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DEVELOPMENT OF NEW CONSTRUCTIONS OF GLULAM BEAMS IN CANADA

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Presented by F. Lam

H. Blass asked how the laminating factors were developed. F. Lam replied that they were obtained via a model calibration procedure where the smaller (0.3 m) beams were used in the calibration and the deeper (0.6 m) confirmed the factors. Also this type of factor was reported by Falk.

J. Kohler asked about the correlation between the tension strength of the laminae and the finger joints considered. F. Lam replied that it was not considered; even though there might be some correlations, the program still gives good results when it was ignored.

DEVELOPMENT OF NEW CONSTRUCTIONS OF GLULAM BEAMS IN CANADA

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In Canada the manufacturing of Glulam beams and the grading rules of laminating stock are stipulated under Canadian Standards CSA 0122. This paper reports on procedures undertaken to develop new constructions of Canadian Glulam beams that can fit well with the characteristics of the wood resource. Detailed study of the lam-stock was first conducted via a series of grading analysis and testing. The lam-stock was testing non-destructively for modulus of elasticity and then destructively for tension strength. Grading rules were modified to establish new grades of lam-stock. Subsequently, a detailed knot database was developed to study the performance of these grades based on the US-GAP program. Tension testing was also conducted to establish the strength of finger joints for various new grades of lam-stock. A stochastic finite element program was used to evaluate different prototype construction of glulam beams. An experimental program was then conducted to test full size glulam beams in bending and shear to verify program predictions including size effects issues. Excellent agreement between program predictions and test results was observed.

1. INTRODUCTION

In North America the minimum requirements for the manufacturing of Glued laminated timber (Glulam) beams are specified in CSA O122 M89 (Canada) and ANSI/AITC AI90.1 (US). CSA O122 M89 uses visual grading and modulus of elasticity (MOE) assessment to build different grades of glulam while ANSI additionally requires the knot distribution of the material to be considered. CAN/CSA 0122 M89 specifies four grades of lam-stock B-F, B, C and D. B-F is the highest grade designated for the extreme tension zones of 20f and 24f beams. For this grade, knots or other similar defects exceeding 10 mm and local slope of grain steeper than 1:16 shall not be permitted within 13 mm of the edge of the outer tension face lamination after finishing. D is the weakest grade, generally placed at the mid zone of the beam. The laminating boards of this grade are allowed to have knot sizes up to 50% of the board width.

The current Canadian specifications generally deal with pre-established lamina grades and specify whether the given beam lay-up is admissible. The US procedures require tedious knot assessments to qualify the material grade. It is recognized that there is a need for more efficient beam design procedures which will increase the performance of the glulam beams as well as improving the efficient use of timber resource. One of the key-issues from the glulam manufacturers' point of view is the available supply of the high grade material needed for the extreme tension zone of the 24f beams. Here the interest is to investigate the possibility to modify some of the knot size restrictions at the extreme tension zone of the 24f beams in order to match the strength requirements to the knot size characteristics of the lamina resource for the tension lamina-grades. In this way the current research has been formulated to developed/validate new procedures to construct more efficient glulam beams and to optimize the lamina grade specifications for the construction of 24f Douglas fir glulam beams. The study consists of a series of laboratory investigations to test the strength characteristics of lamina and full scale glulam beams coupled with computer analysis using ULAG, a stochastic finite element program developed at the University of British Columbia (UBC). The program can simulate virtual construction of glulam beams/columns with progressive loading until collapse to investigate the bending capacities and failure behaviors of the glulam.

2. DEVELOPMENT OF NEW LAMINA GRADES

The initial guidelines for the new lamina grades were proposed by Western Archrib - Structural Wood Systems. This consists of the specifications for a set of seven laminating grades T1, T2, Cc, B, C, Dc, and D. Here T1 and T2 are tension lamina grades and Cc and Dc are compression lamina grades.

Douglas fir 38 mm x 140 mm laminae were used for all the grade assessment and verifications. Lamina samples were randomly selected from the mills and delivered to UBC in batches. The first four batches of materials were used for the primary grade development process and verification. These batches consist of one hundred and eighty-nine 2.44 m long boards and five hundred and nine 4.88 m long boards.

