CIB-W18/34-12-1

**INTERNATIONAL COUNCIL FOR RESEARCH AND INNOVATION
IN BUILDING AND CONSTRUCTION**

WORKING COMMISSION W18 - TIMBER STRUCTURES

HIGH-STRENGTH I-JOIST COMPATIBLE GLULAM MANUFACTURED WITH LVL TENSION LAMINATIONS

by

Borjen Yeh
T G Williamson
APA - The Engineered Wood Association

U.S.A.

MEETING THIRTY-FOUR
VENICE
ITALY
AUGUST 2001

High-Strength I-Joist Compatible Glulam Manufactured with LVL Tension Laminations

Borjen Yeh, Ph.D., P.E.
Thomas G. Williamson, P.E.
APA - The Engineered Wood Association, U.S.A.

Abstract

In recent years, the growing popularity of I-joists in residential construction has spawned strong demands for high-strength structural glued laminated timber (glulam) with I-joist compatible (IJC) depths in North America. Using the model prescribed in ASTM D3737, *Standard practice for establishing stresses for structural glued laminated timber*, APA - The Engineered Wood Association has developed glulam layup combinations using full-length (without end joints) laminated veneer lumber (LVL) as tension laminations to satisfy the market needs. These high-strength IJC glulam products have a characteristic flexural strength ($f_{m,g,k}$) of 43 MPa (6300 psi) and a mean modulus of elasticity ($E_{0,g,mean}$) of 14.5 GPa (2.1 x 10^6 psi), which represent the highest performance level that has ever achieved by the commodity glulam used in North America.

This paper describes the details of the layup combinations and the results of full-scale glulam beam confirmation tests. For quality assurance purposes, the required control values for the LVL tension laminations are established and reported. These layup combinations are being recognized by the evaluation service agencies of the major building codes in the United States.

Results obtained from this study suggested that relationship between the characteristic tensile strength of the LVL tension laminations ($f_{t,0,l,k}$) and the characteristic flexural strength of the glulam beams ($f_{m,g,k}$) is likely to depend upon not only the LVL, but the glulam manufacturers. It was noticed that the relationship between $f_{t,0,l,k}$ and $f_{m,g,k}$ did not necessarily follow the American National Standards Institute (ANSI) A190.1, *American National Standard for Wood Products -- Structural Glued Laminated Timber*. Therefore, the required $f_{t,0,l,k}$ value for QA purposes should be confirmed by LVL tension and full-scale glulam beam tests. Without the confirmation data, the $f_{t,0,l,k}$ should be assigned the same value as $f_{m,g,k}$.

1. Introduction

The development of high-strength layup combinations for I-joist compatible (IJC) structural glued laminated timber (glulam) was an interest of several glulam manufacturers in North America. This product is intended primarily for residential and light commercial and industrial buildings where the flexural strength or stiffness controls the design. Examples include floor or roof beams and garage door headers. The maximum depth for this product is typically limited to 457 mm (18 inches).

Based on the current glulam manufacturing specifications [1,2], the most common glulam produced in the United States has a characteristic (5th percentile with 75% confidence) flexural strength ($f_{m,g,k}$) of 35 MPa (5040 psi) with a mean modulus of elasticity ($E_{0,g,mean}$)

of 12.4 GPa (1.8 x 10^6 psi). In some instances, glulam beams manufactured from Southern pine can achieve a characteristic flexural strength ($f_{m,g,k}$) of 43 MPa (6,300 psi) and a mean modulus of elasticity ($E_{0,g,mean}$) of 14.5 GPa (2.1 x 10^6 psi), which represent the highest performance level that has ever achieved by the commodity glulam used in North America. In the working stress design, which is still the mainstream methodology used in wood design in the United States, these high-strength Southern pine glulam beams have an allowable flexural stress (F_b) of 21 MPa (3000 psi) with a beam MOE of 14.5 GPa (2.1 x 10^6 psi). This product is typically referenced as 30F-2.1E glulam in the marketplace and will be used in this paper.

These 30F-2.1E Southern pine glulam beams are limited to a maximum of 152 mm (6 inches) in width due primarily to the difficulty in manufacturing wider end joints with consistent quality at this strength level. In addition, a very high grade of E-rated Southern pine lumber required for the outer 10% of the tension zone for this high-strength glulam is getting difficult to procure.

Laminated veneer lumber (LVL) has been used in North American for more than 30 years. With improved technology in veneer grading, adhesives, and machining, LVL is known for its excellent load-carrying capacities and consistent quality. Since the grade and quality of each individual layer of veneers can be closely controlled in the LVL manufacturing processes, the variability in product properties is typically lowered than that of sawn lumber. Due to its unique manufacturing processes, LVL can be customized, just like glulam, to a wide variety of widths, thickness, and lengths. Most importantly, the end (scarf or lap) joints within the same veneer layer are staggered to minimize the strength reducing effect on the flexural and tensile strengths of LVL. Therefore, LVL is a natural choice for the tension lamination of high-strength glulam. In addition to its high tensile strength, the use of LVL tension laminations eliminates the need for high-strength and consistent-quality end joints in the glulam manufacturing.

APA has practiced the development of commercial glulam layup combinations for years using the GAP computer program that is recognized by the major building code evaluation services as an alternative method for determining design stresses of a given layup combination of glulam [3,4]. Even though the majority of glulam layup combinations developed by using GAP have been applied to sawn lumber laminations, prior experience showed that the GAP program could be used to predict the performance of hybrid glulam using LVL tension laminations [5]. This paper provides background information for the development of two 30F-2.1E IJC glulam layup combinations, both of which are now commercially available in the United States.

