Manufacturing & Products

Australian Government

Forest and Wood Products
Research and Development
Corporation

Design Values for Australian Glulam

Project No. PN01.3700

Australian Government
Forest and Wood Products Research and Development Corporation

Publication: Design Values for Australian Glulam

Project no:**PN01.3700**

Researchers:
H. R. Milner
Monash Timber Engineering Centre
Monash University
Clayton Campus, Wellington Road, Clayton, VIC 3800

Forest and Wood Products Research and Development Corporation
PO Box 69, World Trade Centre, Victoria 8005
Phone: 03 9614 7544 Fax: 03 9614 6822 Email: info@fwprdc.org.au
Web: www.fwprdc.org.au

Design Values for Australian Glulam

Prepared for the

Forest & Wood Products
Research & Development Corporation

by

H.R. Milner

The FWPRDC is jointly funded by the Australian forest and wood products industry and the Australian Government.

TABLE OF CONTENTS

DESIGN VALUES FOR AUSTRALIAN GLULAM

DESIGN VALUES FOR AUSTRALIAN GLULAM
EXECUTIVE SUMMARY

The project objectives as stated in the proposal put to the FWPRDC were as follows:

1. to determine the bending strength, tension strength, shear strength and bending stiffness of Australian manufactured GL13 softwood glulam and assess its characteristic values. Samples will be drawn from a representative range of suppliers within and without the GLTAA membership,
2. to use the statistical data obtained from 1 above as a basis for determining a capacity factor to be cited in AS1720.1, Table 2.5,
3. to determine the statistical strength and stiffness properties of finger jointed laminations and to relate this data to the characteristic strengths and stiffness of glulam,
4. to determine the extent to which available computer software (eg Statistica QC Charts) can be employed to provide glulam producers with control charts that enable them to better control their manufacturing processes,
5. to establish information on the level of process control used by producers outside the GLTAA membership.

Objective 1 CHARACTERISTIC DESIGN VALUES FOR AUSTRALIAN GL13 GLULAM

Relative to the current AS1720.1 values an adjustment is recommended to the GL13 design values.

	Bending (f'_b)	**Tension parallel to the grain** (f'_t)	**Shear in beams** (f'_s)	**Short duration average modulus of elasticity parallel to the grain** (E)
AS1720.1 currently	33	16	3.7	13300
Recommended values	33	20	3.3	13300

- The bending strengths are approximately correct. The test data indicates that 33 *MPa* is very close to the correct value on the basis of the test data.

- Across the board tension strengths are understated. It is recommended that a value of 20 *MPa* be adopted which represents a 25% increase from the current 16 *MPa*. When the GL grade figures were set it was anticipated that the values would be conservative. This action was necessary at the time because of the lack of test data.

- Shear strengths are overstated because lower grade material is sometimes used in the inner laminations. A drop in value to 3.3 *MPa* is recommended for grades GL13 and below. Although only GL13 was targeted in this test program, it is unlikely that the GL grades below GL13 would use better material in the inner laminations.

- The *E* values are conservatively stated which could lead to the introduction of a grade in-between GL13 and GL17 in the future. For the present it is recommended that the *E* value remain at 13300 *MPa*.

Objective 2 CAPACITY FACTOR FOR AUSTRALIAN GLULAM

The coefficient of variation of glulam has shown to approximate 0.2 indicating values of ϕ = 0.90, 0.83, 0.78 or rounded values of 0.90, 0.80, 0.75. The current values of 0.85, 0.70, 0.65 are too conservative. Taken in conjunction with the amended characteristic strengths and building in some conservatism, it is recommended that the glulam industry adopt capacity factor values of:

All structural elements in houses and secondary structural elements in structures other than houses	Primary structural elements in structures other than houses	Primary structural elements in structures intended to fulfil an essential services or post disaster function
0.90 (0.85)	0.80 (0.70)	0.75 (0.65)

Figures in brackets represent values currently listed in AS1720.1, Table 2.5.

On the basis of finger joint strength data collected by the GLTAA Inspectorate over a number of years it is not believed that coefficients of variation of other glulam grades differ substantially from those in GL13.

Objective 3 RELATIONSHIP BETWEEN LAMINATION AND GLULAM DESIGN VALUES

There was a strong correlation between lamination modulus of elasticity and glulam MOE. Australian GL13 has a somewhat higher MOE than can be inferred from lamination bend values. Attempts to determine glulam strength from finger joint strengths proved to be elusive due to the practice of not machining finger joint test specimens. This results in defects being present in the test specimens that are machined out in glulam with finishing operations. It is recommended that finger joint test specimens be machined in future.

Objective 4 COMPUTER SOFTWARE FOR STATISTICAL QUALITY CONTROL

A system was developed and is currently being implemented that will centralise data collection of glulam manufacture in Australia. Details are given in the body of the report.

Objective 5 QA OUTSIDE THE GLTAA MEMBERSHIP

The study highlights the fact that there was only one member lying outside the GLTAA membership involved in producing structural glulam. The results show that this manufacturer is not manufacturing to AS/NZS 1328.

DESIGN VALUES FOR AUSTRALIAN GLULAM

1. OBJECTIVES

The project objectives as stated in the FWPRDC proposal were as follows:

1. to determine the bending strength, tension strength, shear strength and bending stiffness of Australian manufactured GL13 softwood glulam and assess its characteristic values. Samples will be drawn from a representative range of suppliers within and without the GLTAA membership

2. to use the statistical data obtained from 1 above as a basis for determining a capacity factor to be cited in AS1720.1, Table 2.5

3. to determine the statistical strength and stiffness properties of finger jointed laminations and to relate this data to the characteristic strengths and stiffness of glulam

4. to determine the extent to which available computer software (eg Statistica QC Charts) can be employed to provide glulam producers with control charts that enable them to better control their manufacturing processes

5. to establish information on the level of process control used by producers outside the GLTAA membership

The main focus of the project was associated with objective 1 as no previous studies had ever been undertaken to determine the extent to which the Australian glulam industry was able to deliver reliable product with specified engineering design properties. In this instance, the specified properties were GL13 glulam as defined in AS1720.1—1997, Table 7.1. In essence, this requires achieving the target characteristic strength and elastic modulus values listed in Table 1.

Table 1 Characteristic strengths and elastic moduli (MPa) for GL13 glulam extracted from AS1720.1—1997, Table 7.1.

Bending (f_b')	**Tension parallel to the grain** (f_t')	**Shear in beam** (f_s')	**Short duration average modulus of elasticity parallel to the grain** (E)
33	16	3.7	13300

Objective 2 is met on the basis of statistical analysis of the test data. In pursuit of Objective 3 the following was determined for the specimens despatched by five GLTAA members identified, for reasons of confidentiality, as manufacturer A, B, C, D, E.

1. characteristic bending strength and characteristic modulus of elasticity of finger-jointed laminations
2. characteristic tension strength of finger-jointed laminations
3. the modulus of elasticity of 5m long finger-jointed laminations at three points along its length
4. characteristic bending strength and characteristic modulus of elasticity of glulam beams
5. characteristic tension strength of glulam members
6. characteristic shear strength of glulam beams

A total of 2411 tests were undertaken on 1271 specimens in this project.

Table 2 Summary of test program.

Type of specimen	Property measured[1]	Number of specimens tested	Number of tests undertaken
Finger jointed timber laminations.	Bending strength and modulus of elasticity	258	258
	Tensile strength	209	209
	Modulus of elasticity	570	1710
Full size finger jointed glulam beams	Bending strength and modulus of elasticity	115	115
	Tensile strength	58	58
	Shear strength	61	61
	Total	**1271**	**2411**

In addition, tests were undertaken on the production of a single manufacturer outside the GLTAA identified as manufacturer F in pursuit of Objective 1. It proved possible to find only one manufacturer that was not a GLTAA member and whose beams were readily identifiable in the market place.

Finally, in pursuit of Objective 4, talks were held initially with the Australian agents for the computer program Statistica and a scheme prepared by them was put to a GLTAA meeting. Under the scheme, all in-house test data would be collected at a central source located at Monash University and exported to members. In the event the scheme proved to be too expensive, given the current size of the industry, and a simpler, lower cost, scheme was developed and finally accepted.

---

[1] Characteristic strength and modulus of elasticity values refer to quantities computed in accordance with AS/NZS 4063:1992, Clause 9.1 *Evaluation equations for limit state codes*

2 OBJECTIVE 1 CHARACTERISTIC DESIGN VALUES FOR AUSTRALIAN GL13 GLULAM

2.1 Methodology

2.1.1 Introduction

Initially, a project proposal was developed that had as its objectives the investigation of both GL18 and GL13. At the time of preparing this earlier proposal there were 7 GLTAA manufacturers involved in the production of structural glulam and an unknown number of manufacturers outside the GLTAA. One structural manufacturer withdrew from the GLTAA and another, who was only involved in hardwood glulam, was excluded when the project objectives narrowed to investigating GL13 only.

GLTAA manufacturers were asked to provide samples in what was essentially a two-stage process and were given other advice.

<u>Stage 1</u> The finger jointed lamination stock and shorter finger jointed specimens were supplied to the laboratory. The lamination stock stiffness in bending was measured at three points along each lamination and this material returned to the manufacturer. Finger jointed specimens were tested in bending and tension to identify the strength characteristics of the finger joints.

<u>Stage 2</u> The lamination stock that had been tested for stiffness was returned to manufacturers who fabricated the glulam members. The glulam members were returned and their strength properties in bending, tension and shear were measured and their modulus of elasticity in bending was also determined.

The detailed instructions provided to manufacturers follow.

GLTAA/FWPRDC PROJECT – *DESIGN VALUES FOR AUSTRALIAN GLULAM*

Purchase of timber

Purchase all timber as a single order, i.e., enough to make glulam bend, tension and shear specimens and sufficient for the lamination tests. No distinction is to be made between the material for glulam and lamination specimens. All timber is to be machine stress graded or purchased in some manner that ensures constancy of lamination stock. Likewise the adhesive is to comply with that used in manufacturer’s normal operations.

If you choose not to purchase a lower grade material for the inner laminations then inner lamination test specimens are not required.

All material ordered is to be at least 1m shorter in length than 5 *m*. You can order 2, 3, or 4 *m* stock lengths or anything in between.

Making finger jointed laminations and finger joint specimens

When using this material you are to make every effort to minimise wastage, ie, you must make use of short lengths. You do not need to take this beyond using lengths shorter than say 0.5 *m* unless this is part of your normal operating procedure.

All timber laminations are to be finger jointed to a length of at least 5m and packed separately for each lamination grade used.

Quantities required for each GLTAA manufacturer if using two lamination grades

	Size (mm)	Length (mm)	Number of specimens	Grade	Other requirements
1	65x40	Around 5000	180 separated	Outer laminations	None
2	65x40	Around 5000		Inner laminations	None
3	65x40	2100	60 separated	Outer laminations	None
4	65x40	2100		Inner laminations	None
5	65x40	1000	60	Outer laminations	With one FJ in the middle
6	65x40	3000	30	Outer laminations	With one FJ in the middle
7	65x40	3000	30	Inner laminations	With one FJ in the middle

1. Items 1 & 2 are laminations required to produce full size beams for tension (240x65x4500x10), bending (240x65x4500x20)

2. Items 3 & 4 are required for full size shear tests (240x65x2000x10)

3. Item 5 provides the lamination bending strength of the outer tension laminations

4. Items 6 & 7 provide the tension properties of the finger-jointed laminations

Subsequent actions

1. Monash will then measure the MOE values of all laminations used to produce the full size members for bending. This material will then be returned to you to manufacture the full sized beams.

2. You should separate and identify inner and outer laminations.

3. In measuring the MOE we will spray paint and place an ID code on one end. Make sure that all sprayed ends of laminations are placed to the same end of the finished beam and do not remove the ID code.
   Green - Outer Laminations
   Yellow – Inner Laminations

4. The beams are now ready to be sent back Monash to tested.

2.1.2 Test Rigs and Arrangements

Laminations

The following test arrangements were employed.

Bending strength and stiffness of FJ test specimens (destructive)

The arrangement shown in Figure 1 was used to measure the MOE & MOR of individual finger jointed laminations. The stiffness was measured to determine if manufacturers could simultaneously check both finger joint strength and MOE of the lamination stock. Uncertainty exists about the contribution of the finger joint to the specimen flexibility.

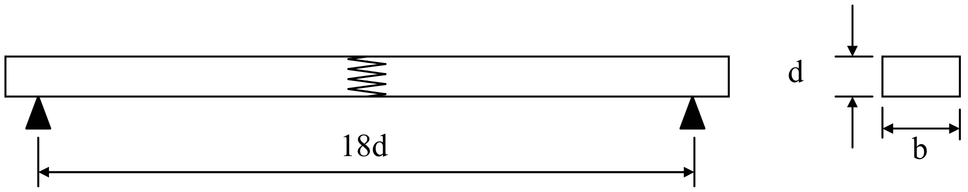


Figure 1 Test arrangement for determining the bending strength of finger joints. MOE values were also determined since similar tests were conducted as part of GLTAA QA test procedures. This proved unsuccessful and has since been replaced by monitoring the MOE of glulam.

