were used, as is standard practice in Europe. The combined combination utilized four high grade outer laminations (C37-14E) and five lower grade (C30-12E) inner laminations. A total of 312 beams, 6 m (19 ft. 8 in.) in length, were manufactured; LH35 (104 beams), LH40 (112 beams), and LC38* (96 beams).

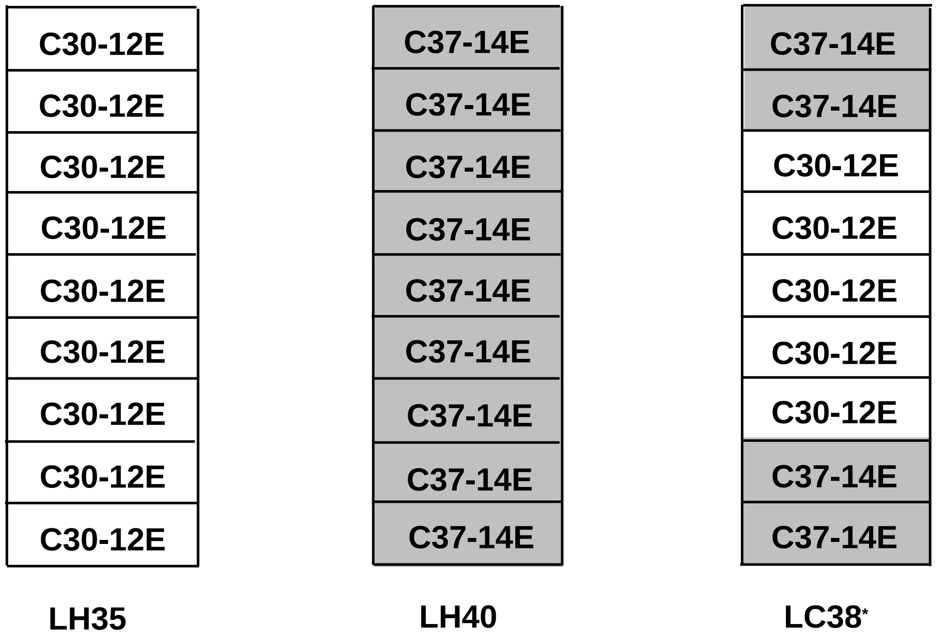

FIGURE 34 - Beam Combinations Tested

9.2 Beam Test Configuration

The beams were tested over a 5.40 m (17 ft. 6 in.) span with 1.80 m (5 ft. 10 in.) between the load heads as shown in Figure 35. The modulus of elasticity was measured in the shear free zone between the load heads over a 1.5 m (4 ft. 11 in.) span using an electronic displacement transducer in a manner similar to ISO 8375 (1985). Moisture content readings were taken on each glulam beam and the modulus of elasticity was adjusted to standard conditions (12% moisture content). The location of all finger joints as well as the identifying number of each lamination was noted before beam testing.

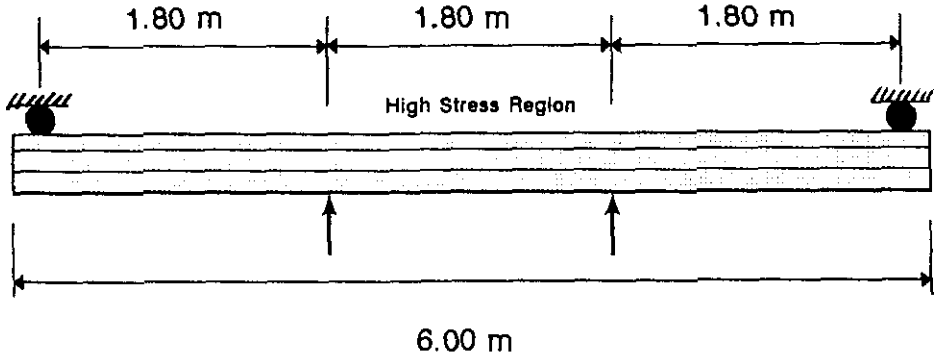

FIGURE 35 - Beam Test Configuration
1.80 m (5 ft. 10 in.), 6.00 m (19 ft. 6 in.)

9.3 Test Results

In general, the 312 glulam beams tested in this study failed as expected, that is, in tension in the outer lamination. However, in one beam, failure was initiated in shear and four beams did not reach ultimate load before the capacity of the test system was reached (10 metric tons). The ultimate bending stress of the beam that failed in shear was assumed to be the bending stress at the shear failure load level. Likewise, the ultimate bending stress of the four beams that did not fail was assumed to be the bending stresses at the test system load capacity.

9.3.1 Beam Bending Strength

Figures 36 through 38 show the distribution of bending strength, $f_{b,g}$, for the LH35, LH40, and LC38* glulam beam combinations, respectively. Table 12 summarizes the statistical estimates of beam bending strength. Note that since the beam depth was 300 mm (12 in.) in all cases, no depth effect adjustment was applied to the data. For the LH35 and LH40 beam combinations, the 5th percentile estimate of beam strength (50% tolerance) is seen to be within 2% of the strength levels required by the CEN standards (Table 10). For the LC38* combination, the CEN standards are exceeded. Applying a more conservative estimate of the 5th percentile (at 75% tolerance), the beam strengths are about 5% less than the required CEN standard values. Nonparametric estimates are also provided in Table 12 for comparative purposes.