2. Objective

The main objective of this study was to develop high-strength 30F-2.1E IJC glulam layup combinations with LVL tension laminations. The maximum depth of the layup combinations was limited to 457 mm (18 inches). The layup combinations were developed using the GAP computer program and confirmed by full-scale beam tests. Results from this study were also intended for use to evaluate the relationship between the characteristic tensile strength of the LVL tension laminations and the characteristic flexural strength of the glulam beams.

3. Layup Development

Given the targeted design values at 30F-2.1E, and the specific depths of 241, 302, 356, and 406 mm (9-1/2, 11-7/8, 14, and 16 inches), which are I-joist compatible depths, APA staff developed the first layup combination using GAP. This layup combination, as shown in Table 1, was assigned a combination symbol of 30F-E2M2. It should be noted that the use of the Southern pine rather than other softwood species laminations in the core of the glulam ensures the highest design shear stress for commercial glulam.

Table 2 shows another 30F-2.1E layup combination, which was assigned a combination symbol of 30F-E2M3. The 30F-E2M3 layup combination has a maximum beam depth of 457 mm (18 inches).

Table 1. Layup combination for 30F-E2M2[(a)]

44 mm	2.4E LVL
38 mm	L1 2.3E/DF
35 mm	N2M8/SP
35 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N2M8/SP
35 mm	N2M8/SP
35 mm	N2M8/SP
38 mm	L1 2.3E/DF
44 mm	2.4E LVL

406 mm (16 inches)

38 mm	2.4E LVL
38 mm	L1 2.3E/DF
34 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N2M8/SP
38 mm	L1 2.3E/DF
38 mm	2.4E LVL

356 mm (14 inches)

44 mm	2.4E LVL
36 mm	N1D 2.3E/SP
36 mm	N2M8/SP
35 mm	N2M8/SP
35 mm	N2M8/SP
36 mm	N2M8/SP
36 mm	N1D 2.3E/SP
44 mm	2.4E LVL

302 mm (11-7/8 inches)

38 mm	2.4E LVL
33 mm	N1D 2.3E/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N1D 2.3E/SP
38 mm	2.4E LVL

241 mm (9-1/2 inches)

(a) Grade designations for the laminating lumber are in accordance with EWS Y117 [1] or AITC 117 [2].

Table 2. Layup combination for 30F-E2M3[(a)]

44 mm	2.4E LVL
34 mm	N1D 2.3E/SP
34 mm	N1D 2.3E/SP
34 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N1D 2.3E/SP
34 mm	N1D 2.3E/SP
44 mm	2.4E LVL

457 mm (18 inches)

44 mm	2.4E LVL
38 mm	N1D 2.3E/SP
35 mm	N2M8/SP
35 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N2M8/SP
35 mm	N2M8/SP
35 mm	N2M8/SP
38 mm	N1D 2.3E/SP
44 mm	2.4E LVL

406 mm (16 inches)

44 mm	2.4E LVL
34 mm	N1D 2.3E/SP
34 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
33 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N1D 2.3E/SP
44 mm	2.4E LVL

356 mm (14 inches)

44 mm	2.4E LVL
36 mm	N1D 2.3E/SP
36 mm	N2M8/SP
35 mm	N2M8/SP
35 mm	N2M8/SP
36 mm	N2M8/SP
36 mm	N1D 2.3E/SP
44 mm	2.4E LVL

302 mm (11-7/8 inches)

35 mm	2.4E LVL
34 mm	N1D 2.3E/SP
34 mm	N2M8/SP
35 mm	N2M8/SP
34 mm	N2M8/SP
34 mm	N1D 2.3E/SP
35 mm	2.4E LVL

241 mm (9-1/2 inches)

(a) see footnote to Table 1.

The 30F-E2M2 and 30F-E2M3 layup combinations were intended to follow the existing 30F-E2 layup combination recognized in ICBO ER-5714 [3] and NES NER-486 [4]. For modeling purposes, the "equivalent characteristic knot" required for GAP input for the 2.4E LVL tension lamination was conservatively assumed to be the same as those reported by Yeh [5] for the 2.0E LVL tension lamination. In addition, the "bending stress index value," as documented in ASTM D3737 [6], for the 2.4E LVL tension lamination was conservatively assigned as 28 MPa (4,000 psi), which is the same as the value assigned to 2.3E sawn lumber lamination in accordance with ASTM D3737 [6].

Based on the layup combination given in Tables 1 and 2, and the input properties mentioned above, the properties for each beam depth were predicted by GAP, as shown in Tables 3 and 4 for 30F-E2M2 and 30F-E2M3, respectively.