The development process involves a series of grading analysis and testing. Grading was conducted by the combination of E rating and visual grading as specified in the new guidelines. Initially the grade yield and the grade distribution across the samples were analyzed. Then the guidelines were modified to improve the grade yield. Based on this a set of five lamina grades with potential grade turnout was chosen for further assessments. Then the samples were tested in tension. The finalized grade set was inspected and verified by National Lumber Grades Authorities (NLGA) personnel and the results were reviewed by experts from the industry and UBC. Some of the key grading factors of the modified guidelines are given in Table 1 and the corresponding grade turnout and MOE data are given in Table 2.

Table 1. Key grading factors considered for the resource assessment

Parameter	T1	B	C_c	C	D
$MOE_{(min)}$, MPa	13,100	12,400	12,400	11,000	-
$MOE_{(average)}$, MPa	15,400			12,000	-
Knot size, mm	35	35	55	55	70
Edge knot, mm	23	-	-	-	-
SOG, all four sides	1:16	1:16	1:12	1:12	1:08
Pith (maximum allowed)[1]	1/8				
Clear wood(minimum requirement), %	67				
SRC spacing, mm	600				
Knot spacing near finger joint[2]	2Φ				

[1]As a ratio of the cross section of the lamina

[2]Any knots over 10 mm in diameter not permitted within 2 knot diameter of any finger joint.

Table 2. Grade turnout

	T1	Cc	B	C	D
Grade turnout, m	419	119	402	885	1,068
MOE, Mean, MPa	15,226	14,155	13,683	11,774	9,992
COV, %	12	7	9	6	17
Total number of boards tested	184	44	223	201	138

Subsequently tension tests were conducted to determine the strengths of the laminae and the finger joints. The lamina tension tests were carried out at two gauge lengths 3.66 m and 1.22 m with a 0.61 m grip length at each end. For each grade the speed of loading was adjusted to maintain an average time-to-failure of 10 minutes. A Metriguard tension testing machine with full resistant grips and a capacity of about 450 kN was used for the testing.

The mean tensile strength values corresponding to the T1 grade tested at 3.66 m and 1.22 m gauge length are 42.9 MPa and 52.6 MPa, respectively. Based on these values a length effect factor k of 5.4 was established for the material tested. The relationship between the strength values and the corresponding material volume (Lam 2000) used in the assessment of k factor is given in equation 1. In the equation (1) τ and V corresponds to the tensile strength and the volume of the material, respectively. The subscripts 1 and 2 refer to the samples corresponding to the two different lengths considered. Then all the lamina strength values were size adjusted to a 2.44 m gauge length in order to establish a unique set of reference strength data. This database was used as input for the ULAG analysis.

$$\frac{\tau_1}{\tau_2}=\left(\frac{V_2}{V_1}\right)^{\left(\frac{1}{k}\right)} \qquad (1)$$

Approximately four hundred finger jointed lamina specimens of the four grades, T1, B, C and D were tested in tension. Here the gauge length and the grip lengths were kept at 0.66 m and 1.22 m, respectively. Again the speed of loading was kept to achieve a time to failure of approximately 10 minutes. As expected, both lamina and finger joint failures were observed during the tests. This resulted in two sets of strength data: one corresponding to the finger joint failure cases and the other corresponding to the lamina failure cases where the finger joint strength is higher than that of the failure load of the specimen. This issue of mixed failure modes was addressed using the Maximum Likelihood Evaluation (MLE) theory to isolate the strength of finger joints from a censored database. The summary statistics of the lamina and finger joint tensile strength test results are given in Table 3.

Table 3. Summary statistics of the lamina and finger joint tensile strength test results

	Lamina				Finger Joint (MLE)			
Material Grade	T1	B	C	D	T1	B	C	D
Mean strength, MPa	50	35	29	24	42	40	33	28
COV, %	24	23	32	27	21	21	19	22
Number of specimens tested	184	223	201	138	126	100	104	100
Number of finger joint failures					110	67	46	31

As expected, in T1 grade's case, the lamina strength is much higher than that of the finger joint's. In B grade's case, both strength values come closer and in C grade's and D grade's cases, the finger joint's strength is higher than that of the lamina.

3 ULAG ANALYSIS

During the ULAG assessments, the finite element glulam beam models were simulated with 0.05 m segments along the beam length. The models were subjected to a virtual progressive loading until collapse yielding the corresponding failure loads, deflections and failure types. For each of the beam case investigated, the beam strength statistics were determined based on a set of one thousand glulam beam simulations and loading data.