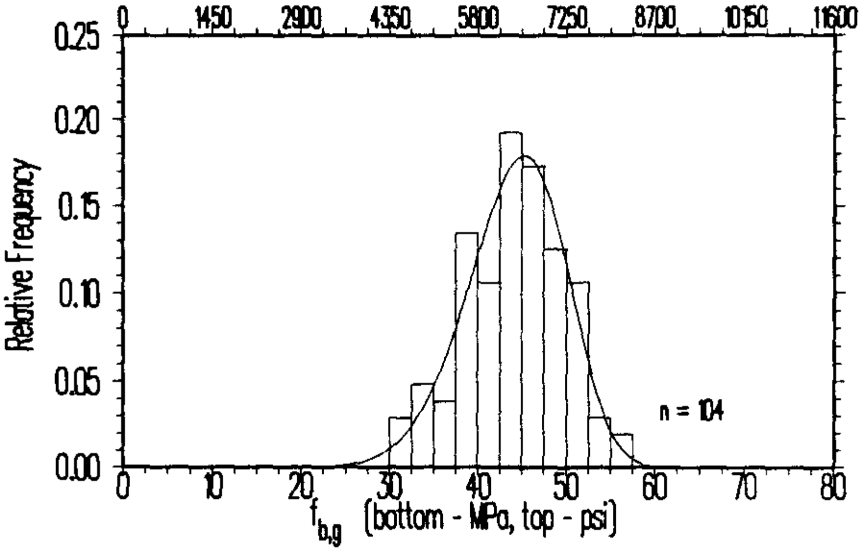

FIGURE 36 - Distribution of Bending Strength, $f_{b,g}$, for Beam Combination LH35

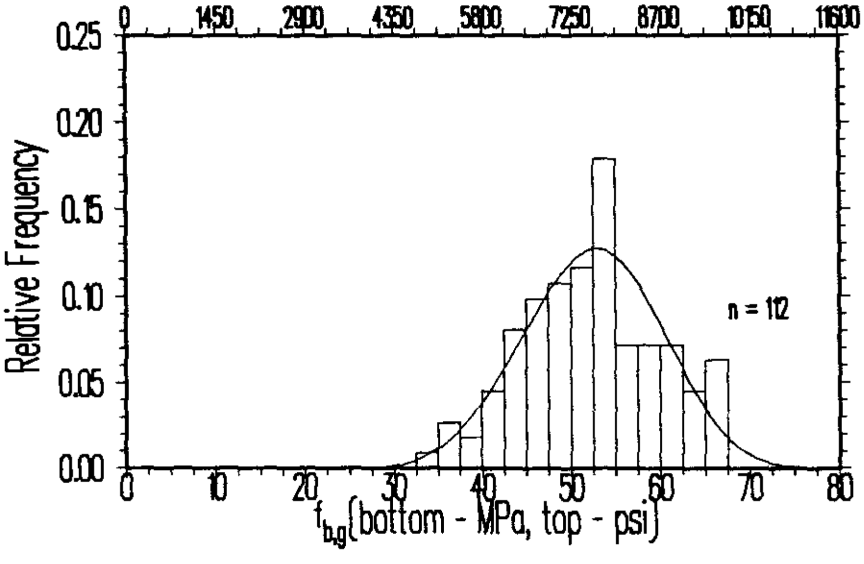

FIGURE 37 - Distribution of Bending Strength, $f_{b,g}$, for Beam Combination LH40

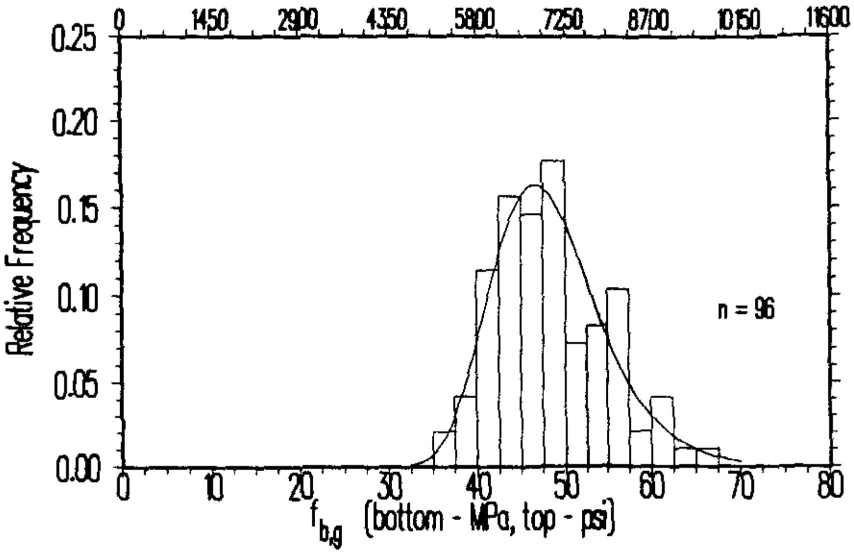

FIGURE 38 - Distribution of Bending Strength, $f_{b,g}$, for Beam Combination LC38*

For the LH35 beam combination, 23% of the beams failed at the finger joints, while 77% failed at defects in the lamination. In contrast, for the LH40 and LC38* beam combinations, 34% and 44%, respectively, failed at the finger joints, while 66% and 55%, respectively, failed at defects in the laminations. The higher percentage of lamination failures for the LH35 beam combination is in agreement with the trends shown in Figures 29 and 30. It is important to note from these results that the LH40 beam combination exhibits a bending strength about equal to that of the LC38* combination; however, the LC38* combination uses less than half the number of high grade laminations. This indicates the structural efficiency gained through the used of combined layups (see Figure 39).