MOE values of the finger jointed laminations (Non-destructive test)

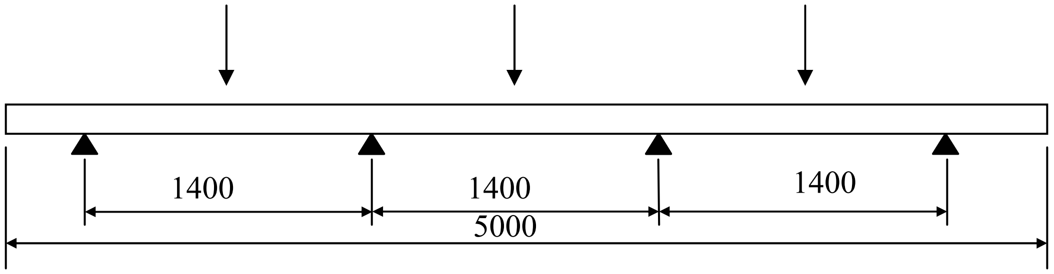


Figure 2 Test arrangement for determining lamination modulus of elasticity. The values are determined using a three point bending test. Each of the above segments is tested as a simply supported span. The lamination was moved successively across the supports.

The set-up shown in Figure 2 was used to measure the MOE of individual finger jointed laminations at the three positions as shown. Each portion of the specimen was tested independently over a span of 1400 mm. The tests were undertaken using an Instron screw loading machine fitted with a 50 kN load cell, SN: UK1330. The load cell had an Australian Calibration Services certificate giving the cell as having an Grade A rating from 0.2 kN to 50 kN.

Tension strengths of finger joints

All finger jointed specimens were 3000mm in length, the grip length was 800mm on each side and, therefore, the clear length subjected to tension was 1400mm. All specimens had only one finger joint at their centre.

All tension testing was undertaken on an in-house designed timber tension testing machine. Both heads of this machine float universally. It is the only such machine in Australia having this capability. Load readings are taken using a 100 *tonne* load cell Tokyo-Sokki Kankyujo CLT-100 and an Australian Calibration Services load recorder with a grade A rating from 20 *kN* to 600 *kN*.

Completed glulam members

All test arrangements were strictly in accordance with AS/NZS 4063:1992 with respect to test dimensions and arrangements, ie, test span lengths, bending tests carried out in four point bending on a simply supported member, shear tests in three point bending on a simply supported member and tension tests carried out over the specified test length.

For the bending and shear tests, loading was applied using a 200 kN Instron Loose Ram fitted with an Instron 100kN, Type 2518-111 load cell, serial Number UK401. It had an Instron calibration certificate during the course of testing giving the machine a Grade A rating in the load range 2 kN to 100 kN. Modulus of elasticity values were determined on the basis of mid-span deflection measurement using a Schaevitz Engineering LVDT, Type 500-DC, S/N 1865. Displacement measurements were recorded automatically using a Dataker/computer system calibrated against a Mitutoyo screw micrometer with a vernier scale over a displacement of 20 mm. The displacement system is used for displacement/MOE determinations, measured in this displacement range. In any event, with a load displacement curve that maintains linearity over a wider range, extrapolation of the calibration factor is regarded as legitimate. Simultaneity of load and displacements readings is guaranteed. The test rig is shown in Figure 3.

Figure 3
Arrangement used to measure MOR/MOE of glulam members

The tension strengths were measured on the same machine used to determine finger joint tension strengths. The tension testing machine is shown in Figure 4 with a glulam member sitting on the main compression struts. The grip zone is visible at the right end.

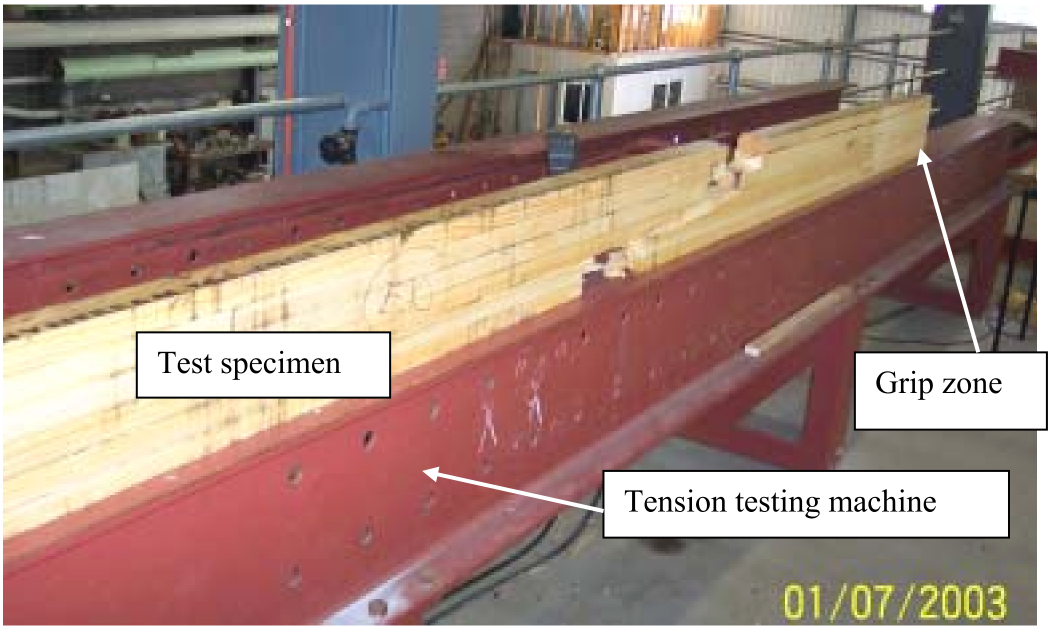


Figure 4 Tension testing machine with a glulam member at the completion of testing. The lighter area on the right is the grip zone.

2.2 Results

2.2.1 Summary of Test Results

The most useful information is contained in Tables 4 to 13. Tables 4-6 present characteristic values and compares them with the GL13 specifications. Tables 7 to 10 provide characteristic design values for bending strength, tension strength, shear strength and modulus of elasticity. Tables 11 and 12 provide characteristic bending and tension strengths of finger joints obtained during destructive tests and Table 13 provides the modulus of elasticity values bend values measured about the minor axis) of the laminations that were used to fabricate the glulam members.

2.2.2 Detailed Test Results

Detailed test results are given in the Appendix. These are individually identified.

2.2.3 Discussion of Results

1. The test numbers of 20 members per manufacturer for MOR/MOE, tension and shear do not comply with AS/NZS4063 which requires a minimum of 30 specimens for strength determinations.

2. The Excel method has been used for estimating the lower 5th percentile values. The method used by Excel is stated as Footnote 1 below Table 5 but is repeated here for convenience. Excel uses a non-parametric method which involves linear interpolation on the basis of computing the cumulative frequency as $(i - 1) / (n - 1)$ as opposed to AS/NZS 4063 which recommends the use of $(i - 0.5) / n$. For obvious reasons it is simpler to use the in-built Excel function.

3. Manufacturers A, B, C all supplied what they defined as GL13. Manufacturer D does not normally manufacture GL13 and, even though this was requested, the product was supplied by the plant and was clearly GL10. GL10 is the product normally produced by manufacturer D. Manufacturer E normally supplies GL17 and the tested product exhibits GL17 characteristics. Manufacturer F is unable to produce GL13, even though the product is sold in the market place as GL13 without GLTAA marks. The results are summarised in Table 4 below.

Table 4 Characteristic values for individual manufacturers. Actual values in *MPa*, % values are measured relative to the GL13 specification in AS 1720.1.

Manufacturer	$f'_{b,test}$	$\frac{f'_{b,test}}{f'_b}$	$f'_{t,test}$	$\frac{f'_{t,test}}{f'_t}$	$f'_{s,test}$	$\frac{f'_{s,test}}{f'_s}$	E_{test}	$\frac{E_{test}}{E}$
GLTAA Members								
A	29.2	0.88	21.1	1.32	3.1	0.84	13350	1.00
B	36.5	1.11	23.0	1.44	5.1	1.38	16390	1.23
C	46.8	1.42	29.2	1.83	4.7	1.27	16740	1.26
D (Note 1)	23.8	1.08	13.9	1.26	3.9	1.05	10340	1.03
E (Note 2)	66.8	1.59	36.6	1.74	5.2	1.41	17700	1.06
Non-GLTAA Member								
F	17.6	0.53	9.4	0.59	4.7	1.27	9960	0.75

NOTES:

1. Compared with the GL10 properties in computing f'_{test}/f' values.
2. Compared with the GL17 properties in computing f'_{test}/f' values.

$f'_{0,test}$ = characteristic strength appropriate to a given failure mode obtained using AS/NZS 4063

$= R_{k,norm} = 1.35\left[1 - 2.7V_R/\sqrt{n}\right]R_{0.05}/\phi(1.3 + 0.7V_R)$

V_R = coefficient of variation of test data

n = sample size

ϕ = 0.8

$R_{0.05}$ = lower 5th percentile strength of R

R = individual test result

f'_0 = characteristic strength of material appropriate to a given failure mode for a given GL grade as given in AS1720.1, Table 7.1

E_{test} = characteristic modulus of elasticity given by the minimum of the following two equations

$E_{test,1} = \left[1 - 2.7V_E/\sqrt{n}\right]E_{0.05}$, $E_{test,2} = \left[1 - 0.7V_E/\sqrt{n}\right]E_{mean}$

E_{mean}, $E_{0.05}$, V_E =average value, lower 5th percentile value and coefficient of variation of test data

4. Manufacturers A, B, C, taken collectively, are the GLTAA manufacturers who regularly market GL13 with a GLTAA mark. It was considered appropriate to pool this data as being representative of GLTAA mark GL13 product.

Table 5 Pooled data for manufacturers A, B, C combined. Actual values in *MPa*

Manufacturer	$f'_{b,test}$	$\frac{f'_{b,test}}{f'_b}$	$f'_{t,test}$	$\frac{f'_{t,test}}{f'_t}$	$f'_{s,test}$	$\frac{f'_{s,test}}{f'_s}$	E_{test}	$\frac{E_{test}}{E}$
A + B + C	35.3	1.07	22.9	1.43	3.3	0.89	15480	1.16
COV	0.20		0.21		0.22		0.11	

Table 6 Recommended amended GL13 values (in *MPa*) for inclusion in AS1720.1

	f'_b	f'_t	f'_s	E
Current	33	16	3.7	13300
Proposed	33	21	3.3	13300

5. There is a problem with manufacturer A that requires investigation. Although the finger joint strengths are excellent, the glulam strengths in both tension and bending are lower than that of other GLTAA members and of the GL13 target. There is also a marginally acceptable E value indicating a possible problem with laminating stock.

6. The collective result for manufacturers A + B + C show that GL13 from GLTAA members is being supplied at levels in excess of the AS1720.1 specification.

7. Manufacturer D supplies GL10 and, due to a misunderstanding, did not deliver GL13 product for the purposes of this investigation. This is not regarded as difficulty for the industry as the material is marketed as GL10.

8. Manufacturer E supplies GL17 and would deliver such product if requested to deliver GL13. There is a problem with pooling this data with other GL13 data in that the lower 5th percentile value does not change but the coefficient of variation is markedly altered.

9. The glulam for manufacturer F was purchased in the market place and was sold to Monash as GL13. Clearly this is a misrepresentation of the product with bending strengths at around one half of the required level and bending stiffness at 0.75 of the required level. Tension strengths are also extremely low relative to those of other manufacturers.

2.2.4 Recommendations

Some minor adjustment is recommended to the GL13 design values for glulam; see Table 6.

- The bending strengths are approximately correct. The test data indicates that 33 *MPa* is very close to the correct value on the basis of the test data. Given the data collected in this test program, the pooled industry data (Manufacturers A, B, C) is 7% above this figure at 35.3 *MPa*.

- Across the board tension strengths (manufacturer F excluded) are understated. It is recommended that a value of 20 *MPa* be adopted which represents a 25% relative to the current 16 *MPa*. When the GL grade figures were set it was anticipated that the tension values would be conservative. This action was necessary at the time because of the lack of test data.

- Shear strengths are overstated because lower grade material is sometimes used in the inner laminations. A drop in value to 3.3 *MPa* is recommended for grades GL13 and below. Although only GL13 was targeted in this test program, it is unlikely that the GL grades below GL13 would use better material in the inner laminations.

- The *E* values are conservatively stated which could lead to the introduction of a grade in-between GL13 and GL17 in the future. For the present it is recommended that the *E* value remain at 13300 *MPa*.