Table 3. Predicted properties for 30F-E2M2 using GAP

Depth	$f_{m,g,k}$	$f_{t,0,g,k}$	$f_{c,0,g,k}$	$f_{c,90,g,mean}$	$f_{v,g,k}$	$E_{0,g,mean}$
406 mm	47 MPa	18.5 MPa	24.5 MPa	7.4 MPa	4.3 MPa	14.5 GPa
(16 in.)	(6830 psi)	(2710 psi)	(3550 psi)	(1090 psi)	(630 psi)	(2.1 Mpsi)
356 mm	47 MPa	18.5 MPa	24.5 MPa	7.4 MPa	4.3 MPa	14.5 GPa
(14 in.)	(6870 psi)	(2690 psi)	(3590 psi)	(1090 psi)	(630 psi)	(2.1 Mpsi)
302 mm	48 MPa	20.0 MPa	26.0 MPa	7.4 MPa	4.3 MPa	15.2 GPa
(11-7/8 in.)	(7020 psi)	(2920 psi)	(3760 psi)	(1090 psi)	(630 psi)	(2.2 Mpsi)
241 mm	48 MPa	20.5 MPa	26.5 MPa	7.4 MPa	4.3 MPa	15.2 GPa
(9-1/2 in.)	(7020 psi)	(2970 psi)	(3850 psi)	(1090 psi)	(630 psi)	(2.2 Mpsi)
All(a)	48 MPa	19.0 MPa	24.5 MPa	7.4 MPa	4.3 MPa	14.5 GPa
	(6930 psi)	(2730 psi)	(3610 psi)	(1090 psi)	(630 psi)	(2.1 Mpsi)

(a) For all depths after rounding in accordance with ASTM D3737 [6].

Table 4. Predicted properties for 30F-E2M3 using GAP

Depth	$f_{m,g,k}$	$f_{t,0,g,k}$	$f_{c,0,g,k}$	$f_{c,90,g,mean}$	$f_{v,g,k}$	$E_{0,g,mean}$
457 mm	49 MPa	20.0 MPa	25.5 MPa	5.9 MPa	4.3 MPa	14.5 GPa
(18 in.)	(7160 psi)	(2880 psi)	(3670 psi)	(850 psi)	(630 psi)	(2.1 Mpsi)
406 mm	47 MPa	20.5 MPa	24.5 MPa	5.9 MPa	4.3 MPa	14.5 GPa
(16 in.)	(6830 psi)	(3000 psi)	(3550 psi)	(850 psi)	(630 psi)	(2.1 Mpsi)
356 mm	47 MPa	21.5 MPa	25.0 MPa	5.9 MPa	4.3 MPa	14.5 GPa
(14 in.)	(6860 psi)	(3140 psi)	(3610 psi)	(850 psi)	(630 psi)	(2.1 Mpsi)
302 mm	48 MPa	23.0 MPa	26.0 MPa	5.9 MPa	4.3 MPa	15.2 GPa
(11-7/8 in.)	(7020 psi)	(3320 psi)	(3760 psi)	(850 psi)	(630 psi)	(2.2 Mpsi)
241 mm	48 MPa	22.5 MPa	26.5 MPa	5.9 MPa	4.3 MPa	15.2 GPa
(9-1/2 in.)	(7020 psi)	(3290 psi)	(3820 psi)	(850 psi)	(630 psi)	(2.2 Mpsi)
All(a)	48 MPa	21.0 MPa	24.5 MPa	5.9 MPa	4.3 MPa	14.5 GPa
	(6930 psi)	(3050 psi)	(3520 psi)	(850 psi)	(630 psi)	(2.1 Mpsi)

(a) see footnote to Table 3.

4. Materials

4.1 LVL tension laminations

The 2.4E LVL products were manufactured by 2 different LVL plants. For the 30F-E2M2, the LVL products were manufactured using all G1 Douglas fir veneers of 2.5-mm (1/10-

inch) thick. On the other hand, the LVL products for 30F-E2M3 were manufactured using a combination of G1 and G2 Douglas-fir veneers of 3.2 mm (1/8 inch) in thickness. The veneers were graded using a machine grading setting specified in the Manufacturing Standard of each LVL plant. The veneer suppliers for each of the LVL plant were not the same. APA staff verified the veneer grades and witnessed the LVL manufacturing.

Given the difference in the LVL layup, veneer resource, and manufacturing parameters (glue spread rate, joint type, compression ratio, ... etc.) between these 2 LVL plants, the mechanical properties of the 2.4E LVL were not expected to be the same. Therefore, the tensile strength and long-span E of the LVL products were independently evaluated prior to the beam manufacturing in accordance with ASTM D4761 [7] and D5456 [8]. APA staff conducted the sampling and witnessed the LVL testing. Summary statistics for the LVL test results are given in Table 5.

Table 5. Summary statistics for 2.4E LVL

	Tensile strength[(a)], psi		Long-span E[(b)], psi	
	For 30F-E2M2	For 30F-E2M3	For 30F-E2M2	For 30F-E2M3
N	53	54	30	54
Mean	50 MPa (7190 psi)	58 MPa (8460 psi)	18.6 GPa (2.7 x 10^6 psi)	19.3 GPa (2.8 x 10^6 psi)
COV	0.124	0.080	0.054	0.046
$f_{t,0,l,k}$ [(c)]	38 MPa (5580 psi)	50 MPa (7230 psi)	--	--

[(a)] Tested with a 4-ft gauge length in accordance with ASTM D5456 [8].

[(b)] Tested with a span-to-depth ratio of 100 in accordance with ASTM D4761 [7].

As shown, the characteristic tensile strength ($f_{t,0,l,k}$ with a 4-ft gauge length) and mean long-span E ($E_{0,l,mean}$) for the LVL tension laminations manufactured for 30F-E2M3 were higher than the LVL manufactured for 30F-E2M2. In addition, the long-span E for the LVL tension laminations is substantially higher than the value of 16.6 GPa (2.4 x 10^6 psi) used in the layup design, suggesting that the test beams are likely to have a higher $E_{0,g,mean}$ than the predicted values given in Tables 3 and 4.