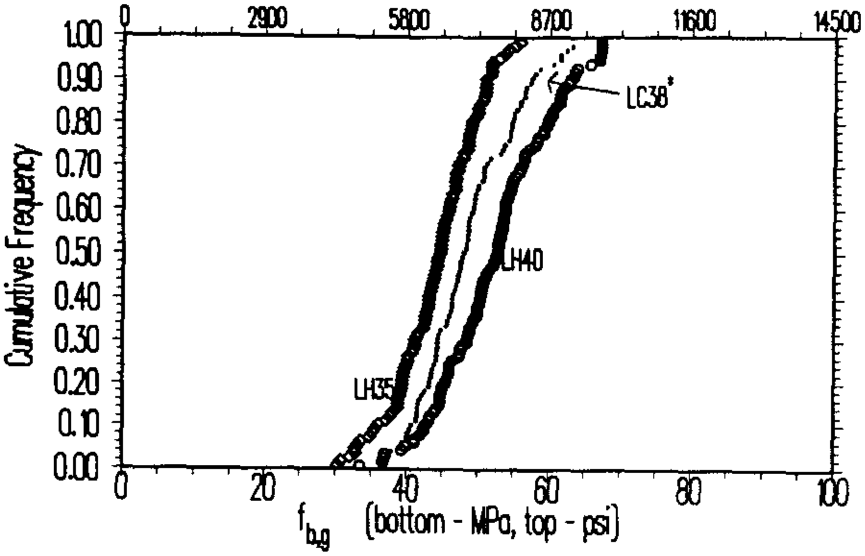

FIGURE 39 - Distribution of Bending Strength for All Beam Groups

TABLE 12
Statistical Estimates of Beam
Bending Strength

BEAM TYPE	**Statistic**	**PERCENTILE ESTIMATES**[1,2] MPa (x10^3 psi)			**COV**[3]
		50th	**5th** (50% Tol.)	**5th** (75% Tol.)	
LH35	**Nonparametric**	44.3 (6.420)	32.8 (4.760)	32.8 (4.760)	-
	Distributional[4]	44.1 (6.390)	34.3 (4.970)	33.4 (4.840)	12.6
LH40	**Nonparametric**	52.5 (7.610)	39.4 (5.710)	37.0 (5.360)	-
	Distributional[4]	52.3 (7.580)	39.4 (5.710)	38.4 (5.570)	14.6
LC38*	**Nonparametric**	47.7 (6.920)	37.9 (5.490)	37.6 (5.450)	-
	Distributional[4]	48.6 (7.045)	39.2 (5.680)	38.6 (5.590)	13.4

[1] Data unadjusted for depth
[2] Tol. is tolerance limit
[3] COV is coefficient of variation
[4] See Appendix 4 for distribution parameters

9.3.2 Modulus of Elasticity

Table 13 summarizes the statistical estimates of modulus of elasticity and bending stiffness distributions of the beam combinations are shown in Figures 40 through 42. It is apparent that all three beam combinations meet or exceed the CEN modulus of elasticity requirements. As expected, the LH40 beam combination has a slightly higher stiffness than the LC38* combination due to the uniform use of the higher stiffness C37-14E lamination grade. Modulus of elasticity results for the three beam groups are compared in Figure 43.

TABLE 13
Statistical Estimates of Beam
Modulus of Elasticity

BEAM GROUP	**Statistic**	**PERCENTILE ESTIMATES**[1,2] MPa (x10^3 psi)			
		50th	**5th** (50% Tol.)	**5th** (75% Tol.)	
LH35	**Nonparametric**	13,073 (1890)	11,305 (1640	11,197 (1620)	-
	Distributional[4]	13,000 (1880)	11,242 (1630)	11,067 (1600)	
LH40	**Nonparametric**	15,395 (2230)	13,421 (1940)	13,146 (1910)	-
	Distributional[4]	15,362 (2220)	13,409 (1940)	13,237 (1920)	7.2
LC38*	**Nonparametric**	14,618 (2190)	12,928 (1870)	12,553 (1820)	-
	Distributional[4]	14,596 (2120)	13,049 (1890)	12,898 (1870)	6.0

[1] Adjusted to 12% moisture content
[2] Tol. is tolerance limit
[3] COV is coefficient of variation
[4] See Appendix 4 for distribution parameters