Table 7 Bending strength of glulam members

	Bending strength (MPa)					
	Manufacturer A	**Manufacturer B**	**Manufacturer C**	**Manufacturer D**	**Manufacturer E**	**Manufacturer F**
Mean	38.6	48.6	49.1	33.7	74.5	26.1
Standard Deviation	7.0	10.1	5.1	6.9	10.1	4.8
Coefficient of variation	18%	21%	10%	20%	14%	18%
Lower 5th percentile value[2]	27.7	35.7	40.6	23.7	60.2	19.8
Normalized characteristic bending strength $R_{k,norm}$	29.2	36.5	46.8	23.8	66.8	17.6
Mean Density kg/m^3	513	645	617	510	722	496
Mean M.C.	8.9%	7.5%	9.9%	11.1%	12.6%	10.3%
n	20	20	20	15	20	20

---

[2] Lower 5th percentiles have been determined using Microsoft Excel functions. AS/NZS 4063 recommends a non-parametric fit of the data using interpolation after ranking values and assigning a cumulative frequency equal to (i – 0.5) / n. Excel uses (i – 1) / (n – 1) for the cumulative frequency. Practical experience shows that the two procedures produce almost identical lower 5th percentile values for specimen sizes of around 30. For the lower 5th percentile, with 30 test results, instead of being the second lowest value will lie midway between the second and third lowest values.

Table 8 Tension strength of glulam members

	Tension strength (MPa)					
	Manufacturer A	**Manufacturer B**	**Manufacturer C**	**Manufacturer D**	**Manufacturer E**	**Manufacturer F**
Mean	24.9	30.4	36.9	19.2	48.3	13.7
Standard Deviation	2.3	5.2	5.0	3.9	8.2	3.0
Coefficient of variation	9%	17%	13%	20%	17%	22%
Lower 5th percentile value	21.1	23.0	29.2	13.9	36.6	9.4
Normalized characteristic tension strength $R_{k,norm}$	24.1	23.1	31.3	13.3	37.3	8.9
Mean Density kg/m^3	503	657	608	478	713	480
Mean M.C.	9.6%	10.1%	9.1%	12.6%	11.5%	11.3%
n	10	9	10	9	10	10

Table 9 Shear strengths of glulam members

	Shear strength (MPa)					
	Manufacturer A	**Manufacturer B**	**Manufacturer C**	**Manufacturer D**	**Manufacturer E**	**Manufacturer F**
Mean	4.6	6.1	5.8	4.6	6.1	5.8
Standard Deviation	1.3	0.7	0.9	0.6	0.6	0.9
Coefficient of variation	29%	10%	15%	13%	10%	15%
Lower 5th percentile value	3.1	5.1	4.7	3.9	5.2	4.7
Normalized characteristic shear strength $R_{k,norm}$	2.6	5.5	4.9	4.2	5.9	4.9
Mean Density kg/m^3	510	637	596	519	722	532
Mean M.C.	8.6%	7.7%	10.3%	10.5%	10.6%	11%
n	10	8	10	10	13	10

Table 10 Bending modulus of elasticity of glulam members

	Bending modulus of elasticity (MPa)					
	Manufacturer A	**Manufacturer B**	**Manufacturer C**	**Manufacturer D**	**Manufacturer E**	**Manufacturer F**
Mean	13490	16560	16860	10430	17810	10190
Standard Deviation	870	1100	750	530	740	1480
Coefficient of variation	6%	7%	4%	5%	4%	15%
Lower 5th percentile value	12630	14890	15570	9640	16890	8080
Normalized characteristic modulus of elasticity *E*	13350	16390	16740	10340	17700	9960
Mean Density kg/m^3	513	645	617	510	722	496
Mean M.C.	8.9%	8.9%	9.9%	11.1%	12.6%	10.3%
n	20	20	20	15	20	20

Table 11 Finger joint bending strengths.

	Bending strength (MPa)					
	Manufacturer A		**Manufacturer B**	**Manufacturer C**	**Manufacturer D**	**Manufacturer E**
	Inner laminations	Outer laminations	Inner and Outer laminations	Inner and Outer laminations	Inner and Outer laminations	Inner and Outer laminations
Mean	42.4	64.8	55.4	63.7	41.8	78.0
Standard Deviation	6.3	10.4	10.9	6.9	6.4	9.1
Coefficient of variation	15%	16%	20%	11%	15%	12%
Lower 5th percentile value	33.1	51.3	34.8	52.9	32.7	64.5
Normalized characteristic bending strength $R_{k,norm}$	36.8	56.5	37.8	62.4	36.4	75.5
Mean Density kg/m^3	478	560	632	585	520	710
Mean M.C.	10.1%	9.6%	9.7%	9.1%	13.0%	11.2%
n	30	30	50	58	31	60

Table 12 Finger joint tension strengths.

	Tension strength (MPa)					
	Manufacturer A		**Manufacturer B**	**Manufacturer C**	**Manufacturer D**	**Manufacturer E**
	Inner laminations	Outer laminations	Inner and Outer laminations	Inner and Outer laminations	Inner and Outer laminations	Inner and Outer laminations
Mean	21.9	30.3	26.1	20.2	19.1	39.3
Standard Deviation	9.3	4.5	5.3	5.3	7.1	10.4
Coefficient of variation	42%	15%	20%	26%	37%	27%
Lower 5th percentile value	7.4	23.4	19.1	12.2	9.6	25.9
Normalized characteristic tension strength $R_{k,norm}$	6.4	25.6	20.4	12.1	8.4	26.4
Mean Density kg/m^3	564	582	613	581	475	702
Mean M.C.	11.0%	10.2%	9.5%	9.3%	12.3%	13.0%
n	20	40	40	30	30	49

Table 13 Modulus of elasticity of laminations used subsequently to construct glulam members.

	Bending modulus of elasticity (MPa)					
	Manufacturer A		**Manufacturer B**	**Manufacturer C**	**Manufacturer D**	**Manufacturer E**
	Inner laminations	Outer laminations	Inner and Outer laminations	Inner and Outer laminations	Inner and Outer laminations	Inner and Outer laminations
Mean	8800	13110	13750	14290	8090	13200
Standard Deviation	1440	1350	1560	1520	830	1610
Coefficient of variation	16%	10%	11%	11%	10%	12%
Lower 5th percentile value	5960	11550	10930	12360	6490	9930
Characteristic modulus of elasticity *E*	8210	12940	13600	14140	7990	13060
Mean Density kg/m^3	478	560	632	585	520	710
Mean M.C.	10.1%	9.6%	9.7%	9.1%	13.0%	11.2%
n	120	60	180	180	120	120

The individual test results are shown in the Appendix.

3 OBJECTIVE 2 CAPACITY FACTOR FOR AUSTRALIAN GLULAM

3.1 Introduction

According to Ravindra and Galambos[3] (1978) strength limit states are defined according to eqn 1

$$\overline{R}e^{-0.75\beta V_R} = \overline{S}e^{0.75\beta V_S} \qquad 1$$

where

$\overline{R}$, $\overline{S}$ = mean values of resistance and load actions
β = reliability index
V_R , V_S = coefficient of variation for resistance and load actions

There exists a problem in how to select β values that make LSD and working stress methodology give approximately the same results. Leicester[4] has undertaken a study that concluded that, for domestic construction, $\beta = 3$. By introducing the lower 5th percentile strength and other manipulations it can be shown that the capacity factor is given by eqn 2

$$\phi = k_{com}\left(\frac{\overline{R}}{R_{0.05}}\right)e^{-0.75\beta V_R} \qquad 2$$

where
k_{com} = committee factor
$R_{0.05}$ = lower 5th percentile strength

It is usual to assume that the member resistance follows a log-normal distribution for which $\overline{R}/R_{0.05} = 0.9903e^{1.7878V_R}$; see Figure 5.

It has been accepted that the reliability index that is to apply to timber structures should lie within the range 3 to 4, specific values are given below:

Domestic & secondary elements in industrial structures	Primary elements in industrial structures	Primary elements in essential and post-disaster structures
3	3.5	4

The value of K_{com} has never been discussed directly by TM001 nor is its chosen on a consistent basis that is consistent with eqn 2 which is supposedly its basis. It therefore appears appropriate to set $k_{com} = 1$ and to allow the industry sectors to build conservatism into the characteristic strength and stiffness values cited in the associated material specific tables, eg, AS1720.1, Table 7.1. Bearing in mind that the members in bending dominate timber construction, this action is further justified in the case of glulam by the fact that, in this study, GL13 bending strength is understated by 7% and MOE by 16%.

---

[3] Ravindra, MK, Galambos, TV, Load and resistance factor design for steel, JStructDiv, ASCE, 104, ST9, 1978.
[4] Leicester, RH, Mud map to AS 4063, Unpublished paper, March 1999.

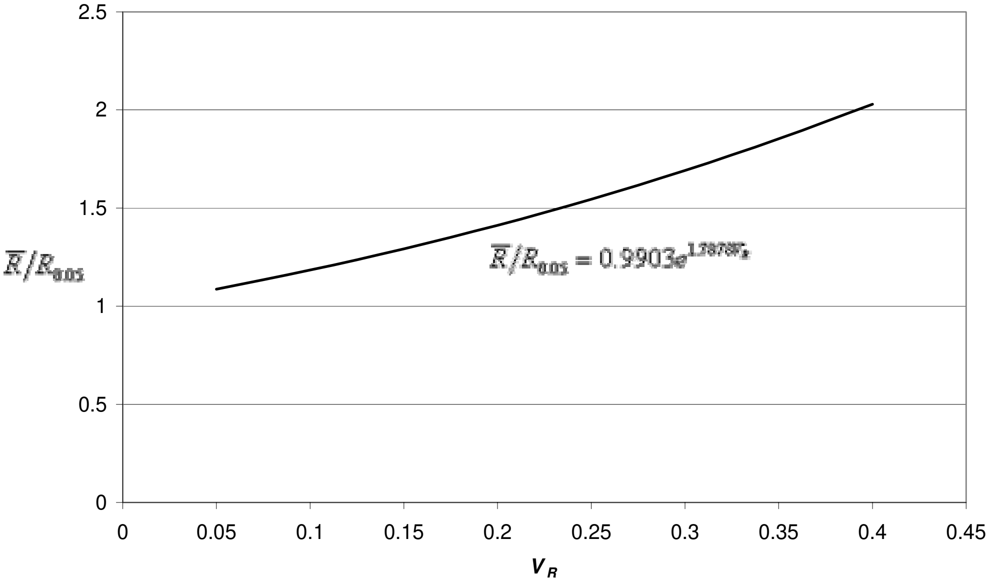


Figure 5 Ratio $\left(\overline{R}/R_{0.05}\right)$ versus V_R for a log-normal distribution.

This leads to the Table 14 capacity factors with $k_{com} = 0.9$.

Table 14 Capacity factors estimated for calibration with AS1720.1 according to eqn 2. In computing the values a log-normal distribution was assumed and $k_{com} = 0.9$. Note that log-normal usually provides the most conservative value of the ratio $\left(\overline{R}/R_{0.05}\right)$ for the statistical distributions used to define timber strengths.

V_R	3	3.5	4	V_R	3	3.5	4
0.10	0.95	0.91	0.88	0.88	0.79	0.72	0.88
0.11	0.94	0.90	0.87	0.87	0.78	0.71	0.87
0.12	0.94	0.89	0.86	0.87	0.78	0.70	0.87
0.13	0.93	0.88	0.84	0.87	0.77	0.70	0.87
0.14	0.93	0.88	0.83	0.86	0.76	0.69	0.86
0.15	0.92	0.87	0.82	0.86	0.76	0.68	0.86
0.16	0.92	0.86	0.81	0.85	0.75	0.67	0.85
0.17	0.91	0.85	0.80	0.85	0.75	0.66	0.85
0.18	0.91	0.85	0.79	0.85	0.74	0.66	0.85
0.19	0.90	0.84	0.78	0.84	0.73	0.65	0.84
0.20	0.90	0.83	0.78	0.84	0.73	0.64	0.84
0.21	0.90	0.82	0.77	0.84	0.72	0.63	0.84
0.22	0.89	0.82	0.76	0.83	0.72	0.63	0.83
0.23	0.89	0.81	0.75	0.83	0.71	0.62	0.83
0.24	0.88	0.80	0.74	0.83	0.70	0.61	0.83
0.25	0.88	0.80	0.73				

The Table 14 data is shown graphically in Figure 6.