It should be noted that according to the provisions of American National Standards Institute (ANSI) A190.1, *American National Standard for Wood Products -- Structural Glued Laminated Timber* [9], the required characteristic tensile strength of the tension lamination, $f_{t,0,l,k}$, can be correlated to the characteristic strength of the glulam beam, $f_{m,g,k}$, by a factor of 1.67/2.1 or 0.8. In other words,

$$f_{t,0,l,k} = 0.8 \text{ x } f_{m,g,k} \qquad \text{[Eq. 1]}$$

Therefore, for a 30F glulam with a $f_{m,g,k}$ of 43 MPa (6300 psi), the required $f_{t,0,l,k}$ is 35 MPa (5010 psi). As noted from Table 5, the $f_{t,0,l,k}$ values for both LVL products meet this requirement for 30F glulam beams. However, the applicability of Equation 1 has been validated with glulam made of lumber tension laminations and its applicability with glulam made of LVL tension laminations has not been fully established.

4.2 Glulam beams

With the purpose of confirming the predicted $f_{m,g,k}$ and $E_{0,g,mean}$ of the glulam layups given in Tables 1 and 2, it was determined that full-scale glulam beam tests should be conducted. For 30F-E2M2, 15 glulam beams with a nominal dimension of 140 mm x 302 mm x 7010 mm (5-1/2 inches x 11-7/8 inches x 23 feet) and another 15 glulam beams with a nominal dimension of 140 mm x 406 mm x 9140 mm (5-1/2 inches x 16 inches x 30 feet) were manufactured by an APA glulam member.

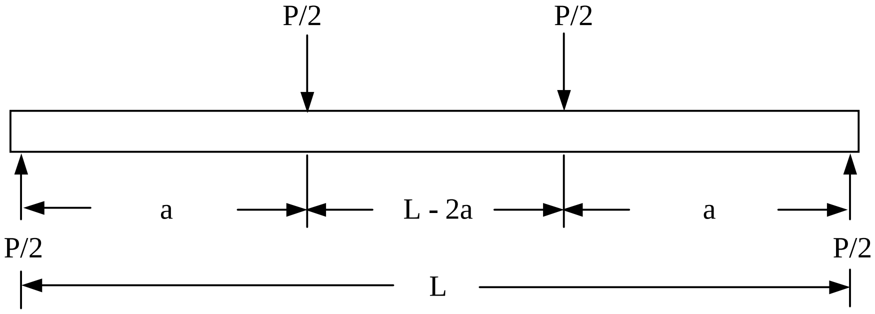
For 30F-E2M3, 17 glulam beams with a nominal dimension of 89 mm x 302 mm x 7010 mm (3-1/2 inches x 11-7/8 inches x 23 feet) and another 18 glulam beams with a nominal dimension of 178 mm x 457 mm x 10360 mm (7 inches x 18 inches x 34 feet) were manufactured by another APA glulam member. The choice of the glulam beam sizes was based on the consideration of the largest beam depths from Tables 1 and 2, and the predominant size of 302 mm (11-7/8 inches) in the market place.

All test beams were manufactured following the provisions of ANSI A190.1 [9]. Face bonding of the LVL to lumber was previously qualified in accordance with AITC 402, *Standard for Laminated Veneer Lumber (LVL) Used in Structural Glued Laminated Timber* [10]. A phenol resorcinol-type adhesive was used for all face bonding, while a melamine-formaldehyde adhesive was used for end (finger) joints of the lumber laminations. There were no end joints in the LVL laminations. The position of the end joints in each beam was random and not specifically excluded from the center one-half (high tensile stress) portion of the lamination. APA staff witnessed the beam manufacturing.

5. Test Methods and Data Analyses

All beam tests described in this paper were conducted at the APA Research Center in Tacoma, Washington, in February and May 2000. A four-point load method, as shown in Figure 1, was applied to test each beam using a constant span-to-depth ratio of approximately 21. This loading configuration resulted in a similar moment distribution as uniform loads, while giving a shear-free section between loading points. The test apparatus, including rocker-type reaction supports, reaction bearing plates and rollers, load bearing block, and load bearing rollers were set up following ASTM D198 [11]. A load button was installed between a 222-kN (50000-lbf) capacity load cell and load bearing block/rollers to function as a load-alignment device. Lateral supports were provided to avoid lateral buckling during testing.

Before testing, the cross-sectional dimensions of the beam were measured at loading points. The mean of the readings was used to calculate the sectional properties of the beam. A 9.5-mm (3/8-inch) hole was drilled at the neutral axis of the beam above one end reaction point. The same size of steel pin was then driven into the hole to provide a support for a stranded 890-N (200-lbf) capacity steel wire. A pulley was attached at the neutral axis above the other end of the reaction point. The wire was then tensioned between the steel pin and the pulley with a 445-N (100-lbf) dead weight. At the neutral axis of the midspan, a linear potentiometer (LP) with accuracy to 0.025 mm (0.001 inch) was attached on the beam. The frictionless shank of the LP was connected to the wire to measure beam deflections.



L = 6400 mm (21 ft); a = 2286 mm (7-1/2 ft) for the 302-mm (11-7/8-inch) deep beams
L = 8534 mm (28 ft); a = 3048 mm (10 ft) for the 406-mm (16-inch) deep beams
L = 9144 mm (30 ft); a = 3353 mm (11 ft) for the 457-mm (18-inch) deep beams

Figure 1. Schematic loading configuration for flexure tests

Load was applied by a hydraulic cylinder at a constant rate to fail the beam in flexure in about 10 minutes. Both load and deflection were continuously recorded by a computerized data acquisition system. At about 75% of the estimated maximum load, the LP was removed from the beam to prevent damage when the beam failed. The load was continuously recorded up to the ultimate load.