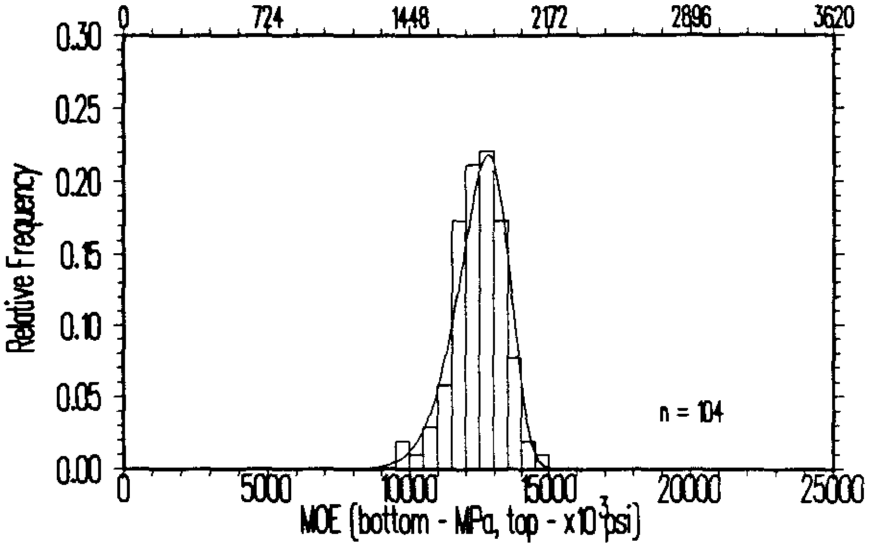

FIGURE 40 - Distribution of Modulus of Elasticity for LH35 Beams

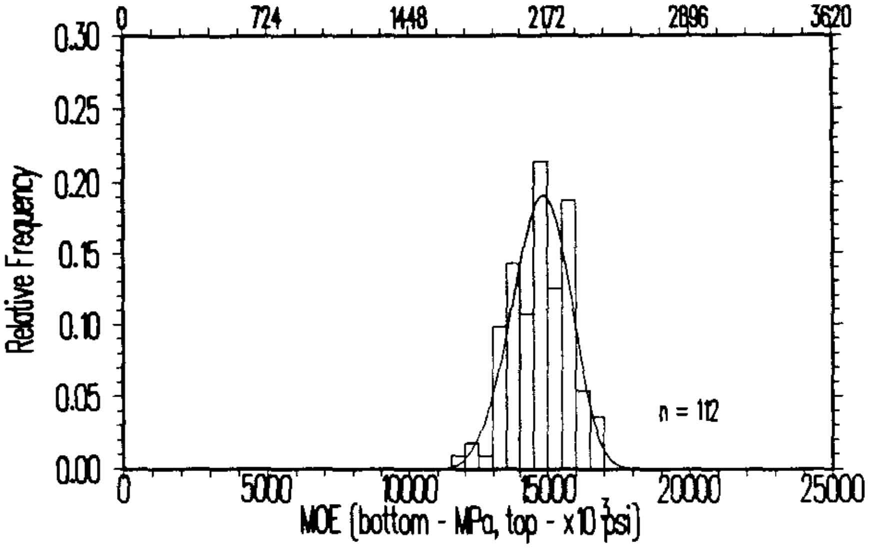

FIGURE 41 - Distribution of Modulus of Elasticity for LH40 Beams

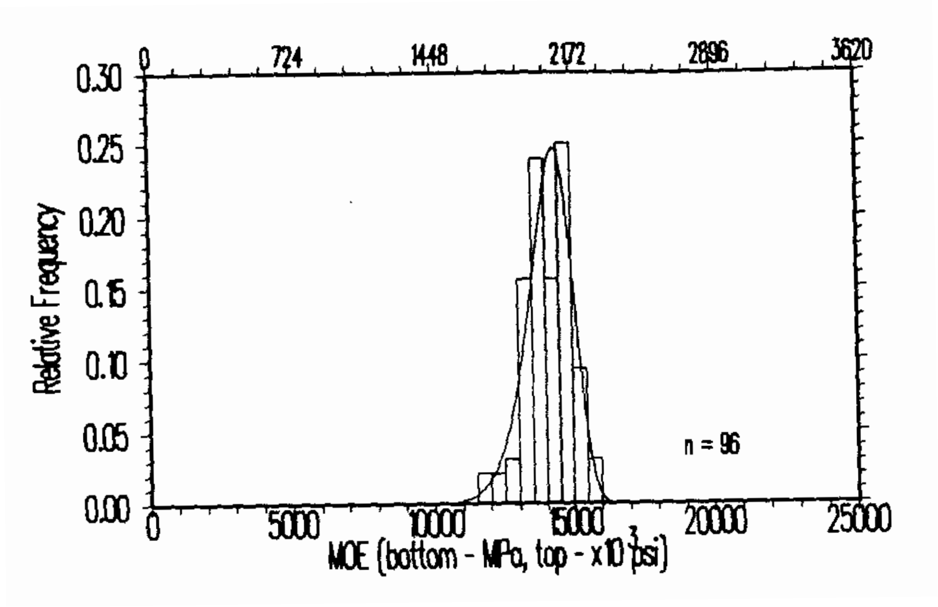

FIGURE 42 - Distribution of Modulus of Elasticity for LC38* Beams

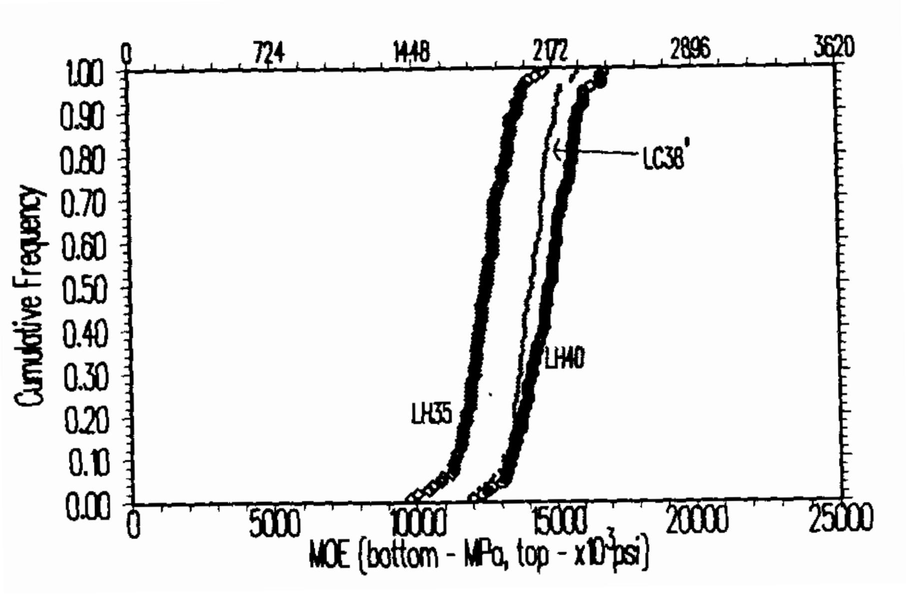

FIGURE 43 - Distribution of Modulus of Elasticity for All Beam Groups

10. INFLUENCE OF FINGER-JOINT AND LUMBER QUALITY ON BEAM STRENGTH

It is well recognized that the strength of finger joints has a dominant effect on glulam beam strength. Of obvious importance to the manufacturers of glulam timber is the level of finger-joint strength necessary to assure a targeted level of beam strength. The determination of this required finger-joint strength level requires a measure of lamination effect.

Since characteristic bending and tensile strength data has been collected for the lumber and finger joints used in beam construction, lamination factors can be easily evaluated from the following expressions:

$$k_{lam,b,l} = f_{b,g,l} / f_{b,k,l} \tag{13}$$

$$k_{lam,t,l} = f_{b,g,l} / f_{t,k,l} \tag{14}$$

$$k_{lam,b,fj} = f_{b,g,fj} / f_{b,k,fj} \tag{15}$$

$$k_{lam,t,fj} = f_{b,g,fj} / f_{t,k,fj} \tag{16}$$

where

$k_{lam,b,1}$ = bending lamination factor based on lumber bending strength
$k_{lam,t,1}$ = tension lamination factor based on lumber tensile strength
$k_{lam,b,fj}$ = bending lamination factor based on finger-joint bending strength
$k_{lam,t,fj}$ = tension lamination factor based on finger-joint tensile strength
$f_{b,g,1}$ = characteristic bending strength of beams failing in the lamination
$f_{b,g,fj}$ = characteristic bending strength of beams failing at a finger joint
$f_{b,k,1}$ = characteristic lumber bending strength
$f_{t,k,1}$ = characteristic lumber tensile strength
$f_{b,k,fj}$ = characteristic finger-joint bending strength
$f_{t,k,fj}$ = characteristic finger-joint tensile strength

It should be noted that equation 13 is a different measure of k_{lam} than is currently used in Norway (NS 3470, 1989).

In calculating laminating factors using the above equations, $f_{b,k,1}$ is based upon data adjusted to the standard 200 mm (7.8 in.) depth (Table 5), while $f_{t,k,1}$ and $f_{t,k,fj}$ are computed from unadjusted data (90 mm (3.5 in.) depth or width). The factor $f_{b,k,fj}$ is computed from the unadjusted finger-joint bending strength data described earlier (Table 10). No depth adjustment is made to the beam test data since all beams were at the beam reference depth of 300 mm (12 in.).