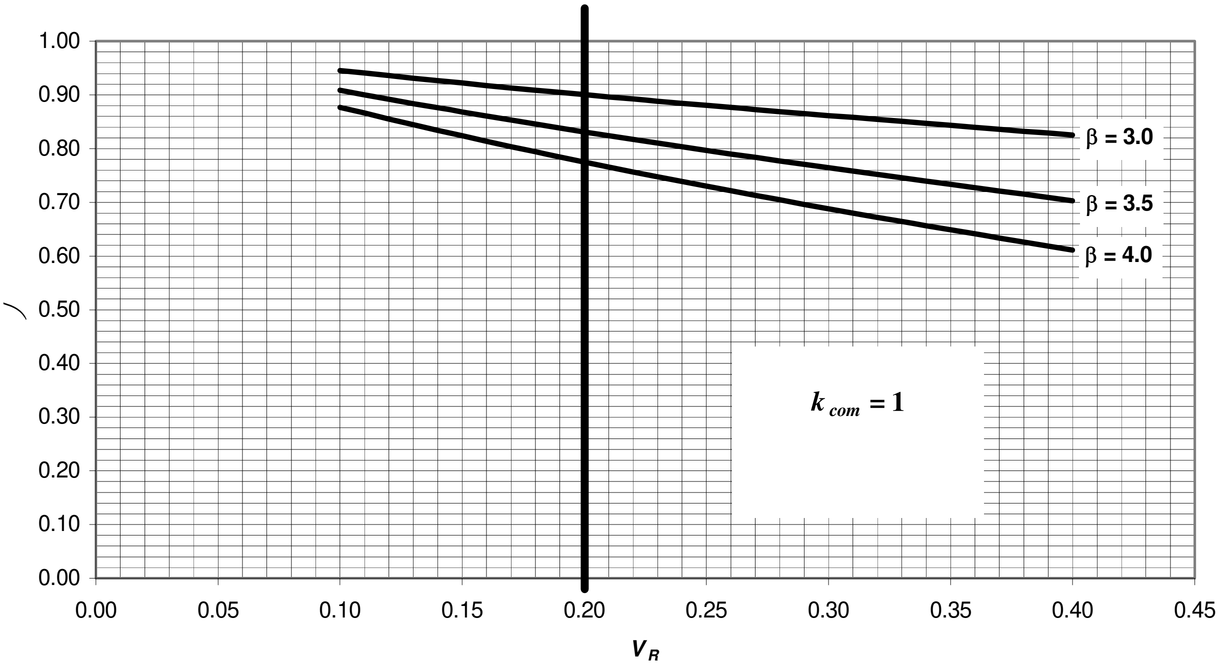


Figure 6 Capacity factor as a function of V_R.

3.2 Estimate of Capacity Factor Based on Test Data

The coefficient of variation of glulam has been shown to approximate 0.2 indicating values of ϕ = 0.90, 0.83, 0.78 or rounded values of 0.90, 0.80, 0.75 on the basis of eqn 2.2. The current values of 0.85, 0.70, 0.65 are too conservative. Building in some element of conservatism, the values shown below are recommended for adoption.

3.3 Recommendations

The recommended values of capacity factor to be cited in AS1720.1, Table 2.5 should be

All structural elements in houses and secondary structural elements in structures other than houses	Primary structural elements in structures other than houses	Primary structural elements in structures intended to fulfil an essential services or post disaster function
0.90 (0.85)	0.80 (0.70)	0.75 (0.65)

Figures in brackets represent values currently listed in AS1720.1, Table 2.5.

On the basis of finger joint strength data collected by the GLTAA Inspectorate over a number of years it is not believed that coefficients of variation of other glulam grades differ substantially from those in GL13.

Detailed discussion of values adopted for the committee factor and capacity factor is given in Appendix B. This discussion is written as a response to comments made by a reviewer.

4 OBJECTIVE 3 RELATIONSHIP BETWEEN LAMINATION AND GLULAM DESIGN VALUES

A reason for undertaking this study was some uncertainty of the method for computing glulam characteristic values from finger joint values in spite of the fact that this is done universally in various standards. From a theoretical (fracture mechanics) point of view, the finger joints and defects of the outer laminations of structural glulam are reinforced by the inner laminations which reduce the stress intensity factors or *J-integrals* at the tips of fingers and around knots. Very few studies of this type have been carried out and then only on specific finger geometries. Studies by Bui at Monash show how relatively small amounts of fibre plastic reinforcement placed over finger joints rapidly reduce J-integral values.

Herein a simpler approach has been adopted of obtaining ratios of measured finger joint strengths in tension and bending to glulam strengths. Unfortunately the study has not been successful due to the fact that considerable material is machined off finger joint specimens after they are laminated into a glulam member. A major reason that this causes problems getting a consistent relationship is that defects are often present in the finger joint test specimens. This was very apparent in one case where the back of the finger joint was breaking away due to an incorrectly sharpened finger cutter. While this affected the finger joint strength, which is measured on a specimen that is not subsequently dressed down, it does not affect the lamination within the glulam where the finishing operations effectively machine out the defect

As a consequence, it is likely that, in the future, dressing of finger joint test specimens will be required in the standard (AS/NZS 1328).

5 OBJECTIVE 4 COMPUTER SOFTWARE FOR STATISTICAL QUALITY CONTROL

5.1 Introduction

All accredited GLTAA members are required to have plant manuals with detailed "Instructions" that relate to product quality, irrespective of company size. Such manuals detail the following critical issues - laminating stock and adhesive purchasing, finger profiles, finger cutter sharpening, and cutting methods, adhesive mix details, adhesive application, preparation of laminations and lay-up methods, curing, finishing, in-house testing. Instructions are required to be on display at work stations thus ensuring a high level of process control.

In addition, GLTAA members are required to measure, in-house on a daily basis, indicators of the quality of the finished product. Under current AS/NZS1328 rules this involves observing the finger joint strengths and measuring face bond quality. The proposal below sets out a means by which finger joint strengths can be made available in-house and to the GLTAA Inspectorate as the tests are performed and it provides a means by which the data will be available to track long-term trends within the industry.

5.2 Scheme Outline

Prior to this project, it was the practice of individual manufacturers to record their in-house data on hand written sheets which were collected by Inspectors during auditing, forwarded to the Inspectorate and simply filed. At the outset of this project it was thought that Statistica, with some further development, could be used as vehicle for pooling data. The final system adopted is based on Excel.

5.2.1 Data Management

Input All GLTAA members will install copies of an Excel based computer program through which they will enter data. The data input will be processed by existing software that converts failure loads and deflections into MOR values. Because of differences in test equipment it has not been possible to write a completely universal Excel program. Some manufacturers have already linked this pre-processing to the QA spreadsheet. The data is also emailed to Monash University.

Data security Given the importance of the data received from GLTAA members, special attention will be given to safe storage and to avoid accidental loss of data. Various multimedia and storage devices will be employed to achieve this purpose. In addition to the copy of data stored by each individual manufacturer in the plant, a copy of each file will be saved on receipt onto (a) two local computers at Monash (b) Monash server (up to 100MB of data) (c) Compact discs.

5.2.2 Data Processing

The data is entered into the Excel spreadsheet at each manufacturer's plant on a batch or daily basis – 3 finger joint bend test results per batch or day. This data is processed at the local site to provide a screen output that indicates whether or not the batch or daily production has passed. The pass/fail decision is made on the basis of the minimum of the 3 test results exceeding the lower 5th percentile strength required to meet the GL grade requirements and the average of the last 15 test results. This value is computed using formulae provided in AS/NZS 4063 and AS/NZS1328 and AS/NZS1491; see details below. A message is printed out indicating if the batch passes or fails the criteria.

On a monthly basis this data will be forwarded to Monash University where Shewhart charts will be prepared showing the individual results as a series of diamond markers and the last 15 results average as a continuous line plot. Lower Control Limits (LCLs) are shown for the minimum of the last 3 test results and the last 15 mean. The Shewhart charts will then be returned to the individual companies so that more gradual degradation in glulam properties can be detected.

Annual Shewhart charts will be prepared with individual manufacturers identified only by a code so that manufacturers can compare their performance with the industry average. It is expected that this information will be reviewed at the GLTAA,s AGM.

5.3 Mathematical Basis for Data Processing

AS/NZS 1328.1:1998, eqn 3, indicates that the beam and finger joint strengths are related by

$$f_b^{'} = 0.75(1 + 0.1S_{\min})f_{b,ej}^{'} \qquad 3$$

where

$f_b^{'}$ = characteristic strength of glulam grade

$f_{b,ej}^{'}$ = characteristic strength of the finger joints in bending about the minor axis

$S_{\min}$ = minimum spacing of finger joints in the outer zone laminations

This formula can be inverted to give

$$f_{b,ej}^{'} = \frac{1.33 f_b^{'}}{\left(1 + 0.1S_{\min}\right)} \qquad 4$$

The finger joints characteristic strength, $f_{b,ej}^{'}$, is related to the lower fifth percentile strength, $f_{b,ej,0.05}$, by a relationship given in AS/NZS 4063

$$f_{b,ej}^{'} = \frac{1.35}{\phi}\frac{f_{b,ej,0.05}^{'}}{\left(1.3 + 0.7V\right)} \qquad 5$$

where $\phi = 0.8$

This relationship can be rearranged to relate the finger joint fifth percentile and its characteristic strength values

$$f_{b,ej,0.05} = \frac{\phi}{1.35}\left(1.3 + 0.7V\right)f_{b,ej}^{'} \qquad 6$$

To avoid reference to AS/NZS4063 laminators are simply told that their finger joints must comply with AS/NZS 1491 (the finger jointing standard). This gives equation 4 in the form

$$f_{b,ej,0.05} = \frac{\phi}{1.35}\left(1.3 + 0.7V\right)f_{b,ej}^{'} = \left(0.77 + 0.4V\right)f_{b,ej}^{'} = k_A f_{b,ej}^{'} \qquad 5$$

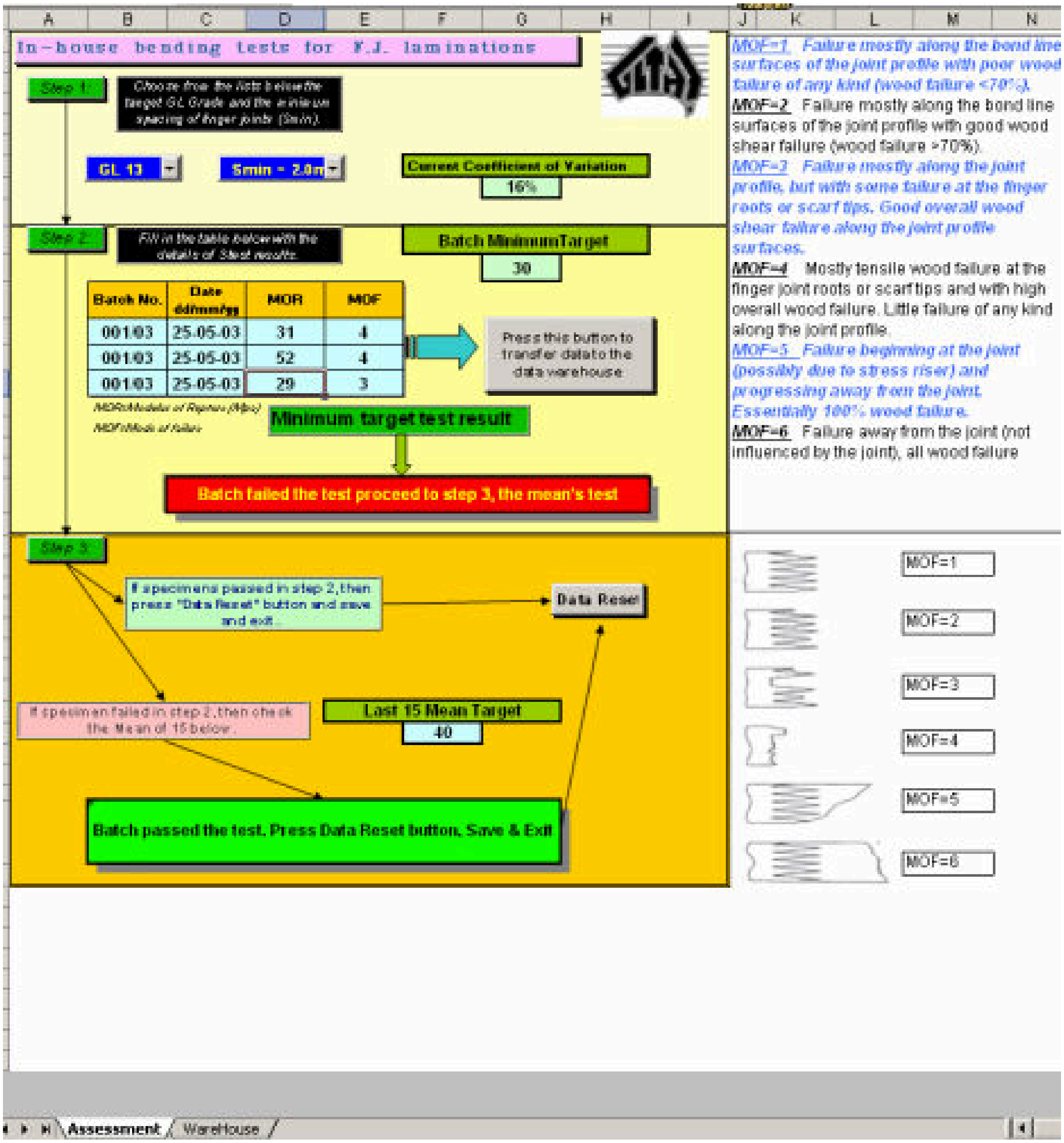
Combine equations 5 and 2, this will give the target fifth percentile strength of the finger joints by

$$f_{b,ej,0.05} = k_A \frac{1.33}{\left(1+0.1S_{\min}\right)} f_b^{'} = \frac{1.33\left(0.77+0.4V\right)}{\left(1+0.1S_{\min}\right)} f_b^{'} \qquad 6$$

A batch passes if the strength of all 3 test specimens are greater than the value given in equation 5, i.e., if $f_{\min,batch} \geq f_{b,ej,0.05}$. Occasionally this will not happen due to statistical accident, if this happens then the last fifteen results are averaged to give $\bar{f}_{b,15}$ and this average value must exceed $k_A k_B f_{b,ej}^{'} = k_A k_B \frac{1.33}{\left(1+0.1S_{\min}\right)} f_b^{'}$. Values of the factor k_B are given in AS/NZS1491, Table 1 or can be calculated from $k_B = 0.99e^{1.851V}$.