Based on the theory of elasticity, the modulus of rupture (MOR) and apparent modulus of elasticity (MOE) were calculated using the following equations:

$$\mathrm{MOR} = \frac{3\,P_{ult}\,a}{b\,d^2} + \frac{3\omega\ell^2}{4bd^2} \qquad \text{[Eq. 2]}$$

$$\mathrm{MOE} = \frac{\theta\,a\,(3\ell^2 - 4a^2)}{4bd^3} \qquad \text{[Eq. 3]}$$

where: MOR = modulus of rupture (MPa or psi),
MOE = apparent modulus of elasticity (MPa or psi),
P_{ult} = ultimate total load excluding the dead weight of the specimen (N or lbf),
a = distance between the reaction to the nearest loading point (mm or in.),
b = measured beam width (mm or in.),
d = measured beam depth (mm or in.),
ω = measured beam weight (N/mm or lbf/in.),
ℓ = test span (mm or in.), and
θ = slope of load vs. deflection plot below the proportional limit (N/mm or lbf/in.).

For determining the characteristic flexural stress of the beam, the MOR value calculated from Equation 1 was adjusted by a volume factor, C_v (as given in Equation 4), in accordance with the 1997 *National Design Specification for Wood Construction* [12].

$$C_v = \left(\frac{5.125}{b}\right)^{0.1}\left(\frac{12}{d}\right)^{0.1}\left(\frac{252}{\ell}\right)^{0.1} \qquad \text{[Eq. 4]}$$

where: C_v = volume factor, and
b, h, ℓ = as defined in Equations 2 and 3.

In addition, another adjustment factor was needed to account for the variation from the standard 12% moisture content. This moisture content adjustment factor, C_M, is shown in Equation 5 based on ASTM D2915 [13]. As a result, the adjusted MOR and MOE values given in this paper were determined by using Equations 6 and 7.

$$C_M = \frac{\alpha - \beta \times 12}{\alpha - \beta \times M} \qquad \text{[Eq. 5]}$$

where: C_M = moisture content adjustment factor,
M = actual moisture content of the beam, %,
α = 1.75 for MOR and 1.44 for MOE, and
β = 0.0333 for MOR and 0.02 for MOE.

$$\text{AdjustedMOR} = \frac{\text{CalculatedMOR (Eq. 2)}}{C_v} \qquad \text{[Eq. 6]}$$

Adjusted MOE = Calculated MOE from Eq. 3 x C_M from Eq. 5 [Eq. 7]

After the flexure tests, a 51-mm (2-inch) section was cut from each tested beam at about 457 mm (18 inches) away from each beam end to determine the beam moisture content, and density and specific gravity in accordance with the oven-drying method of ASTM D4442 [14] and D2395 [15], respectively. The mean of these two measurements was reported as the beam moisture content, and density and specific gravity. The mean density was used to calculate the beam weight for use in Equation 2, and the mean moisture content was used to calculate the moisture content adjustment factor based on Equation 5.

6. Results and Discussions

6.1 30F-E2M2 Glulam

All 30F-E2M2 glulam beams failed as a result of tension failure in the LVL tension lamination. Summary statistics for the 302-mm (11-7/8-inch) and 406-mm (16-inch) beam groups are given in Table 6.

Table 6. Summary statistics for 30F-E2M2 glulam beam tests

	406 mm (16 in.)				302 mm (11-7/8 in.)			
	MC	SG[(a)]	MOR[(b)]	MOE[(c)]	MC	SG[(a)]	MOR[(b)]	MOE[(c)]
N	15				15			
Mean	11.3%	0.58	55 MPa (7980 psi)	16.5 GPa (2.4 Mpsi)	10.1%	0.58	54 MPa (7900 psi)	15.9 GPa (2.3 Mpsi)
COV	0.025	0.013	0.070	0.039	0.030	0.029	0.066	0.028
$f_{m,g,k}$			47 MPa (6860 psi)				47 MPa (6860 psi)	

(a) Density based on weight and volume at beam test.
(b) Adjusted MOR based on Equation 6.
(c) Adjusted MOE based on Equation 7.

Based on the Smith-Saterthwaite statistical test [16], which is an alternate statistical t-test for equal/unequal sample sizes and/or non-homogeneous variances, the adjusted MOR data obtained from the 302-mm (11-7/8-inch) and 406-mm (16-inches) beam groups are not statistically significantly different at the 5%-α significance level. This is also evident from the observation that the mean and COV between these 2 beam groups are very similar. Therefore, it is justifiable to combine the data obtained from these 2 beam groups for deriving the characteristic flexural strength. Table 7 shows the summary statistics of the adjusted MOR and MOE based on the combined data.

Table 7. Summary statistics of combined data for 30F-E2M2

	MOR(a)		MOE(b)
	Normal	Lognormal	Normal
N	30		
Mean	55 MPa (7940 psi)	--	16.3 GPa (2.4 Mpsi)
COV	0.067	--	0.034
$f_{m,g,k}$	48 MPa (6940 psi)	48 MPa (6960 psi)	--
SEE(c)	2.4%	2.1%	--

(a,b) see footnotes to Table 6.

(c) A standard error of estimate (SEE) of 5% or less is generally considered acceptable for engineered wood products.