The ULAG study deals with two main aspects: fine tuning and validating the ULAG program for glulam strength assessments to confirm code requirements and to assess the performance of the new lamina grades. The basic input material for the ULAG analysis were the tensile strength and the MOE test databases of the lamina and finger joints and the length distribution of the lamina. Another characteristic of interest is the laminating effect between the lamina which is not considered in the original ULAG program. During the current analysis a trial set of laminating factors were proposed for the new lamina grades (Table 4). These factors were used in subsequent ULAG analysis to determine the beam configuration and loading setup for the calibration tests. It is noted that laminating factors are not only grade dependent. Additional considerations are needed to establish laminating factors: 1) the position of the lamina within the member, 2) whether the lamina is supported by adjacent laminae on one side or both; and 3) the relative stiffness of the lamina in comparison to the adjacent laminae. Care must be taken when applying the trial laminating factors to unconventional lay-ups that differ significantly from the material tested in this research program.

Table 4. Trial sets of laminating factors proposed for the new lamina grades and beam lay-ups

Material grade	T1	B	C	D
Laminating factor	1.1	1.2	1.3	1.4

A series of ULAG simulations were performed to assess the performance of the lamina grades. For these analyses, glulam beams were simulated with a span to depth ratio of 15:1 assuming that the lamina consist of 75% 4.88 m and 25% 2.44 m long members. The beam lay-ups used for the assessments are given in Table 5 and the corresponding characteristics (5[th] percentile) strength and specified strength values predicted are given in Table 6. The target specified strength of these beams is 30.6 MPa. All of the beams except #1 (8) and #4(8) met the target level.

Table 5. Glulam lay-ups used for the ULAG assessments

Lamina number(from the bottom of the beam)		20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Beam lay-up cases	#1(8)													Cc	C	D	D	D	D	B	T1
	#4(8)													Cc	C	D	D	D	D	C	T1
	U1(10)											Cc	Cc	C	D	D	D	D	C	B	T1
	U2(10)											Cc	C	C	D	D	D	D	C	C	T1
	U1(20)	Cc	Cc	Cc	C	C	D	D	D	D	D	D	D	D	D	D	C	C	B	T1	T1
	U2(20)	Cc	Cc	C	C	C	D	D	D	D	D	D	D	D	D	D	C	C	C	T1	T1
	#4(20)	Cc	Cc	Cc	C	C	D	D	D	D	D	D	D	D	D	D	C	C	B	B	T1

Table 6. ULAG predicted specified strength values

Parameter	Beam lay-up cases						
	#1(8)	#4(8)	U1(10)	U2(10)	U1(20)	U2(20)	#4(20)
Depth, m	0.30	0.30	0.38	0.38	0.76	0.76	0.76
Width, m	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Number of laminations	8	8	10	10	20	20	20
Characteristic strength, ULAG, MPa	37.2	35.6	38.5	38.0	34.8	34.7	32.5
Specified strength, ULAG, MPa	30.1	28.3	32.8	32.6	35.3	35.2	32.8

4 GAP ASSESMENTS

The knot database on the new lamina grades developed in this study was provided to Dr. Borjen Yeh (APA) to conduct a parallel assessment using the U.S. code approved program GAP. The lamina lay-ups given in Table 5 were used for this assessment as well for comparison purposes. GAP program predicts the allowable strength capacities equivalent to a standard glulam beam of 0.13 m x 0.30 m x 6.40 m for the U.S. These values are converted to specified strengths for the Canadian Code corresponding to a standard beam size of 0.13 m x 0.61 m x 9.10 m. Comparisons between GAP and ULAG predicted glulam specified strengths are given in Table 7.

Table 7. Comparisons between the ULAG and GAP predicted specified strength

Parameter	Beam lay-up cases						
	#1(8)	#4(8)	U1(10)	U2(10)	U1(20)	U2(20)	#4(20)
Allowable strength predicted by GAP, MPa	17.8	17.2	17.8	16.9	18.4	18.0	17.7
Specified strength, GAP, MPa (1)	32.8	31.2	33.3	31.8	36.0	35.1	34.5
Specified strength, ULAG, MPa (2)	30.1	28.3	32.8	32.6	35.3	35.2	32.8
Ratio (1)/((2)	0.92	0.91	0.98	1.03	0.98	1.00	0.95

The GAP predicted specified strength values are above 30.6 MPa indicating satisfactory performance for all the lay-ups considered. In all cases GAP predictions tend to higher than ULAG except for U2(10) and U2(20). It is noted that the GAP procedure does not consider finger joint strengths which may partially explain why it seems to be less conservative than ULAG.