As indicated in Tables 14 through 16, lamination factors are computed from equations 13-15 for the three combinations of beams tested, LH35, LH40, and LC38*. For each combination, three groups of beams are investigated: (1) all beams tested, $f_{b,g}$,

(2) only beams failing at finger joints, $f_{b,g,fj}$ and (3) only beams failing at defects in the laminations, $f_{b,g,1}$.

As seen from Table 14 for the LH35 beam combination, $k_{lam,b,1}$ is computed as 1.14 and 1.15. These values are quite close to the 1.16 laminating factor assumed in the CEN standards (see Appendix 1) and indicate that the bending strength of the lamination need only be about 87% as strong as the bending strength of the glulam beam. For the LH40 combination, Table 14 indicates lower $k_{lam,b,1}$ values of 1.08 and 1.07. CEN standards assume 1.08 for this combination. For the LC38* beam combination, Table 15 indicates $k_{lam,b,1}$ values of 1.04 and 1.06, slightly greater than the 1.03 factor assumed by the CEN standard.

TABLE 14

Laminating Factors Computed from LH35 Beam Test Results

LH35	n	$f_{b,g}$	$k_{lam,b,1}$	$k_{lam,b,fj}$	$k_{lam,t,1}$	$k_{lam,t,fj}$
All beams	104	34.3	1.15	0.70	1.65	1.35
Finger joint failures only	24	35.8	-	0.74	-	1.41
Lamination failures only	80	33.9	1.14	-	1.63	-

for C30-12E laminations:	for C30-12E finger joints:
$f_{t,1}$ = 20.8 MPa	$f_{t,fj}$ = 25.4 MPa
$f_{b,1}$ = 29.7 MPa	$f_{b,fj}$ = 48.7 MPa

TABLE 15

Laminating Factors Computed from LH40 Beam Test Results

LH40	n	$f_{b,g}$	$k_{lam,b,1}$	$k_{lam,b,fj}$	$k_{lam,t,1}$	$k_{lam,t,fj}$
All beams	112	39.4	1.07	0.76	1.51	1.40
Finger joint failures only	38	38.4	-	0.74	-	1.36
Lamination failures only	74	40.0	1.08	-	1.53	-

for C37-14E laminations:	for C37-14E finger joints:
$f_{t,1}$ = 26.1 MPa	$f_{t,fj}$ = 28.2 MPa
$f_{b,1}$ = 36.9 MPa	$f_{b,fj}$ = 51.9 MPa

TABLE 16

Laminating Factors Computed from LC38
Beam Test Results

LC38*	n	$f_{b,g}$	$k_{lam,b,1}$	$k_{lam,b,fj}$	$k_{lam,t,1}$	$k_{lam,t,fj}$
All beams	96[1]	39.2	1.06	0.76	1.50	1.39
Finger joint failures only	42	39.1	-	0.75	-	1.39
Lamination failures only	53	38.5	1.04	-	1.48	-

The results of Ehlbeck and Colling (1986) suggests that the bending strength of a glulam beam can be calculated from the flatwise bending strength of outer laminations containing finger joints according to the following equation:

$$f_{b,k,g} = 0.80\, f_{b,g,fj} \tag{17}$$

As indicated in Tables 14-16, the calculation of $k_{lam,b,fj}$ for the three beam combinations tested shows a range of values from 0.70 to 0.76, somewhat lower than suggested by equation 17.

The use of a bending lamination factor allows manufacturers to perform a convenient quality control test of finger joints. The flatwise bending strength of an individual finger joint and the stresses that finger joint will experience on the tension side of a glulam beam are of questionable relation. This is the reason that, in the United States, the tension performance of finger joints is referenced in quality control testing of glulam beams (ANSI/AITC A190.1, 1992). The individual tension performance of a lamination is not unlike its performance on the tension side of a glulam beam.

For this reason, a laminating factor for tension is also calculated. Table 14 shows that for the LH35 beam combination $k_{lam,t,1}$ values were found to be 1.63 and 1.65. Tables 15 and 16 show lower $k_{lam,t,1}$ factors for the beam combinations LH40 and LC38*, ranging from 1.48 to 1.53.

The laminating factor based on finger-joint tension, $k_{lam,t,fj}$, for all three beam combinations is found to range between 1.35 and 1.41. Note that in all cases, the tension laminating factor for finger joints is less than the tension laminating factor for lumber pieces. As discussed earlier, it is hypothesized that in a beam, lamination stresses in areas of low stiffness (knots) are redistributed through adjacent laminations. This redistribution has the effect of increasing the capacity of the low stiffness area. Since finger joints are known to have a stiffness about equal to the average stiffness of the connected laminations, it is not expected that the described stress redistribution would be as apparent for finger joints. Larsen (1980) found finger-joint laminating factors to range from 1.36 to 1.71. These laminating factors for tension are roughly 10% higher than those used in the United States. However, the factors found in this study may not be applicable to beams using the special tension lamination grades commonly used in the U.S.

11. CONCLUSIONS

In general, the results of this study showed that high yields of two machine stress rated Norwegian spruce laminating grades meeting the requirements of the CEN standards, C37-14E and C30-12E, can be generated from the supplied laminating lumber. Furthermore, glulam beams manufactured from these grades can meet or exceed the strength and stiffness requirements of CEN beam combinations LH35, LH40, and LC38. Realization of these performance levels is dependent, however, on modifying the current Norwegian machine stress grading system to correct for the grading inaccuracies of the COMPUTERMATIC machine stress grader, as described in Appendix 3.

Several specific conclusions can be drawn from the experimental testing and statistical analyses described in this study:

1. The Norwegian spruce lumber evaluated in this study was found to qualify for CEN laminating grades C37-14E and C30-12E with 48% and 50% yields, respectively.

2. The characteristic bending strengths, tensile strengths, density, and modulus of elasticity for the established C30-12E and C37-14E grades met or exceeded the requirements of the CEN standards.

3. The LH35 and LH40 beam combinations manufactured from the established C37-14E and C30-12E grades, respectively, exhibited bending strengths within 2% of those required by the CEN standard. The LC38* combination exceeded the CEN requirements of the LC38 combination with respect to bending strength.