5.4 Data Presentation for QA Purposes

All these calculations were automated in a user friendly EXCEL spreadsheet, so that the laminator will be able to automatically process their in-house finger joint bending results; see Figure 7.



Choose from the lists below the target GL Grade and the minimum spacing of finger joints (Smin).

Fill in the table below with the details of 3test results.

Batch No.	Date dd/mm/yy	MOR	MOF
001/03	25-05-03	31	4
001/03	25-05-03	52	4
001/03	25-05-03	29	3

MOR:Modulus of Rupture (Mpa)
MOF:Mode of failure

Press this button to transfer data to the data warehouse

If specimens passed in step 2, then press "Data Reset" button and save and exit .

If specimen failed in step 2, then check the Mean of 15 below .

MOF=1 Failure mostly along the bond line surfaces of the joint profile with poor wood failure of any kind (wood failure <70%).

MOF=2 Failure mostly along the bond line surfaces of the joint profile with good wood shear failure (wood failure >70%).

MOF=3 Failure mostly along the joint profile, but with some failure at the finger roots or scarf tips. Good overall wood shear failure along the joint profile surfaces.

MOF=4 Mostly tensile wood failure at the finger joint roots or scarf tips and with high overall wood failure. Little failure of any kind along the joint profile.

MOF=5 Failure beginning at the joint (possibly due to stress riser) and progressing away from the joint. Essentially 100% wood failure.

MOF=6 Failure away from the joint (not influenced by the joint), all wood failure

Figure 7 Screen shot of the spreadsheet designed to process the finger joint bending test data for the laminators. This screen is used to make daily decisions about the current batch. It does not require Shewhart charts. Note that the Mode Of Failure (MOF) is also entered.

The test data will be received on monthly basis from the laminators. This data will be processed for each individual laminator and Shewhart charts will be produced for each Laminator-GL grade combination on quarterly basis. See Figure 8 for a sample. The Shewhart charts, especially the "last 15 average" line is useful in detecting slow degradation in processing such as might arise if a finger cutter was degrading and had somehow gone undetected.

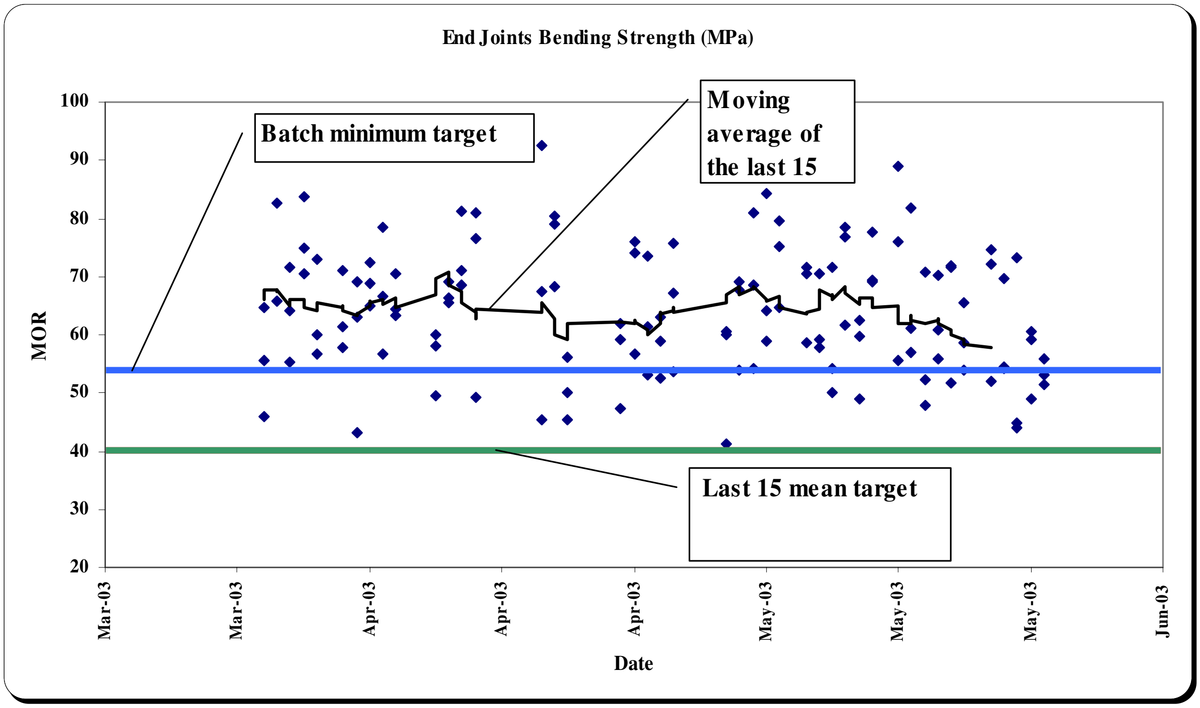


Figure 8 A sample Shewhart chart produced for a laminator, where

- Last 15 mean target = $\bar{f}_{b,15}$ = mean of the 15 most recent test results,
- Batch minimum target = $f_{b,ej,0.05}$ = minimum of the 3 test results taken from the current batch.
-

The current batch passes the test if either one of the above conditions is satisfied. The value of the Shewhart chart rests with its being capable of indicating slow degradation in product quality as might be inferred with the last 15 average declining in the case illustrated above. This data is taken from the finger joint test results of Manufacturer B.

6 OBJECTIVE 5 QA OUTSIDE THE GLTAA MEMBERSHIP

The benefits of GLTAA accreditation are clear. The only manufacturer whose product does not comply with the requirements of GL13 glulam as specified in AS 1720.1 was not a member. The company has since decided to become a GLTAA member (unaccredited) which will, hopefully, result in considerable improvement in its performance.

APPENDIX A

DETAILED RESULTS

A.1 Bending strength and modulus of elasticity of finger-jointed laminations

A.1.1 Manufacturer A

OUTER LAMINATIONS			INNER LAMINATIONS		
Specimen ID	MOR	MOE	Specimen ID	MOR	MOE
1	59.6	14130	1	34.9	11650
2	70.1	11580	2	42	8400
3	61.6	12770	3	47.5	8480
4	70.5	12820	4	43.3	7050
5	57.4	16180	5	37.3	8360
6	62.9	12280	6	45.8	9170
7	65.9	13070	7	39.7	8810
8	70.2	13270	8	54.8	10390
9	80.5	14380	9	46.8	9340
10	66.3	13670	10	47.3	8580
11	72.1	15730	11	51.3	9560
12	58.5	12850	12	42.8	6100
13	69.6	12760	13	49.3	8610
14	50.9	11530	14	35.9	8890
15	70.3	13870	15	47.9	10000
16	74.2	13410	16	47.2	10930
17	65.7	14470	17	36.8	9930
18	72.1	12530	18	32.6	6660
19	58.0	12120	19	41	10050
20	35.8	11090	20	42.2	8400
21	73.3	12060	21	40.5	9110
22	54.0	12050	22	41.7	7910
23	76.8	16330	23	35.4	9190
24	85.5	14490	24	33.6	5870
25	59.2	12010	25	35.2	
26	57.4	11700	26	44.4	8860
27	78.9	13420	27	32	9710
28	57.5	12500	28	39.7	5720
29	57.3	12350	29	48.8	9990
30	51.8	11990	30	53.4	9560

A.1.2 Manufacturer B

Specimen ID	MOR	MOE		Specimen ID	MOR	MOE
1	58.5	14320		26	36.2	12580
2	51.3	13780		27	59.5	13060
3	63.7	13350		28	63.1	14840
4	37.2	12690		29	60.1	15130
5	67.4	14380		30	64.2	14860
6	66.1	13820		31	51.0	12660
7	37.7	12660		32	53.0	14660
8	57.9	14950		33	59.4	13470
9	52.9	15370		34	64.8	13690
10	62.3	14690		35	33.9	10690
11	62.8	14280		36	54.9	13910
12	60.0	14250		37	54.9	13360
13	35.9	11220		38	47.6	14080
14	54.5	14040		39	67.9	14340
15	64.9	16750		40	27.88	8200
16	61.6	13630		41	57.6	13160
17	65.4	14300		42	68.4	15710
18	33.0	14960		43	39.4	16480
19	59.2	15540		44	68.0	14710
20	60.6	13560		45	54.6	12910
21	60.3	12910		46	56.1	14230
22	64.7	15320		47	57.2	9150
23	52.9	12770		48	51.1	12420
24	66.6	14110		49	48.4	13860
25	72.9	13940		50	40.5	13620

A.1.3 Manufacturer C

Specimen ID	MOR	MOE
1	60.2	12650
2	59.6	12430
3	66.0	12670
4	57.2	13050
5	69.5	16570
6	61.2	14010
7	54.5	14750
8	77.0	16530
9	61.1	13850
10	73.4	15230
11	71.4	14660
12	55.2	12930
13	57.5	13180
14	48.5	13910
15	60.5	18380
16	51.8	11480
17	73.1	14950
18	69.6	14460
19	60.9	14630
20	67.3	16230
21	67.3	14800
22	53.1	14730
23	65.8	16000
24	68.4	13570
25	57.7	17600
26	57.7	16440
27	61.6	17490
28	62.3	11910
29	63.7	14790
30	75.9	14200
31	62.4	13350
32	76.4	15440
33	58.1	12440
34	68.4	13700
35	63.7	14400
36	60.2	14080
37	61.5	13390
38	60.5	13210
39	64.3	14050
40	56.2	15070
41	66.2	13710
42	51.6	12450
43	60.6	13170
44	64.4	12870
45	57.3	14020
46	56.6	11960
47	69.4	17520
48	74.3	13590
49	68.8	13440
50	74.5	16110
51	67.9	14740
52	57.9	14010
53	63.5	13030
54	69.3	13760
55	60.8	13540
56	72.9	15890
57	74.4	13510
58	65.6	14180

A.1.4 Manufacturer D

Specimen ID	MOR	MOE
1	49.8	8930
2	31.9	8080
3	49.0	8370
4	45.8	7250
5	37.3	7720
6	35.8	8700
7	42.8	8760
8	48.4	8210
9	47.1	8710
10	42.5	9440
11	42.3	9180
12	37.9	8060
13	32.1	7510
14	33.5	8420
15	34.8	8170
16	46.7	7900
17	39.9	6150
18	51.8	8820
19	36.2	6480
20	52.5	8620
21	40.0	8360
22	47.2	8440
23	47.7	8360
24	36.8	8060
25	50.6	7920
26	46.2	9330
27	33.8	6490
28	35.5	6940
29	37.4	7290
30	41.2	8130
31	49.8	8930

A.1.5 Manufacturer E

Specimen ID	MOR	MOE	Specimen ID	MOR	MOE
1	81.6	12030	31	73.1	13300
2	70.6	12970	32	83.3	14390
3	88.5	13210	33	76.1	12330
4	63.6	16010	34	79.6	14200
5	71.2	12040	35	87.3	14080
6	75.6	13350	36	84.4	15390
7	68.1	10680	37	81.5	13750
8	66.6	11970	38	88.6	12390
9	80.9	13330	39	70.5	13490
10	86.1	15430	40	70.4	11730
11	73.9	14140	41	64.5	11730
12	75.2	12870	42	78.7	14070
13	96.9	15610	43	80.1	12260
14	91.1	16520	44	72	9250
15	85.6	14510	45	65.3	11040
16	89.9	14910	46	83.2	14040
17	77.9	11070	47	75.9	12830
18	79.8	14280	48	76.2	14000
19	79.7	13310	49	65	9500
20	85.7	13280	50	89.5	12720
21	88.0	13680	51	77.3	13940
22	45.0	9770	52	67.3	12000
23	74.5	13110	53	84.5	14140
24	85.2	15750	54	85.8	15800
25	75.2	13500	55	67.5	12430
26	78.1	13610	56	76.9	9940
27	73.8	11780	57	87.7	15250
28	60.8	12550	58	89.6	14560
29	83.1	12390	59	80.3	12480
30	83.7	13380	60	79.4	14100

A.2 Tension strength test results

A.2.1 Manufacturer A

OUTER LAMINATIONS	
Specimen ID	**Tension Strength (MPa)**
1	34.3
2	28.6
3	33.2
4	25.3
5	31.3
6	33.7
7	40.4
8	29.3
9	29.9
10	24.8
11	35.2
12	29.7
13	27.8
14	28.9
15	33.1
16	22.7
17	33.5
18	27.1
19	34.4
20	23.4