5 BENDING SIMULATIONS

Initially ULAG bending simulations were carried out to identify the beam lay-ups satisfying a 24f 1.8 E grade. For this purpose a series of trial analysis were carried out using trial beam lay-ups. Beam lay-ups and dimensions of the finalized beam sets selected for the bending tests are given in Table 8.

Table 8. Beam Lay-ups selected for bending simulation

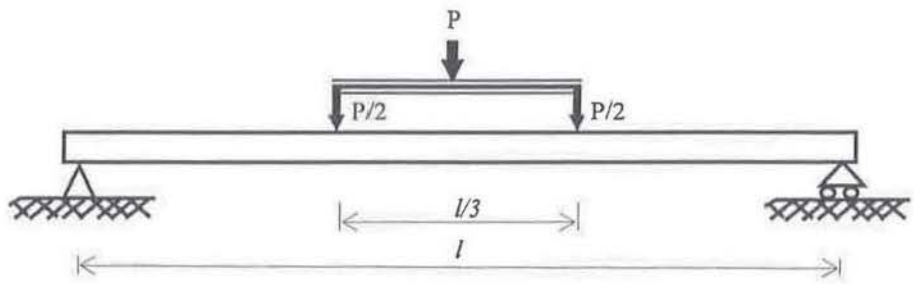
Lay-up ID	Lamina number from top of the beam															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A8U	Cc	C	D	D	D	D	C	T1								
A5U	Cc	B	C	C	D	D	D	D	D	D	D	D	C	C	B	T1

Two sets of twenty four 0.30 m and 0.61 m deep glulam beams manufactured according to the proposed beam lay-up (Table 8) were used for the bending calibration and verification tests respectively. The tests were carried out with a third point loading (Figure 1). The test apparatus consists of two end supports, two loading heads attached to a loading bar and the machine head. The advancement of the machine head and the corresponding load is monitored and controlled by a computerized data acquisition system. The 0.3 m deep beams were tested at 21:1 span to depth ratio and 0.61 m deep beams were tested at 18:1 span to depth ratio. The loading rates of these sets were kept at 10 mm/min and 13 mm/min respectively to maintain an average failure time of 10 minutes.

MOE values for all the bending beams were evaluated from load-deformation curves obtained prior to the ultimate loading. A specially designed cable yoke system was used to obtain the required load-deflection data with a loading level of 25% of the ULAG predicted mean failure load.

The summary of the bending test results is given in Table 9 and a comparison between the ULAG predicted strength distribution and the laboratory test results are given in Figure 2.