4. The measured modulus of elasticity in bending of beam combinations LH35, LH40, and LC38* exceeded the requirements of CEN.

5. The combined beam layup was found to be much more efficient than the homogenous beam combinations tested. Using less than half the number of high grade laminations, the combined layup achieved the same bending strength and only slightly lower bending stiffness.

6. The bending laminating factor, $k_{lam,b,1}$, for the tested beams ranged from 1.04 to 1.15 and agreed closely with values assumed in the CEN standard.

7. The tension laminating factor, $k_{lam,t,1}$, for the tested beams ranged from 1.48 to 1.65, which is significantly higher than the 1.25 factor used by the United States glulam industry.

8. The ratio of the characteristic bending strength of the glulam beams to the characteristic bending strength of finger joints was found to range from 0.70 to 0.76, somewhat lower than the findings of previous research.

9. The characteristic finger-joint tensile strength was found to be 52% and 54% of the characteristic finger-joint bending strength for the C30-12E and C37-14E grades, respectively. This is somewhat lower than the 60% generally assumed.

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APPENDIX 1: CEN Glulam Standards

The following tables are extracted from draft CEN standards and are reproduced here to provide the reader with the requirements relevant at the time this project was initiated. Table A1.1 is from EN TC 124.203 (1990a) and provides the material property requirements for strength classes applicable for glulam beam construction. Tables A1.2 and A1.3 are from EN TC 124.207 (1990b) and indicate the characteristic strength properties for homogeneous and combined glulam layups, respectively. Table A1.4 shows the classification of glulam produced from laminations meeting the requirements of Table A1.1.

TABLE A1.1

Strength Classes

Strength classes			C13-7E	C15-8E	C15-11E	C18-9E	C21-10E	C21-13E	C24-11E	C30-12E	C30-15E	C37-14E	C48-20E	C60-22E
Strength properties in MPa														
BENDING	$f_{m,k}$		13	15	15	18	21	21	24	30	30	37	48	60
TENSION PARALLEL	$f_{t,o,k}$		8	9	9	11	13	13	14	18	18	22	29	36
TENSION PERPENDICULAR	$f_{t,90,k}$		0,3	0,3	0,3	0,3	0,4	0,4	0,4	0,4	0,4	0,4	0,6	0,7
COMPRESSION PARALLEL	$f_{c,o,k}$		16	17	17	19	20	20	21	24	24	28	35	40
COMPRESSION PERPENDICULAR	$f_{c,90,k}$		4,8	4,8	5,2	5,2	5,4	5,7	5,7	6,3	6,7	6,7	9,0	10,5
SHEAR	$f_{v,k}$		1,6	1,7	1,7	1,8	2,1	2,1	2,4	3,0	3,0	3,7	4,8	6,0
stiffness properties	in MPa													
MOE MEAN PARALLEL	$E_{o,mean}$		7000	8000	11000	9000	10000	13000	11000	12000	15000	14000	20000	22000
MOE MINIMUM PARALLEL	$E_{o,min}$		4900	5500	7400	6500	7000	8700	7400	8500	10300	10000	14000	15000
MOE MEAN PERPENDICULAR	$E_{90,mean}$	S'Woods	230	270	370	300	330	430	370	400	500	450	-	-
		H'Woods	470	530	730	600	670	860	730	800	1000	900	1300	1500
SHEAR MODULUS MEAN	G_{mean}		440	500	690	560	630	800	690	750	900	800	1250	1400
Density in kg/m^3														
DENSITY	ρ_k		290	300	450	320	350	480	380	410	520	450	600	700

TABLE A1.2
Characteristic Strength Properties for Homogeneous Glulam (MPa)

Strength class		LH25	LH28	LH30	LH35	LH40
Bending	$f_{m,k,g}$	25	28	30	35	40
Tension						
- par.	$f_{t,0k,g}$	20	23	25	28	32
- perp.	$f_{t,90,k,g}$	0.3	0.4	0.4	0.4	0.4
Compression						
- par.	$f_{c,0,k,g}$	25	26	27	29	33
- perp.	$f_{c,90,k,g}$	5.7	5.9	6.3	6.9	7.4
Shear	$f_{v,k,g}$	2.7	2.9	3.1	3.5	4.0
modulus of Elasticity par.						
+ bending	$E_{mean,m,g}$	10000	11000	11500	12500	13000
+ axial	$E_{mean,a,g}$	10000	11000	11500	12500	13000
Density	kg/m^3	320	350	380	410	450

TABLE A1.3
Characteristic Strength Properties for Combined Glulam (MPa)

Strength class		LC24	LC26	LC28	LC33	LC38
Bending	$f_{m,k,g}$	24	26	28	33	38
Tension						
- par.	$f_{t,0,kg}$	17	19	21	24	26
- perp.	$f_{t,90,k,g}$	0.3	0.3	0.3	0.4	0.4
Compression						
- par.	$f_{c,0,k,g}$	22	23	25	27	30
- perp.	$f_{c,90,k,g}$	5.7	5.9	6.3	6.9	7.4
Shear	$f_{v,k,g}$	2.5	2.6	2.7	2.9	3.1
modulus of Elasticity par.						
+ bending	$E_{mean,m,g}$	9500	10500	11000	12000	13000
+ axial	$E_{mean,a,g}$	8500	9500	10500	11500	12000
Density	kg/m^3	250	300	320	350	380

TABLE A1.4
Classification of Glulam Produced from Laminations Meeting the Requirements of EN TC 124.203

Strength classes for homogeneous glulam	LH25	LH28	LH30	LH35	LH40
Required lamination strength class	C18-9E	C21-10E	C24-11E	C30-12E	C37-14E
Strength classes for combined glulam	LC24	LC26	LC28	LC33	LC38
Required strength class of:					
Outer laminations	C18-9E	C21-10E	C24-11E	C30-12E	C37-14E
Inner laminations	C13-7E	C15-8E	C18-9E	C21-10E	C24-11E

APPENDIX 2: Visual Grading Requirements

This appendix provides the visual grading requirements pertinent to the lamination lumber tested in this study (Norwegian glulam industry laminating grades, LT20 and LT30). Limitations on face and edge knot sizes, slope of grain limitations, and ring count for the utilized visual grades are provided. Table A2.1 shows the requirements of these grades and compares these requirements to those of other relevant grading standards, including the visual standard used for Norwegian produced Sawn lumber, NS 3080 (1988), and the CEN visual grading standard, EN TC 124.204 (1990c).