The data distribution for the adjusted MOR is shown in Figure 2, which suggests that the data can be fitted well with either normal or lognormal distribution. The goodness-of-fit by the Kolmogorov-Smirnov statistical test indicates that both assumed distribution functions cannot be rejected at the 20% statistical significance level (the higher the significance level, the easier to reject the null hypothesis that assumes the test data can be characterized by the underlying empirical function). The Kolmogorov-Smirnov D for the test data was 0.11 and 0.12, respectively, for the normal and lognormal distributions, whereas the critical D at the 20% statistical significance level is 0.19 for 30 observations.

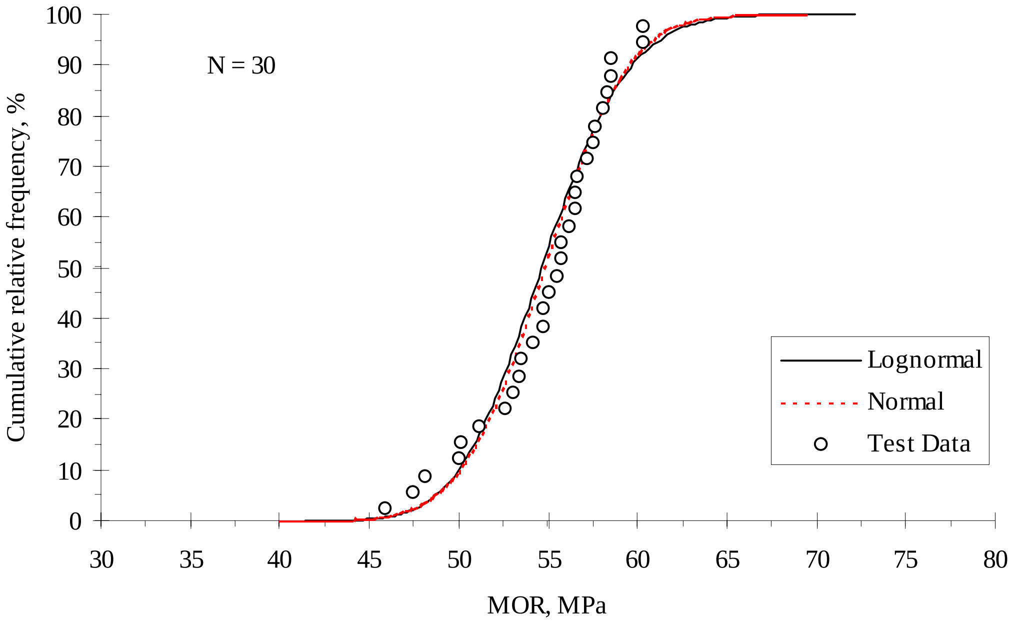


Figure 2. Adjusted MOR with empirical distribution functions overlaid for 30F-E2M2

As shown in Table 7, the characteristic flexural stress ($f_{m,g,k}$) is practically the same for both distribution functions. As a result, the $f_{m,g,k}$ value for the 30F-E2M2 layup combination can be estimated as 48 MPa (6940 psi). This $f_{m,g,k}$ value is identical to the value predicted by GAP (see Table 3), confirming the appropriateness of using GAP to predict the glulam beam performance with LVL tension laminations.

As also noted from Table 7, the $E_{0,g,mean}$ value obtained from full-scale beam tests was 16.3 GPa (2.4 x 10^6 psi). This value is significantly higher than the $E_{0,g,mean}$ value of 14.5 GPa (2.1 x 10^6 psi), as predicted by GAP (see Table 3), due primarily to the fact that the LVL tension laminations had an $E_{0,l,mean}$ value of 18.6 GPa (2.7 x 10^6 psi) (see Table 5) instead of the assumed 16.6 GPa (2.4 x 10^6 psi) used in the layup design.

6.2 30F-E2M3 Glulam

All 30F-E2M3 glulam beams also failed as a result of tension failure in the LVL tension lamination. However, there were 6 beams that were noted to have a questionable face bond between the LVL tension lamination and the adjacent lumber lamination. Summary statistics for the 302-mm (11-7/8-inch) and 457-mm (18-inch) beam groups are given in Table 8.

Table 8. Summary statistics for 30F-E2M3 glulam beam tests

	457 mm (18 in.)				302 mm (11-7/8 in.)			
	MC	SG$^{(a)}$	MOR$^{(b)}$	MOE$^{(c)}$	MC	SG$^{(a)}$	MOR$^{(b)}$	MOE$^{(c)}$
N	18				17			
Mean	12.4%	0.60	59 MPa (8520 psi)	17.0 GPa (2.5 Mpsi)	11.4%	0.60	56 MPa (8100 psi)	17.6 GPa (2.6 Mpsi)
COV	0.051	0.027	0.060	0.034	0.025	0.030	0.085	0.058
$f_{m,g,k}$			52 MPa (7520 psi)				47 MPa (6750 psi)	

(a,b,c) see footnotes to Table 6.

The adjusted MOR data obtained from the 302-mm (11-7/8-inch) and 457-mm (18-inch) beam groups are not statistically significantly different at the 5%-α significance level based on the Smith-Saterthwaite statistical test [16]. Therefore, it is justifiable to combine the data obtained from these 2 beam groups for deriving the characteristic flexural strength. Table 9 shows the summary statistics of the adjusted MOR and MOE based on the combined data.

Table 9. Summary statistics of combined data for 30F-E2M3

	MOR$^{(a)}$		MOE$^{(b)}$
	Normal	Lognormal	Normal
N	35		
Mean	57 MPa (8315 psi)	--	17.3 GPa (2.5 Mpsi)
COV	0.076	--	0.034
$f_{m,g,k}$	49 MPa (7150 psi)	50 MPa (7190 psi)	--
SEE$^{(c)}$	2.5%	2.1%	--

(a,b,c) see footnotes to Table 7.