Figure 1. Typical third point loading configuration used for the bending test

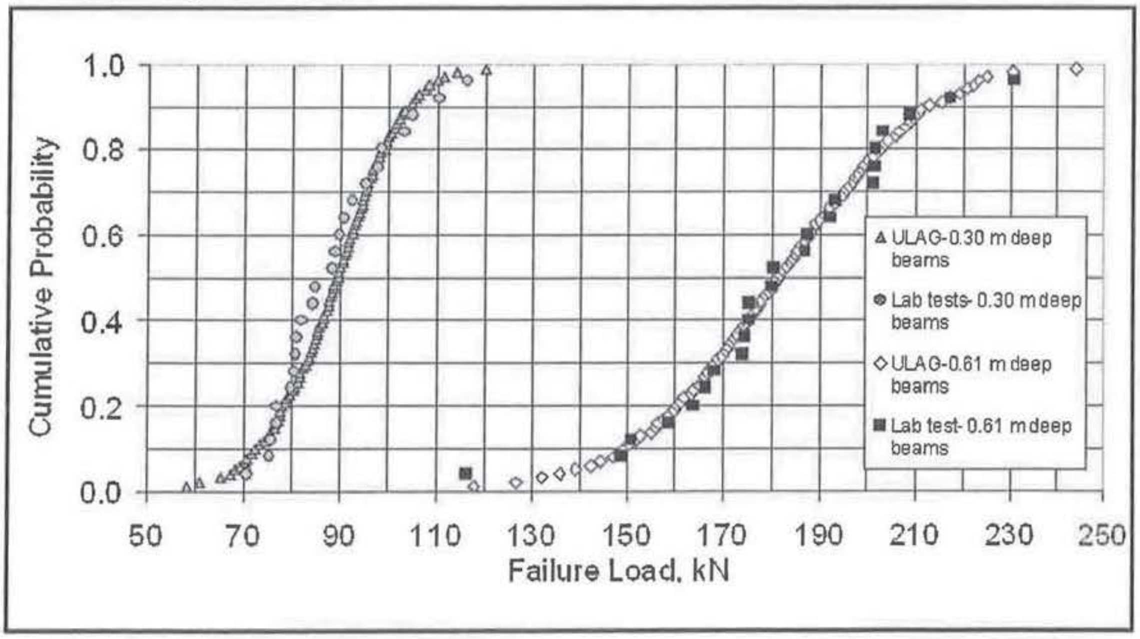


l - test span
P- total load on the beam

Table 9. Summary of the bending test results

		Tested		Predicted		Error, %	
Beam depth, m		**0.30**	**0.61**	**0.30**	**0.61**	**0.30**	**0.61**
MOR	Mean, MPa	48.3	41.8	49.0	42.0		
	COV	11	14	14	13		
MOE	Mean, MPa	13,326	12,923	12,484	12,278	-6.3	-5.0
Specified strength, MPa		34.5	32.2	34.5	32.7	-0.2	1.6

Figure 2. Comparisons between the ULAG predicted strength distribution and the laboratory test results



6 GLULAM SHEAR

A finite element model volume integration scheme of Foschi & Barrett (1976) and Lam et al. (1997) was followed to perform the shear strength predictions. This model predicts the failure load of a full scale beam that has a common probability of failure as a clear wood block shear specimen. The shear strain distribution was extracted from the ULAG predicted nodal displacements. The corresponding shear stress distribution in the member was determined. Now based on the weakest link theory the mean shear failure load $P_{0.5}$ can be written as:

$$P_{0.5} = \frac{P\tau^*_{0.5}}{I^{1/K}} \qquad (2)$$

where,

$\tau^*_{0.5}$ - mean shear strength of a unit volume 1.64E-05 m^3

I - shear stress field integrated over the volume under the applied load P

k - Weibull shape parameter.

$\tau^*_{0.5}$ can be determined based on the following relationship (Foschi & Barrett 1976) :

$$\tau^*_{0.5} = \beta_t \tau_{ASTM} \qquad (3)$$

where,

$$\beta_t = 1.333+0.336(k-4) \qquad if\ 4 \leq k \leq 8$$

$$\beta_t = 2.678+0.251(k-8) \qquad if\ 8 \leq k \leq 10$$

τ_{ASTM} is the ASTM block shear strength at the probability of interest.

The D grade Douglas fir clear wood mean-shear strength value of 8.98 MPa with 16% COV reported by Lam et al. (1997) was used for the assessments of the beam-lay-up given in Table 10. The results are given in Table 11.

Table 10. Shear calibration beam lay-up (A1)

Lamina number (from the bottom of the beam)	8	7	6	5	4	3	2	1
Lamina grades	T1	B	D	D	D	D	B	T1

Table 11. Results of the initial shear simulations

Beam depth, m	Span to depth ratio	Predicted shear capacity, kN	Predicted shear strength, MPa
0.30	7	345	6.21
0.30	6	433	7.79

The D grade material used in the glulam shear zone (middle core of the beam) is the weakest grade, expected to be having inferior strength parameters. Therefore, the clear wood strength corresponding to the Douglas fir D grades should be weaker than that of reported by Lam et al. (1997). In this way the predicted strength values given in Table 11 can be considered as an upper bound for the shear capacity of the glulam beams considered.