As described in the main body of this report, 838 bending and tension specimens were visually graded according to NS 3080 (1988). Table A2.2 shows the results of this grading.

Since the LT20 grade falls somewhere between the T24 and T18 grades, Table A2.2 indicates that between 10% and 42% of the lumber supplied for this study did not meet the LT20 grade requirements.

Table A2.1

Visual Grading Requirements[1,2]

Applicable Standard — Visual Grade

Norwegian Glulam Industry

	LT30	LT20
Ring	5	8
SG	1/10	1/7
Face	b/4	b/3
Edge	t/3	t/2

NS 3080 (1988)

	T30	T24	T18	T12
Ring	4	6	6	UL
SG	1/10	1/7	1/7	UL
Face	b/6	b/4	b/3	b/2
Edge	t/3	t/2		

INSTA 142 (1991)

	T3	T2	T1
Ring	4	6	UL
SG	1/10	1/7	1/5
Face	b/6	b/4	2b/5
Edge	t/3	t/2	4t/5

---

[1] Vertical columns indicate similar grading requirements

[2] Ring = ring count per centimeter, SG = slope of grain, Face = face knot (or cant knot), Edge = edge knot, UL = unlimited, b = width, t = thickness

TABLE A2.2
Results of Lamination Visual Grading

GRADE (NS 3080)	Lumber Pieces Meeting Grade (%)
T30	20
T24	38
T18	32
T12	7
<T12	3

APPENDIX 3: Vibration Correction of Machine Stress Grader

This appendix describes the procedure used to correct the collected machine stress grader displacement data for the effects of induced vibration. As was shown in Figure 2 in the text, the COMPUTERMATIC machine stress grader generated displacement data for each lumber piece. Because the tested pieces were of variable length, **n** number of data were read for each lumber piece. Figure 2 is typical of many pieces of lumber tested in that the first displacement values were significantly greater than those along the rest of the piece. An analysis of the data read from the COMPUTERMATIC for all lumber indicates that the greatest displacement occurred in the first five readings in over 65% of the pieces (see Figure A3.1).

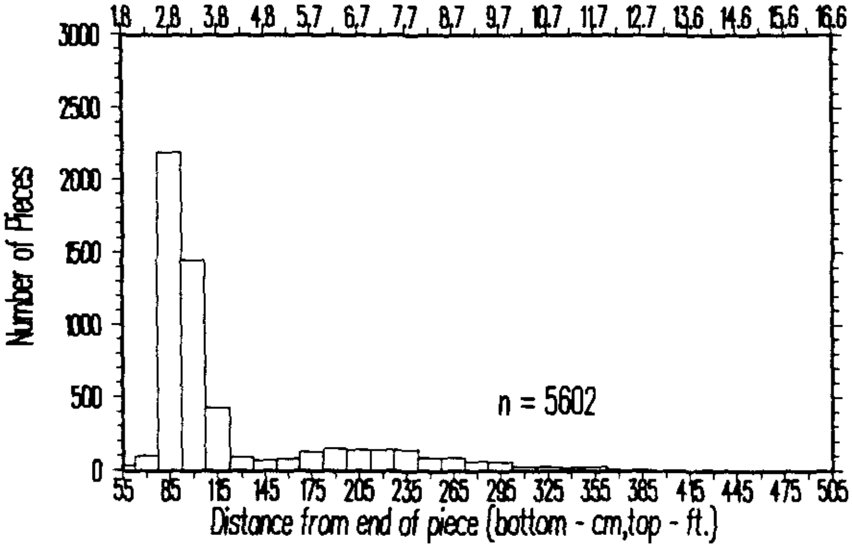

FIGURE A3.1
Location of High Bit Value in Lumber Piece

The maximum variability in mean displacement in data points six through **n** was only a few bits (the machines unit of displacement measurement), while the variability in the first six readings was radically higher. Using this information, a statistical analysis was performed where the first six readings were compared to the mean value of displacement data for the rest of the piece (data points 6 through **n**). If this difference exceeded the population variability of the mean displacement, the high displacement in the first six readings was reduced to the mean displacement (of readings six through **n**).

The effects of this correction are seen by comparing Figures A3.2 and A3.3. Both figures show a correlation between the MOE_{mac} and the low point modulus of elasticity $MOE_{lowpoint}$ for each lumber piece. These values directly correspond to the average displacement and high displacement, respectively, for each piece. Unless there is a very severe defect in a lumber piece, it would be expected that a strong Correlation should exist between the average and lowpoint stiffness. Figure A3.2 shows the correlation before correction for vibration. The correlation in this case is rather poor. After correction for the vibration, as shown in Figure A3.3, a more rational relationship results.