INNER LAMINATIONS	
Specimen ID	**Tension Strength (MPa)**
1	33.6
2	37.0
3	27.5
4	32.9
5	31.8
6	34.2
7	32.0
8	34.7
9	17.4
10	16.7
11	27.0
12	35.8
13	14.3
14	26.5
15	21.1
16	14.8
17	10.9
18	29.9
19	35.5
20	18.1
21	14.9
22	31.5
23	28.2
24	13.1
25	25.6
26	26.4
27	22.8
28	14.9
29	12.0
30	10.3
31	17.0
32	15.7
33	20.4
34	16.4
35	25.0
36	22.9
37	5.8
38	5.6
39	7.5
40	9.3

A.2.2 Manufacturer B

Specimen ID	Tension Strength (MPa)		Specimen ID	Tension Strength (MPa)
1	21.9		21	33.2
2	24.0		22	35.4
3	24.4		23	17.6
4	23.1		24	22.2
5	23.9		25	20.7
6	32.4		26	29.4
7	32.8		27	26.0
8	34.6		28	19.8
9	21.5		29	34.6
10	35.1		30	33.6
11	22.7		31	24.9
12	29.9		32	25.2
13	22.6		33	22.8
14	19.0		34	31.0
15	23.2		35	21.0
16	26.4		36	22.1
17	27.7		37	22.4
18	20.1		38	28.3
19	25.3		39	34.0
20	19.1		40	31.8

A.2.3 Manufacturer C

Specimen ID	Tension Strength (MPa)		Specimen ID	Tension Strength (MPa)
1	21.8		16	20.8
2	22.4		17	12.5
3	24.2		18	21.4
4	17.9		19	31.2
5	13.7		20	26.3
6	16.6		21	21.0
7	17.4		22	18.7
8	20.4		23	13.3
9	23.1		24	11.4
10	19.1		25	20.7
11	16.6		26	34.1
12	19.6		27	16.7
13	18.4		28	25.1
14	23.7		29	25.4
15	11.9		30	21.0

A.2.4 Manufacturer D

Specimen ID	Tension Strength (MPa)		Specimen ID	Tension Strength (MPa)
1	14.3		16	30.0
2	13.9		17	17.7
3	25.5		18	34.1
4	15.5		19	21.8
5	20.6		20	20.9
6	22.9		21	12.3
7	14.1		22	15.4
8	24.3		23	33.5
9	16.3		24	23.6
10	11.3		25	7.9
11	14.6		26	10.1
12	30.3		27	15.2
13	26.7		28	20.0
14	9.1		29	13.0
15	22.2		30	14.3

A.2.5 Manufacturer E

Specimen ID	Tension Strength (MPa)	Specimen ID	Tension Strength (MPa)
1	25.8	26	28.2
2	40.6	27	33.9
3	48.3	28	40.6
4	47.8	29	54.0
5	26.0	30	28.8
6	43.7	31	42.1
7	61.6	32	44.0
8	29.5	33	34.9
9	28.5	34	37.8
10	44.7	35	38.1
11	49.8	36	48.4
12	41.4	37	31.0
13	55.5	38	62.0
14	46.4	39	33.9
15	26.7	40	31.1
16	23.7	41	29.7
17	33.4	42	18.2
18	35.9	43	29.0
19	54.5	44	51.8
20	45.4	45	37.0
21	32.1	46	45.4
22	38.0	47	29.6
23	53.9	48	34.0
24	35.6	49	55.5
25	36.2		

A.3 Modulus of elasticity along the finger-jointed laminations

A.3.1 Manufacturer A

OUTER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
1	12540	13560	12400
2	12490	11440	13050
3	13990	14160	14550
4	10840	12400	13810
5	15750	12670	12300
6	14870	15190	15510
7	13550	12530	13650
8	13100	13850	11450
9	14420	13220	13060
10	12830	13130	12360
11	13010	12700	14150
12	11700	12070	13400
13	15140	12350	14850
14	16680	10280	12270
15	15100	15840	16490
16	14760	11440	12750
17	14850	13440	12230
18	14340	12400	12890
19	14280	13170	12830
20	14740	12360	13430
21	12760	14460	13370
22	14370	12900	15650
23	14390	15850	14070
24	13540	12850	13440
25	13240	13590	13710
26	13630	14630	14510
27	12960	12320	13420
28	12980	14080	13270
29	13490	13280	14250
30	13860	13240	15060

OUTER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
31	12740	13800	11590
32	15710	15480	10820
33	12050	12640	13400
34	12050	13440	14010
35	15190	14580	15160
36	13190	13200	11470
37	15530	15100	14940
38	12810	11700	12330
39	13620	14120	13440
40	13270	14060	11690
41	11450	15840	12460
42	13290	15170	13500
43	14820	14250	17520
44	12280	13580	14630
45	12750	13390	13380
46	13460	13500	12500
47	11560	14140	11880
48	13920	12660	13100
49	13310	14250	14360
50	12480	11790	14050
51	14320	12630	13250
52	15370	13590	14290
53	13440	16010	15170
54	14160	13440	13590
55	12240	12830	12480
56	13620	13678	13160
57	12850	11956	14080
58	13670	12250	12550
59	12400	12500	14480
60	14920	13500	14968

INNER LAMINATIONS(Black text)			
Specimen ID	**E1**	**E2**	**E3**
1	8370	8430	8500
2	11750	6530	9910
3	9140	6770	7500
4	16140	7560	12690
5	10250	11820	5330
6	8600	8260	6720
7	9460	7410	3580
8	9170	9270	6620
9	10260	9220	7580
10	8230	7675	6875
11	10920	9520	10140
12	5910	12530	9270
13	8310	7850	10060
14	8670	10630	8150
15	11640	8330	11150
16	10220	10100	11970
17	9950	11000	10230
18	9170	8490	7727
19	15030	9610	9930
20	11830	12480	12620
21	8520	6660	10900
22	11000	10120	7650
23	8380	7680	10350
24	9100	10970	10150
25	7090	7540	8470
26	11000	10860	8370
27	11770	11650	8150
28	8170	8410	11820
29	9350	17140	9910
30	8730	11200	9890

INNER LAMINATIONS(Black text)			
Specimen ID	**E1**	**E2**	**E3**
31	9300	10720	9890
32	10690	9420	10520
33	8880	10190	8740
34	7500	7410	9950
35	9366	11900	11620
36	9980	10020	7460
37	8850	8644	11190
38	12910	12010	6630
39	8180	5870	8500
40	6880	11780	9350
41	9920	10670	10060
42	7610	10620	10440
43	10570	10090	8490
44	10000	11650	9440
45	4930	7800	9190
46	11350	9920	8270
47	10120	9480	6150
48	4090	7380	9690
49	9810	10110	7540
50	9050	11990	10010
51	7460	7100	10960
52	9420	10270	13710
53	11980	10690	7930
54	7940	11240	8670
55	10620	10330	11060
56	9490	8340	7000
57	7480	8190	10240
58	11360	9860	9520
59	10300	9110	9600
60	10050	9500	8430

INNER LAMINATIONS(Red text)			
Specimen ID	**E1**	**E2**	**E3**
1	9980	11610	8330
2	11800	12000	15430
3	7930	12010	13460
4	13880	10560	12450
5	8760	8530	9270
6	10900	11770	9390
7	10820	11620	10680
8	11520	10920	11450
9	11570	11000	12380
10	12090	7920	9590
11	11000	7380	11870
12	11560	10910	13670
13	9387	11960	9960
14	8970	9580	11000
15	9660	9840	11360
16	7450	8650	10460
17	11890	9770	10880
18	12170	13030	12630
19	9440	10710	7090
20	9040	13900	9850
21	10090	11330	9065
22	10530	11490	11190
23	8660	11040	11210
24	11820	11830	10660
25	11490	10150	11780
26	9430	11140	10580
27	9610	7610	13920
28	11350	10200	13710
29	9320	11070	11350
30	9390	10240	10430

INNER LAMINATIONS(Red text)			
Specimen ID	**E1**	**E2**	**E3**
31	11810	10820	12610
32	7290	11080	10290
33	6590	10920	11530
34	13020	13640	15080
35	10970	11450	10390
36	9750	9830	13020
37	13500	12670	11040
38	11080	11120	11380
39	12210	8680	11130
40	11260	10630	10750
41	10830	11590	10890
42	9820	11300	11160
43	12360	11010	10280
44	11150	10420	10700
45	10380	10180	9712
46	10860	9540	11160
47	10420	10620	10180
48	9769	12940	11010
49	8290	10080	11310
50	13570	9320	12230
51	12600	12200	10870
52	10500	12010	8950
53	9020	8830	9050
54	10410	12210	11350
55	12660	11340	11540
56	12000	10710	9390
57	9650	10310	13620
58	11180	11350	11580
59	7750	12340	10690
60	12430	10650	12130

A.3.2 Manufacturer B

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
1	14470	16590	18040
2	16720	17470	19790
3	17300	20170	20370
4	15250	15480	16480
5	17880	21990	19940
6	16070	17370	15950
7	19520	16200	12410
8	18320	15710	15640
9	17040	14410	16360
10	17900	19120	18510
11	14840	15880	15510
12	18980	19850	17590
13	15320	14030	16460
14	14700	15920	15770
15	16850	16280	15610
16	15590	15280	15920
17	15350	15790	17340
18	13940	13490	13990
19	16010	15070	15920
20	17280	19710	20680
21	14010	15910	10000
22	16800	12560	17840
23	15470	12310	16250
24	17630	14490	13960
25	14590	16740	20200
26	17250	9670	18670
27	17800	16200	17960
28	17550	15700	15790
29	16770	16750	17410
30	18080	16390	18270

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
31	14120	14420	16100
32	15380	15330	16290
33	16610	16910	15810
34	12680	18920	15680
35	21300	19380	16750
36	16040	15550	16350
37	15830	13990	16190
38	14070	16030	10000
39	17260	20430	19330
40	15740	19350	15260
41	20130	16350	14150
42	16190	16470	15690
43	16260	16810	14970
44	17580	15910	14450
45	14180	16000	20630
46	16520	15850	17740
47	17520	16480	16960
48	14680	15520	14180
49	20430	17420	17620
50	15730	16090	17500
51	14670	14270	19500
52	17600	15820	19730
53	17330	14810	14850
54	17420	15560	14060
55	14690	16300	16480
56	14110	15420	15410
57	15580	18900	21250
58	17250	18750	12150
59	18940	17010	14180
60	15790	18900	15590

OUTER & INNER LAMINATIONS

Specimen ID	E1	E2	E3
61	12460	14930	17370
62	15640	12180	14650
63	16040	14810	14710
64	16910	13710	13590
65	12810	13900	15510
66	13790	14000	13950
67	15340	13300	13980
68	13500	13480	15350
69	13840	14410	13300
70	15900	12380	15770
71	12550	9200	13710
72	14340	15410	15460
73	14790	15440	13750
74	12160	13750	15320
75	11890	17030	15480
76	14160	13520	12350
77	15510	14090	17080
78	13640	13820	15140
79	18780	13840	13620
80	20210	16840	13530
81	15370	12250	15930
82	15230	15260	14370
83	11180	12060	13890
84	16830	15300	15950
85	13740	15310	13390
86	14010	17760	16680
87	10670	15420	11890
88	17060	12120	19120
89	16430	15940	10580
90	17710	17530	18660

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
91	14110	12140	15180
92	14620	13700	14070
93	8860	13610	15500
94	13950	11890	13300
95	15400	15650	16670
96	12100	11980	17000
97	16730	16920	18640
98	15660	15130	16140
99	13810	15860	15110
100	15110	13510	8730
101	14830	14500	15620
102	13510	12150	10800
103	13730	16920	13830
104	15170	16690	20180
105	13520	15050	15610
106	13910	12950	18930
107	16310	13110	8741
108	11430	13150	13910
109	14080	15580	15570
110	15760	14410	12640
111	15750	12620	16640
112	13670	12290	12590
113	15310	14420	15710
114	17660	15240	12500
115	15120	13890	13070
116	13530	13770	17380
117	16770	15710	17390
118	12020	18280	14630
119	17060	15400	18930
120	17080	15540	14010

OUTER & INNER LAMINATIONS

Specimen ID	E1	E2	E3
121	15120	14560	15650
122	13870	13660	17000
123	19610	15780	13920
124	14120	20390	17680
125	17330	19620	20000
126	18000	12020	13820
127	15000	16200	16540
128	15570	13890	17730
129	16380	14080	15470
130	15590	15700	15570
131	18060	13950	17650
132	16480	14310	15490
133	16770	16210	17170
134	15720	19800	15570
135	21090	16640	18190
136	18900	17110	20680
137	17410	17230	22560
138	14160	13660	15760
139	15600	14560	18080
140	17790	17300	20170
141	17220	13880	14250
142	17370	15600	15660
143	18620	19090	21190
144	17360	17370	18750
145	20270	18100	17090
146	15840	15620	17170
147	19190	19120	14010
148	18790	17310	17650
149	15400	16970	14020
150	15650	19980	18710