Figure 3 shows the data distribution for the adjusted MOR, which suggests that the data can be fitted well with either normal or lognormal distribution. The goodness-of-fit by the Kolmogorov-Smirnov statistical test indicates that both assumed distribution functions cannot be rejected at the 20% statistical significance level. The Kolmogorov-Smirnov D for the test data was 0.11 and 0.12, respectively, for the normal and lognormal distributions, whereas the critical D at the 20% statistical significance level is 0.18 for 35 observations.

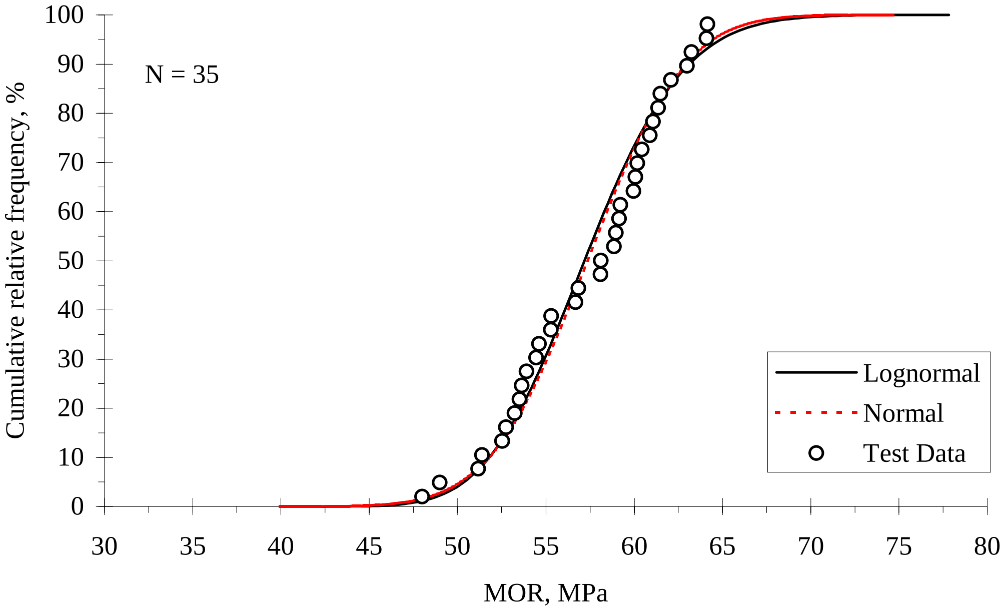


Figure 3. Adjusted MOR with empirical distribution functions overlaid for 30F-E2M3

The characteristic flexural stress ($f_{m,g,k}$) is practically the same for both distribution functions, as shown in Table 9. As a result, the $f_{m,g,k}$ value for the 30F-E2M3 layup combination can be estimated as 49 MPa (7150 psi). This $f_{m,g,k}$ value is very similar to the value of 48 MPa (6930 psi) predicted by GAP (see Table 4). In addition, the $E_{0,g,mean}$ value obtained from full-scale beam tests was 17.3 GPa (2.5 x 10^6 psi). This value is significantly higher than the $E_{0,g,mean}$ value of 14.5 GPa (2.1 x 10^6 psi), as predicted by GAP (see Table 4), due primarily to the high $E_{0,l,mean}$ value from the LVL tension laminations.

6.3 Relationship between $f_{t,0,l,k}$ and $f_{m,g,k}$

Based on Tables 5, 7, and 9, the relationship between $f_{t,0,l,k}$ and $f_{m,g,k}$ can be expressed as follows:

For 30F-E2M2 $f_{t,0,l,k} = 0.8 \times f_{m,g,k}$ [Eq. 8]

For 30F-E2M3 $f_{t,0,l,k} = 1.0 \times f_{m,g,k}$ [Eq. 9]

In other words, the relationship between the characteristic tensile strength of the LVL tension laminations and the characteristics flexural strength of the glulam beams does not necessarily follow the relationship prescribed in ANSI A190.1 [9] (see Equation 1). It was originally theorized that the high ratio for 30F-E2M3 might have been associated with the questionable face bond between the LVL tension lamination and adjacent lumber lamination, as previously noted. It was suspected that the questionable glue bond might have caused an incomplete stress transfer between the inner laminations and the LVL tension lamination, thereby demanding a higher share of tensile stress on the LVL tension lamination.

This hypothesis, however, could not be substantiated in 2 other similar testing programs conducted for the same glulam manufacturer soon after the completion of this study. The glue bond did not have any problems in those 2 studies. However, the relationship between the characteristic tensile strength of the LVL tension laminations and the characteristics flexural strength of the glulam beams was the same as that described by Equation 9. Likewise, another similar testing program conducted for the same glulam manufacturer who produced the 30F-E2M2 glulam tested in this study showed a consistent relationship as that described in Equation 8. Details of those 3 studies will be reported in the near future.

Results obtained from this study suggested that relationship between the characteristic tensile strength of the LVL tension laminations ($f_{t,0,l,k}$) and the characteristic flexural strength of the glulam beams ($f_{m,g,k}$) is likely to depend upon not only the LVL, but the glulam manufacturers. It was noticed that the relationship between $f_{t,0,l,k}$ and $f_{m,g,k}$ did not necessarily follow ANSI A190.1 [9]. Therefore, the required $f_{t,0,l,k}$ value for QA purposes should be confirmed by LVL tension and full-scale glulam beam tests. Without the confirmation data, the $f_{t,0,l,k}$ should be assigned the same value as $f_{m,g,k}$.