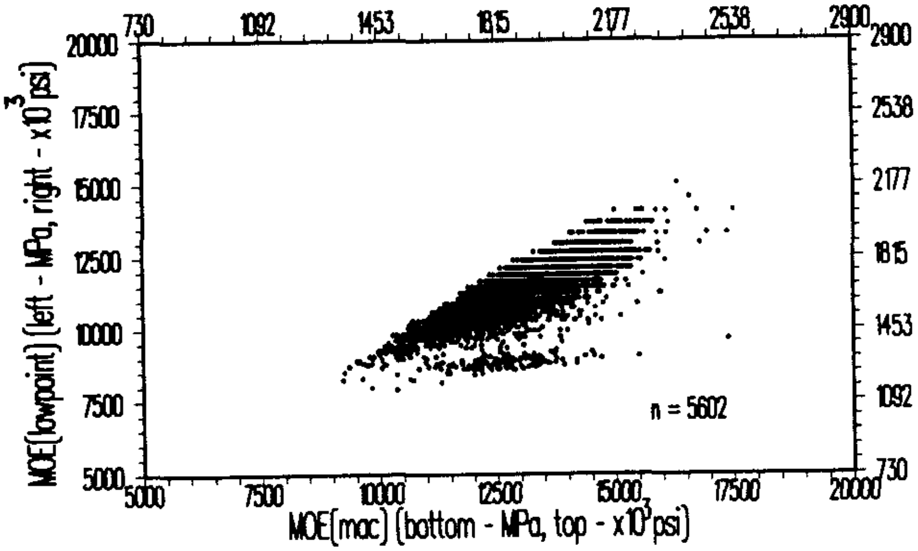

FIGURE A3.2
Uncorrected COMPUTERMATIC Data

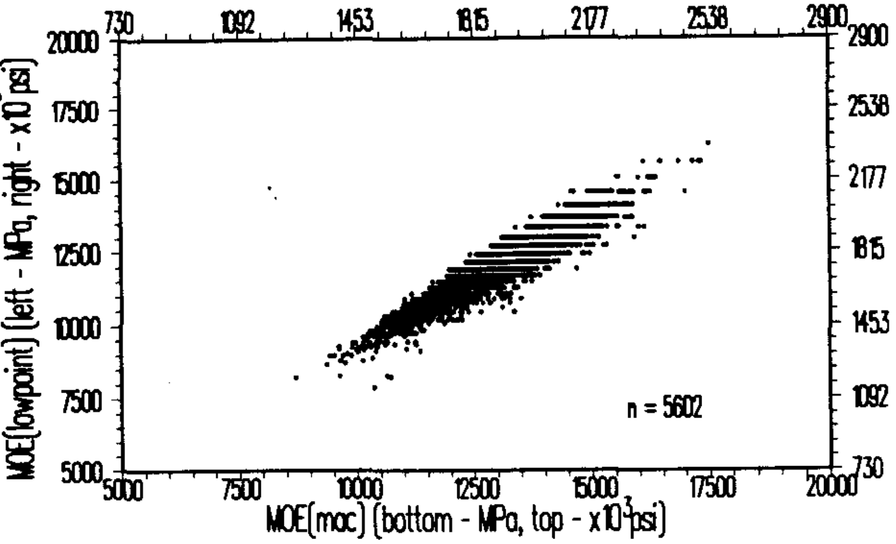

FIGURE A3.3
Corrected COMPUTERMATIC Data

APPENDIX 4: Distribution Parameters

The following tables summarize the best fit parameter estimates for the lumber and beam properties evaluated in this study. A distribution fitting computer program, PC-DATA[1], was used to analyze each data set. PC-DATA uses maximum likelihood estimators to determine distribution parameters assuming the location parameter is known.

Five distributions were fit to each set of data, including normal, two-parameter Weibull and lognormal, and three-parameter Weibull and lognormal. The distribution that best fit the data was determined through a visual assessment of probability plots generated from the distribution fitting algorithm.

Table A4.1 summarizes the best fit parameters for the data sets representing the entire population of tested lumber. Tables A4.2 and A4.3 summarize the parameters for the established CEN laminating grades and finger-joint material properties, respectively. The best fit parameters for the strength and stiffness properties of the tested glulam beam combinations are given in Table A4.4. Note that these parameters are only valid for distributions expressed in MPa.

TABLE A4.1

Best Fit Parameters for the Entire Population of Tested Lumber

	Weibull Parameters			**Lognormal Parameters**		
	Shape	**Scale**	**Loc.**	**Mean** (LN(x))	**S.D.** (LN(x))	**Loc.**
f_b	3.356	41.53	11.21	-		-
MOE$_{mac}$[3]	-	-	-	-	-	-
MOE$_{edge}$	4.138	10,442	4131	-	-	-
	4.198	32.72	1.962	-	-	-
Density	-	-	-	6.174	0.0755	0

[2] Density in kg/m^3

[3] Normally Distributed, mean = 11,772; S.D. = 1751.2

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[1] PC-DATA™ Version 2.00, Structural Reliability Consultants, Box 56164, Madison, WI 53705.

TABLE A4.2

Parameter Estimates for Established C30-12E and C37-14E Lamination Grades (MPa)[1]

		Weibull Parameters			Lognormal Parameters		
		Shape	**Scale**	**Loc.**	**Mean** (LN(x))	**S.D.** (LN(x))	**Loc.**
C30-12E	$\mathbf{f_b}$	3.467	31.10	16.53	-	-	-
	$\mathbf{MOE_{edge}}$	6.598	11,999	1316	-	-	-
	$\mathbf{f_t}$	5.263	31.19	0	-	-	-
	Density	-	-	-	5.586	0.1358	208.9
C37-14E	$\mathbf{f_b}$[2]	-	-	-	-	-	-
	$\mathbf{MOE_{edge}}$	-	-	-	9.461	0.1696	2144
	$\mathbf{f_t}$	3.367	26.15	11.45	-	-	-
	Density	-	-	-	5.739	0.1308	208.9

[1] Density is in kg/m^3

[2] Normally Distributed, mean = 56.3 , S.D. = 11.8

TABLE A4.3

Parameter estimates for Finger Joint
Bending and Tension Properties

		Weibull Parameters		
		Shape	**Scale**	**Loc.**
C30-12E	$\mathbf{f_{b,fj}}$	5.476	23.98	34.76
	$\mathbf{f_{t,fj}}$	3.484	17.67	17.91
C37-14E	$\mathbf{f_{b,fj}}$	12.91	65.27	0
	$\mathbf{f_{t,fj}}$	4.631	24.37	15.37

TABLE A4.4

Parameter Estimates for LH35, LH40, and LC38[*] Beams
(MPa)

		Weibull Parameters			Lognormal Parameters		
		Shape	**Scale**	**Loc.**	**Mean** (LN(x))	**S.D.** (LN(x))	**Loc.**
LH35	$\mathbf{f_{b,g}}$	5.473	46.29	17.68	-	-	-
	MOE	8.393	7117	5783	-	-	-
LH40	$\mathbf{f_{b,g}}$	3.925	55.11	25.58	-	-	-
	MOE	4.366	4.333	10,771	-	-	-
LC38[*]	$\mathbf{f_{b,g}}$	-	-	-	3.387	0.212	18.312
	MOE	8.039	6040	8408	-	-	-

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