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
151	14670	15640	15860
152	17010	16170	14950
153	12060	17220	14590
154	20330	18860	21170
155	14570	13160	15430
156	20330	17290	15130
157	17530	15020	16850
158	15100	20320	20060
159	19920	19000	19060
160	16140	15560	15490
161	15860	16240	16390
162	20900	17220	14850
163	19140	16010	13560
164	17490	15400	13820
165	16510	16030	15490
166	15950	16220	14700
167	18770	17600	14100
168	14280	14970	18070
169	18770	18520	15300
170	17000	15770	17990
171	17410	18270	15160
172	15830	20810	19230
173	16040	14240	20570
174	18670	15850	18660
175	13020	15730	15110
176	15860	14140	15010
177	16130	16220	15820
178	14680	13950	16500
179	17250	16080	19000
180	19330	14150	15820
181	19870	15110	16180

A.3.3 Manufacturer C

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
1	16510	16680	16460
2	18200	16330	16410
3	18200	18400	18330
4	14080	16380	14860
5	16020	16560	16510
6	20240	18530	16810
7	18390	15230	15060
8	15890	14950	17140
9	16500	21070	19140
10	20120	19520	17770
11	16220	15740	17340
12	17330	15220	14790
13	14710	15470	15450
14	15460	15940	16720
15	21180	15340	15590
16	15620	14560	16110
17	17340	18760	16240
18	14140	16560	16990
19	16550	16730	17860
20	14710	13610	15800
21	19110	17630	16450
22	18070	16120	16270
23	17150	16010	20710
24	20710	18000	19430
25	17550	17320	14740
26	17090	17500	20190
27	16820	17870	17490
28	17530	17790	16490
29	15810	14430	13770
30	17310	16740	15540

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
31	14990	15960	14110
32	17340	15640	15890
33	16010	18990	17940
34	16460	16470	16190
35	14850	14690	15870
36	15870	16650	17510
37	14970	16850	16630
38	17720	17690	18320
39	18160	18370	18310
40	15850	17760	19200
41	15200	16320	15430
42	14890	17160	17120
43	14910	16320	16770
44	15410	17370	15650
45	18140	20400	18400
46	17410	15980	19720
47	16700	18600	17240
48	16230	17290	15920
49	20940	16040	16580
50	17090	16050	14130
51	19340	17790	16900
52	17640	17510	17580
53	14900	17860	15190
54	17970	18150	18020
55	18140	14670	19490
56	14380	16030	16700
57	18420	16500	18190
58	15060	18230	19830
59	21890	20100	15040
60	15650	16110	14000

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
61	18940	16470	16290
62	18520	16330	16410
63	18830	17990	17150
64	17190	16860	16430
65	17330	15930	19350
66	16990	19200	16870
67	19840	16750	16950
68	18500	19070	19590
69	14840	16720	18590
70	14360	15640	14290
71	20400	14510	17690
72	20230	18630	17830
73	16550	17850	16000
74	16810	20220	17640
75	16700	16090	18190
76	16750	19360	16760
77	17010	16880	17700
78	15930	16880	15440
79	17570	16860	18170
80	16920	17580	18860
81	17510	16830	16760
82	17030	17750	17910
83	17130	17660	16850
84	17410	19930	17710
85	15010	16960	14470
86	18150	17400	16720
87	15320	16110	17230
88	17830	17360	17200
89	16080	14740	15960
90	15570	19820	15720

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
91	15260	15950	15860
92	17130	16070	14950
93	15350	16570	14590
94	18090	18960	21170
95	20370	22690	15430
96	17770	18450	15130
97	18630	16740	16850
98	17700	18560	20060
99	15470	16240	19060
100	17290	16040	15490
101	18330	18250	16390
102	15560	15830	14850
103	16180	17270	13560
104	21610	18260	13820
105	18810	20446	15490
106	16550	16320	14700
107	14860	16470	14100
108	19650	16880	18070
109	17550	19100	15300
110	17750	17300	17990
111	20190	20150	15160
112	22030	22730	19230
113	17130	16880	20570
114	22710	21020	18660
115	19090	17890	15110
116	15690	17350	15010
117	16000	15720	15820
118	17860	18690	16500
119	18230	17070	19000
120	22180	14750	15820

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
121	16600	14890	15950
122	20410	20840	20590
123	20920	22970	17060
124	18380	17620	19600
125	15510	16760	16100
126	16110	16040	15070
127	17590	17010	16540
128	15650	17160	15750
129	17190	17450	18830
130	16000	19760	17870
131	18940	20100	15790
132	15490	16790	17590
133	17950	16690	18340
134	17760	17930	16750
135	15850	16850	16060
136	20350	18360	17970
137	16360	17550	16560
138	19720	19740	20250
139	16180	19430	18760
140	17800	16420	17270
141	19520	18180	19590
142	15670	16500	17350
143	16630	15980	15630
144	18240	16890	17610
145	19360	18800	20720
146	17130	17610	18970
147	20260	19980	20430
148	15670	19770	21960
149	18470	15920	18900
150	16510	17180	15780

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
151	16210	17320	20280
152	15650	15940	16810
153	18480	17660	15740
154	18650	18260	16580
155	17630	17050	17220
156	16750	17010	16470
157	17390	15370	14590
158	17160	16860	17010
159	18850	18620	18210
160	19500	18990	17350
161	16360	17480	16470
162	17300	17040	18430
163	16890	16120	18010
164	16900	18160	16180
165	14570	15290	17050
166	17040	18000	17060
167	14580	17080	17480
168	16640	15430	16920
169	16500	16580	16590
170	16290	17600	16190
171	16590	16450	16760
172	16640	18660	15760
173	17870	16950	18510
174	18370	15470	17110
175	18340	15840	17400
176	14660	15940	15730
177	16570	17420	18250
178	19040	18530	18790
179	16650	16500	17240
180	16860	15550	17140

A.3.4 Manufacturer D

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
1	8810	10270	11020
2	10580	8440	7400
3	8340	13320	13590
4	8120	10010	10960
5	10920	8110	9060
6	9670	9340	11750
7	6410	10420	13910
8	8920	10430	7870
9	6780	6360	10890
10	8250	9020	12500
11	12210	8460	9830
12	9700	10130	11590
13	9730	10430	10000
14	10830	9010	9920
15	7180	6750	11570
16	10210	10230	7480
17	10240	10570	12610
18	10280	9270	7170
19	11280	12510	7710
20	9450	9560	8490
21	13540	8660	6930
22	7800	8060	9750
23	9870	8970	12940
24	8090	7060	9190
25	16320	17020	10040
26	8930	11730	13300
27	10640	10790	10700
28	16470	16770	10650
29	11300	6530	9910
30	9490	13620	9640

OUTER & INNER LAMINATIONS

Specimen ID	E1	E2	E3
31	7270	9770	8870
32	8830	9210	7940
33	12660	9620	13620
34	10760	9130	14070
35	7200	6700	7420
36	11510	9690	11920
37	10000	10120	12730
38	7680	8690	13950
39	7940	7410	10900
40	5780	7860	7590
41	9190	9110	8370
42	8510	12810	9430
43	9880	12460	5460
44	10350	12120	6400
45	7210	7230	9210
46	7730	9200	11630
47	6340	6880	8270
48	9450	10970	10420
49	8780	12020	9940
50	8810	8150	10490
51	8160	10970	12780
52	15950	9290	8110
53	6500	12250	11500
54	7700	9530	10730
55	9690	9610	11410
56	10500	12690	16580
57	9570	7140	10160
58	10230	8180	13010
59	11310	8780	6880
60	10600	9010	5650

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
61	11040	12590	10700
62	9280	8450	9930
63	14190	12710	14140
64	13450	14680	13580
65	8550	13350	1260
66	7890	13890	13150
67	10620	9210	11900
68	6450	6420	12310
69	8590	8740	8610
70	8160	9140	10500
71	10790	8200	8400
72	7560	9760	10730
73	7690	12480	10810
74	8280	12630	11870
75	9970	12910	8480
76	12330	9180	14940
77	12560	6300	9290
78	11820	5440	9830
79	8060	13900	12130
80	8010	13450	18650
81	5510	12080	13020
82	6090	13110	13780
83	6920	9350	15130
84	7250	8720	13660
85	5360	9760	12240
86	6040	9190	12760
87	8700	13450	9900
88	6270	9410	11790
89	6010	9260	11160
90	11750	8240	8160

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
91	14430	8770	11560
92	12340	8930	8870
93	10970	10220	10680
94	11950	10800	8430
95	16300	9170	10090
96	13710	9210	10690
97	11040	12860	11550
98	11590	14720	12630
99	13310	7600	12580
100	10820	6910	12490
101	6600	8650	15540
102	6180	10540	17720
103	10520	6640	10690
104	12690	9230	10170
105	12130	9230	14560
106	10110	10430	5920
107	11850	7450	9590
108	9490	7140	11770
109	8590	10570	10630
110	6970	11280	10590
111	7620	5530	7100
112	10860	10260	8450
113	10360	11370	11450
114	11800	9720	10240
115	9050	10190	9860
116	8590	14790	11230
117	7840	6620	12550
118	10710	11230	9060
119	5200	14450	10800
120	6790	8670	9170

A.3.5 Manufacturer E

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
1	18730	15770	17680
2	15650	15470	15620
3	14820	16460	16050
4	18760	16580	16480
5	18870	17750	17520
6	14990	14400	17240
7	16170	14830	14130
8	16690	14450	16140
9	16830	16760	17830
10	16640	18330	
11	19220	15910	14670
12	18040	17500	19240
13	17110	16850	16710
14	17740	15180	14180
15	17620	16810	15660
16	16270	14970	14970
17	16830	16880	16350
18	16020	16320	12760
19	17640	17740	17430
20	15850	15690	14100
21	17650	17480	15810
22	17050	18420	17620
23	13940	18390	18950
24	14880	16330	14750
25	13280	17420	16790
26	14980	15020	14670
27	15140	15740	16450
28	17210	15210	16940
29	15520	18400	16160
30	14980	16040	15020

OUTER & INNER LAMINATIONS

Specimen ID	E1	E2	E3
31	16920	18360	17750
32	17290	17220	17450
33	15210	17430	15120
34	17500	18180	14730
35	18990	15550	16380
36	14630	19840	18820
37	14960	16450	17390
38	15250	16870	13760
39	21470	21300	13100
40	19540	18110	18280
41	15720	19660	18460
42	18570	20610	14330
43	19240	15590	15070
44	20250	21190	19880
45	16380	13440	20410
46	15860	15760	12750
47	17240	18250	16220
48	19580	17670	16780
49	15510	17620	14380
50	15120	16840	15280
51	16270	16240	15910
52	16030	16850	17280
53	16620	15620	16670
54	17580	16580	15460
55	21000	20490	16060
56	16300	18190	20440
57	12090	16430	17280
58	15400	16260	17970
59	16470	15460	14480
60	19150	13830	15660

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
61	17240	19560	15510
62	19950	16050	17370
63	17660	15710	17650
64	19050	18100	17330
65	16150	17650	17750
66	16940	17440	18710
67	17690	20420	13550
68	16360	16600	16060
69	16140	17520	16390
70	11820	15850	15600
71	20170	17800	15730
72	17880	18410	18930
73	20290	14910	15760
74	17670	18550	18030
75	13770	16290	15080
76	14710	14990	17850
77	17000	16380	16100
78	16940	17270	15850
79	20050	17780	15360
80	17590	17210	17540
81	16650	14730	14150
82	20000	16690	19150
83	16130	14910	16680
84	16100	10738	15300
85	18700	13260	15740
86	19480	18110	17510
87	15820	17250	18670
88	17200	18020	18580
89	17260	14160	15720
90	14540	19260	18060

OUTER & INNER LAMINATIONS			
Specimen ID	**E1**	**E2**	**E3**
91	19150	16180	14850
92	15980	18700	16400
93	16770	15660	18120
94	16030	16250	16720
95	16140	19110	18720
96	16810	14560	15690
97	15570	15790	15290
98	14730	21310	17780
99	16070	16820	16100
100	16730	17560	17820
101	16110	18720	14880
102	14260	15840	15980
103	13980	14500	17380
104	16690	12690	17170
105	17400	17960	16180
106	16630	17770	20180
107	15200	15000	15480
108	19270	20290	19210
109	19210	17560	17240
110	17800	14900	17870
111	15910	17140	18070
112	15670	15880	15400
113	14150	21770	17010
114	16020	19790	19480
115	17860	17380	17000
116	17980	17690	15320
117	18280	21210	20230
118	14930	15360	15980
119	18420	17630	15380
120	17850	17050	17290