Laboratory assessment consists of three sets of 0.30 m and 0.45 m deep glulam beams (without finger joints). Each of these sets consists of 24 beams. First two sets (Cases B and C) of the 0.30 m deep beams were used for model calibration and the third set (Case G) was used for the model verification. The details of the test configuration used for the shear tests are given in Table 12 and the schematic diagram of the typical shear testing arrangement used is shown in Figure 3. The shear test data was processed using the MLE technique in order to determine the uncensored statistical parameters corresponding to the pure shear failures. The summary of the shear test results is given in Table 13. Without consideration of stress volume effect, the mean load in case G is expected to be 1.5 times higher than that of case C. The clear observed disagreement can be explained by stress volume effect in shear as shown in the analysis following Equations 2 and 3.

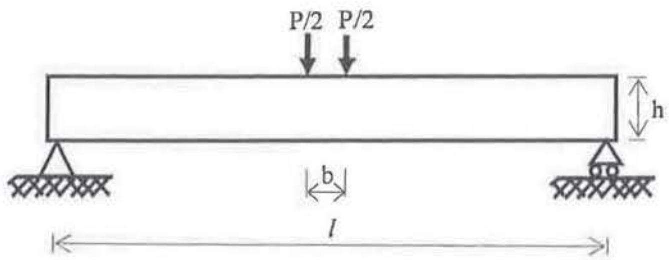
Table 12. Shear test configuration

Beam depth	0.30 m (1 ft)	0.30 m (1 ft)	0.46 m (1.5 ft)
Beam width	0.129 m (5 ¼ in.)		
Span to depth ratio	7	6	6
Test span, *l*	2.13 m (7')	1.83 m (6')	2.74 m (9 ft)
Beam length	2.44 m (8')	2.13 m (7')	3.1 m (10 ft and 2 in.)
Loading type	Four point loading		

Table 13. Summary of the shear test results

Beam Case	Depth, m	Span to depth ratio	Failure load		Number of shear failures	Based on MLE Simulation	
			Mean (kN)	COV (%)		Mean Load, (kN)	COV (%)
C	0.3	6	311	9	20	313	13
B	0.3	7	263	10	17	275	8
G	0.46	6	389	10	18	397	11

Figure 3. Configuration of the typical shear testing arrangement



l - test span
b = 0.46 m, the spacing between the pair of loading heads at the center
h= beam depth
P- total load on the beam

After the shear beam testing the clear wood strength parameters used in the shear-stress volume model were fine-tuned based on the test results. This was done by a series of trial and error assessments using different sets of the clear wood strength parameters which are close to the values given in Lam et al. (1997). The selected clear wood strength set which produce the minimum errors between the tested and predicted average shear loads is given in Table 14. This is the predicted clear wood strength values for the Douglas fir D grade material. About 25% of the beams broke in bending mode. In a couple of cases the failures were initiated by the tensile cracks and the ultimate failure occurred in shear. The results of this analysis considering stress volume effect in shear compared with the shear test results are given in Table 15.

Table 14. Predicted clear wood shear strength values corresponding to Douglas fir D grade laminae

Parameter	Mean, MPa	COV, %
τ_{ASTM}	9.0	18

Table 15. A comparison of predicted and tested shear capacity of the glulam beams

Beam Case	Tested shear capacity (mean), kN	Predicted shear capacity (mean), kN	Error, %
C	313	330	5.4
B	275	266	-3.4
G	397	385	-2.9

7 CONCLUSIONS

The characteristics of Douglas fir lamina were studied based on visual grading, defect mapping, MOE and tensile testing, and finger joint testing. Based on these investigations an optimized set of five Douglas fir lamina grades T1, Cc, B, C and D were developed. Their strength properties assessed and the grade turnout was established.

Various combination of the beam lay-ups built with the new lamina grades was analyzed using the computer models ULAG and GAP to develop new lay up of 24f Dogulas fir glulam beams. ULAG tend to give more conservative results compared to GAP. Subsequently the performance of the new beam construction was demonstrated through full size testing of two sets of 0.30 m deep and 0.61 m deep glulam beam in bending. The target specified strength and MOE requirements for the 24f glulam beams were confirmed and excellent accuracy of ULAG in simulating the flexural strength distribution of glulam was demonstrated. The enhanced ULAG also predicts the shear capacities of glulam with good agreement explaining the observed influenced of stress volume on the shear strength of glulam.

The procedures established from this study demonstrate a new method for glulam beam lay-up design and assessment by using ULAG to predict the flexural capacity of Glulam beams as well as using the tensile strength and the corresponding MOE values of the lamina and the tensile strength of the finger joints as input.

8 ACKNOWLEDGEMENTS

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