6.4 Control Values for 30F-E2M2 and 30F-E2M3

As the LVL tension laminations are crucial to the glulam beam performance, control values for the LVL should be established for quality control purposes when the layup combinations given in Tables 1 and 2 are implemented in production. Based on the full-scale beam test results given in Tables 7 and 9, it appears that the beam performance can be justified at $f_{m,g,k}$ of 48 MPa (6940 psi) and $E_{0,g,mean}$ of 16.3 GPa (2.4 x 10^6 psi) for 30F-E2M2, and $f_{m,g,k}$ of 49 MPa (7140 psi) and $E_{0,g,mean}$ of 17.3 GPa (2.5 x 10^6 psi) for 30F-E2M3, provided that the control values for the LVL tension laminations are established based strictly on the LVL test results given in Table 5. However, as the targeted $f_{m,g,k}$ and $E_{0,g,mean}$ are limited to 43 MPa (6300 MPa) and 14.5 GPa (2.1 x 10^6 psi), respectively, the control values for the LVL tension laminations can be adjusted accordingly.

In lack of further supporting data, the required LVL characteristic tensile strength based on a 4-ft gauge length may be established based on Equations 8 and 9. In other words, the $f_{t,0,l,k}$ value should be required at 43 MPa (6300 psi) x 0.8 = 34 MPa (5040 psi) for 30F-E2M2. On the other hand, the $f_{t,0,l,k}$ value should be required at 43 MPa (6300 psi) for 30F-E2M3. Apparently, the required LVL long-span E can be established at 16.6 GPa (2.4 x 10^6 psi) as the glulam beam MOE is very predictable using GAP or the transformed section method.

7. Conclusions

The following conclusions are supported by the results obtained from this study:

- LVL could be used as tension laminations for high-strength glulams up to, but not limited to, an $f_{m,g,k}$ value of 43 MPa (6300 psi) and $E_{0,g,mean}$ value of 14.5 GPa (2.1 x 10^6 psi).

- The layup combinations given in Tables 1 and 2 could meet the values given above provided that the LVL tension laminations are properly quality-controlled.

- It is also important to recognize that relationship between $f_{t,0,l,k}$ and $f_{m,g,k}$ is likely to depend upon not only the LVL, but the glulam manufacturers. Therefore, the required $f_{t,0,l,k}$ value for QA purposes should be confirmed by LVL tension and full-scale glulam beam tests. Without the confirmation data, the $f_{t,0,l,k}$ should be assigned the same value as $f_{m,g,k}$.

8. References

1. APA - The Engineered Wood Association. 2000. *Glulam Design Properties and Layup Combinations*. EWS Y117. Tacoma, WA.
2. American Institute of Timber Construction. 1993. *Standard Specifications for Structural Glued Laminated Timber of Softwood Species*. AITC 117-93 -- Manufacturing. Englewood, CO.
3. ICBO Evaluation Service, Inc. 2000. *EWS glued laminated timber combinations and the "GAP 2000" computer program for determining design stresses*. Evaluation Report No. ER-5714.
4. National Evaluation Service, Inc. 2000. *EWS glued laminated timber combinations and "GAP" computer program for determining design stresses*. Evaluation Report No. NER-486.
5. Yeh, B.J. 1996. *Using computer models to predict the performance of structural glued laminated timber*. In Proceedings of the International Wood Engineering Conference, 1:136-143. New Orleans, LA.
6. American Society for Testing and Materials. 2000. Standard test method for establishing stresses for structural glued laminated timber (glulam). ASTM D3737. *Annual Book of ASTM Standards.* Philadelphia, PA.
7. American Society for Testing and Materials. 2000. Standard test methods for mechanical properties of lumber and wood-base structural material. ASTM D4761. *Annual Book of ASTM Standards.* Philadelphia, PA.
8. American Society for Testing and Materials. 2000. Standard specification for evaluation of structural composite lumber products. ASTM D5456. *Annual Book of ASTM Standards.* Philadelphia, PA.
9. American National Standards Institute. 1992. *American National Standard for Wood Products - Structural Glued Laminated Timber.* ANSI A190.1. New York, NY.
10. American Institute of Timber Construction. 1992. *Standard for Laminated Veneer Lumber (LVL) Used in Structural Glued Laminated Timber*. AITC 402. Englewood, CO.
11. American Society for Testing and Materials. 2000. Standard methods of static tests of timbers in structural sizes. ASTM D198. *Annual Book of ASTM Standards.* Philadelphia, PA.
12. American Forest & Paper Association. 1997. *National Design Specification for Wood Construction.* Washington, D.C.

13. American Society for Testing and Materials. 2000. Standard practice for evaluating allowable properties for grades of structural lumber. ASTM D2915. *Annual Book of ASTM Standards.* Philadelphia, PA.
14. American Society for Testing and Materials. 2000. Standard test methods for direct moisture content measurement of wood and wood-base materials. ASTM D4442. *Annual Book of ASTM Standards.* Philadelphia, PA.
15. American Society for Testing and Materials. 2000. Standard test methods for specific gravity of wood and wood-based materials. ASTM D2395. *Annual Book of ASTM Standards.* Philadelphia, PA.
16. Miller, I and J.E. Freund. 1977. Probability and Statistics for Engineers, 2nd Edition. Prentice-Hall, Inc., Englewood Cliffs, NJ.