A.4 Bending strength and modulus of elasticity of full size glulam beams

A.4.1 Manufacturer A

Beam ID	MOR (MPa)	MOE (MPa)
1	44.0	14320
2	45.5	13180
3	46.7	16710
4	48.8	13150
5	37.1	13650
6	35.9	13190
7	35.7	13520
8	31.4	12610
9	35.6	13450
10	42.1	13260
11	32.6	13050
12	33.2	13420
13	46.3	12710
14	25.9	13640
15	32.4	13140
16	45.8	13990
17	27.8	13740
18	34.6	12630
19	46.5	13250
20	43.3	13190

A.4.2 Manufacturer B

Beam ID	MOR (MPa)	MOE (MPa)
1	46.8	16270
2	46.3	14910
3	40.2	16540
4	47.7	16460
5	42.8	16650
6	51.8	17020
7	35.8	15640
8	50.7	15370
9	59.6	15340
10	33.7	16580
11	62.6	18150
12	43.5	14500
13	37.3	16900
14	73.5	17610
15	39.0	16960
16	46.1	15800
17	46.0	18220
18	59.6	18460
19	57.7	16300
20	52.0	17570

A.4.3 Manufacturer C

Beam ID	MOR (MPa)	MOE (MPa)
1	51.8	16880
2	45.8	16310
3	48.9	15150
4	56.1	17110
5	47.0	16900
6	52.2	17540
7	54.1	18420
8	40.6	17920
9	53.3	16820
10	49.5	17700
11	52.9	16510
12	44.1	16980
13	41.2	16470
14	46.5	16480
15	47.3	16450
16	40.0	17190
17	48.9	16580
18	55.8	17440
19	49.4	15590
20	56.2	16760

A.4.4 Manufacturer D

Beam ID	MOR (MPa)	MOE (MPa)
1	20.3	8850
2	25.2	10970
3	43.4	10380
4	37.6	10360
5	38.7	10980
6	38.3	10980
7	42.4	10260
8	28.9	10720
9	30.9	10750
10	40.7	10590
11	34.2	10520
12	37.7	10350
13	28.3	10400
14	32.7	9980
15	26.6	10390

A.4.5 Manufacturer E

Beam ID	MOR (MPa)	MOE (MPa)
1	85.0	18690
2	61.3	17610
3	63.6	17320
4	88.5	18030
5	69.3	17130
6	72.0	17790
7	81.7	17190
8	67.5	18850
9	60.5	16930
10	78.4	18400
11	74.3	17990
12	84.7	16120
13	74.8	18970
14	89.4	18280
15	53.6	17260
16	72.3	17600
17	86.7	18130
18	67.3	17210
19	79.1	17930
20	79.4	18790

A.5 Tension strength of full size glulam beams

A.5.1 Manufacturer A

Beam ID	Tension strength (MPa)
1	20.8
2	24.6
3	27.3
4	26.8
5	23.7
6	26.1
7	25.8
8	25.6
9	21.5
10	26.8

A.5.2 Manufacturer B

Beam ID	**Tension strength (MPa)**
1	32.5
2	23.2
3	34.8
4	30.6
5	28.5
6	22.9
7	39.5
8	31.0
9	31.0

A.5.3 Manufacturer C

Beam ID	**Tension strength (MPa)**
1	40.8
2	36.6
3	40.1
4	39.0
5	39.2
6	39.3
7	43.3
8	32.3
9	27.7
10	31.0

A.5.4 Manufacturer D

Beam ID	**Tension strength (MPa)**
1	20.0
2	24.5
3	14.1
4	20.8
5	13.8
6	20.5
7	24.2
8	18.1
9	16.8

A.5.5 Manufacturer E

Beam ID	**Tension strength (MPa)**
1	40.1
2	42.6
3	45.5
4	33.8
5	60.3
6	51.3
7	54.9
8	56.0
9	52.8
10	46.2

A.6 Shear strength of full size glulam beams

A.6.1 Manufacturer A

Beam ID	Shear strength (MPa)
1	3.2
2	3.9
3	3.9
4	3.3
5	6.6
6	4.9
7	6.6
8	4.7
9	3.1
10	5.8

A.6.2 Manufacturer B

Beam ID	Shear strength (MPa)
1	5.7
2	6.5
3	7.1
4	4.9
5	6.0
6	6.4
7	6.7
8	5.5

A.6.3 Manufacturer C

Beam ID	Shear strength (MPa)
1	6.5
2	5.5
3	6.7
4	5.3
5	4.8
6	5.6
7	7.2
8	6.6
9	5.3
10	4.6

A.6.4 Manufacturer D

Beam ID	Shear strength (MPa)
1	3.9
2	4.7

3	5.3
4	4.3
5	5.7
6	4.0
7	5.0
8	4.3
9	4.0
10	5.1

A.6.5 Manufacturer E

Beam ID	**Shear strength (MPa)**
1	5.6
2	6.3
3	6.5
4	7.0
5	5.2
6	6.0
7	5.8
8	5.8
9	6.8
10	7.0
11	5.2
12	6.5
13	6.1

APPENDIX B

CAPACITY FACTOR DISCUSSION

The Committee Factor k_{com} should be 0.9 and not 1.0 as assumed

The reviewer refers us to Leicester (1987)[5], and I quote, “From the derivation by Ravindra and Galambos (1978), the design strength of a member (or joint) is given by $R_{design} = k_{com} R_{mean} \exp(-0.6\beta V_R)$ ”. This expression is proposed by Leicester in this paper for use in conjunction with a safety index of $\beta = 4$. Somewhat later, in the same paper, Leicester gives

$$\phi = k_{com}\left(R_{mean}/R_{0.05}\right)\exp\left(-0.6\beta V_R\right) \qquad 1$$

and links this with $k_{com} = 0.9$.

In the so-called “mud map” Leicester, (1999), advocates

$$\phi = k_{com}\left(R_{mean}/R_{0.05}\right)\exp\left(-0.75\beta V_R\right) \qquad 2$$

k_{com} is not discussed. In report PN01.3700 equation 2 is used in conjunction with $k_{com} = 1.0$.

Taking a log-normal distribution for resistance values and using exponential approximation for the tail, $R_{mean}/R_{0.05} = 0.9903\exp(1.788V_R)$, the results from equations 1 and 2 are compared in Figure 1. At a 20% coefficient of variation there is very little difference in ϕ.

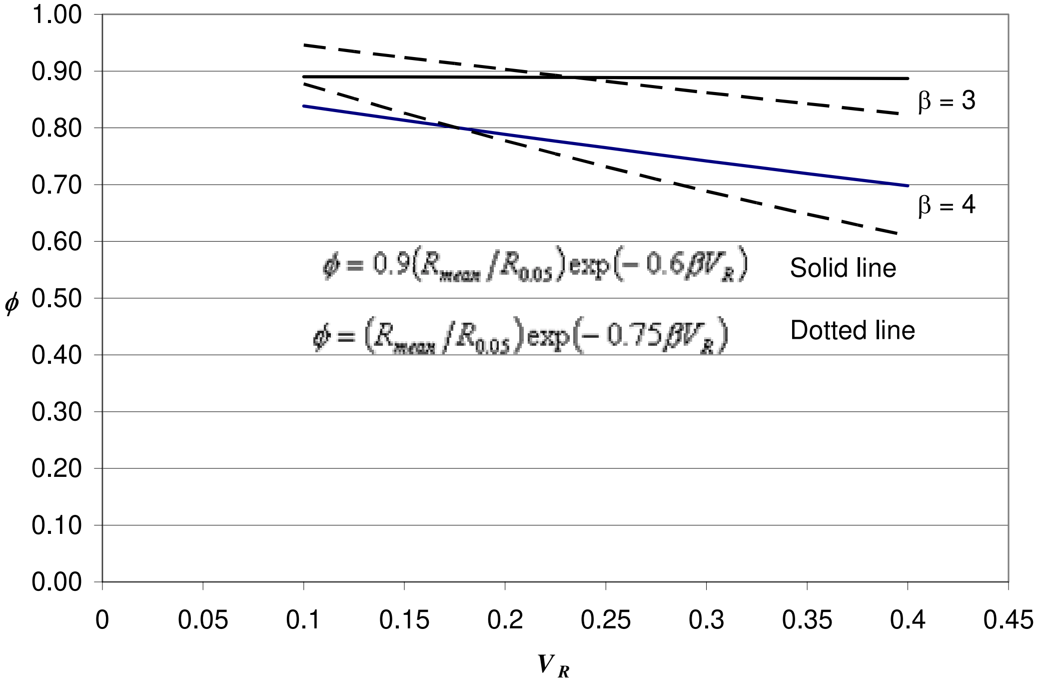


Figure 1 values of capacity factor obtained from equations 1 and 2.

Opinions of the Committee (TM-001 of Standards Australia)

---

[5] Leicester, RH, (1987) Load factors for proof and prototype loading, First National Structural Engineering Conference, Melbourne 26-28 August.

The reviewer also feels that TM-001 arrived at capacity factors based on the opinions of committee members. This may well be the case, but it is contended that these opinions lead to anomalous glulam capacity factors in Table 2.5.

It is possible to invert equation 2 to determine the committee factor, k_{com}, implicit in AS1720.1 Table 2.5

$$k_{com} = \phi\left(\frac{R_{0.05}}{R_{mean}}\right)e^{0.75\beta V_R} \qquad 3$$

For a log-normal distribution $R_{0.05}/R_{mean} = 1.0098e^{-1.7878V_R}$ so that equation 3 becomes

$$k_{com} = 1.0098\phi e^{(-1.7878+0.75\beta)V_R} \qquad 4$$

The two numerical studies detailed in Tables 1 and 2 can now be undertaken. Table 1 represents the current position of AS1720.1, Table 2.5. The V_R values for all materials except glulam have been assumed, the value for glulam comes from the current study and is the mean V_R value. Table 1 clearly shows that glulam was allocated lower k_{com} values across the board. The Table 2 values show the adjustment to k_{com} obtained by adopting the recommendations in the draft PN01.3700 Report. This balances the "committee factor" much better across a range of indices, β.

					3.0	3.5	4.0
	V_R	3.0	3.5	4.0	k_{COM}		
LVL	0.10	0.90	0.85	0.80	0.95	0.93	0.91
Plywood	0.15	0.90	0.80	0.75	0.97	0.92	0.91
Glulam	0.17	0.85	0.70	0.65	0.93	0.81	0.80
MGP & A17	0.30	0.85	0.70	0.65	0.99	0.91	0.94
Sawn	0.40	0.80	0.65	0.60	0.97	0.92	0.98

Table 1 Existing capacity and k_{com} factors implied by AS1720.1, Table 2.5.

					3.00	3.50	4.00
	V_R	3.0	3.5	4.0	k_{COM}		
LVL	0.10	0.90	0.85	0.80	0.95	0.93	0.91
Plywood	0.15	0.90	0.80	0.75	0.97	0.92	0.91
Glulam	0.17	0.90	0.80	0.75	0.98	0.93	0.93
MGP & A17	0.30	0.85	0.70	0.65	0.99	0.91	0.94
Sawn	0.40	0.80	0.65	0.60	0.97	0.92	0.98

Table 2 Amended capacity and committee (k_{com}) factors implied by adjusting AS1720.1, Table 2.5 capacity factors as recommended in Report PN01.3700.

Qualitative Discussion

It is perhaps unfortunate that Table 2.5 was ever presented in AS1720.1 as a normative section. It is supposedly an interpretation of AS1720.1, Table I1 which is also normative. The first set of capacity factors best match the description for the manufacturing and property monitoring of glulam and the second set of capacity factors in AS1720.1, Table I1 are the only ones that match the capacity factors given in AS1720.1, Table 2.5

	Houses = 3	Industrial buildings = 3.5	Post-disaster structures = 4
Basis of design property	Capacity factor		
	Contents of AS1720.1, Table I1		
• Established from in-grade evaluation • Low to medium material variability • High degree of process control during manufacture • Continuous monitoring and periodic monitoring of properties	0.90 **Set 1 best matches the way glulam manufacturing and property monitoring is carried out according to AS/NZS1328.**	0.80	0.75
• Established from in-grade evaluation • Medium to high material variability • Low degree of process control during manufacture • Continuous monitoring and periodic monitoring of properties	0.85 **Set 2 This is the only set of capacity factors in AS1720.1, Table I1 that match the glulam capacity factor values given in AS1720.1, Table 2.5.**	0.70	0.65
	Contents of AS1720.1, Table 2.5 for glulam		
	0.85	0.70	0.65

Assuming that the Table I1 and Table 2.5 capacity values are supposed to match, it follows that AS1720.1, Table 2.5 is inferring about glulam.

In-grade testing Glulam manufactured to AS/NZS 1328 properties are established from in-grade testing or least something equivalent – no argument there.

Material variability The implication is that glulam has medium to high variability. The issue of what constitutes low, medium and high variability is avoided in AS1720.1, Appendix I. If LVL at 10% is low and radiata pine at 40% is high, then glulam at 17% must surely lie in the low to medium range. There is a clear anomaly between Tables 2.5 and I1.

Process control It is also apparently thought that glulam manufactured to AS/NZS 1328 is produced with a low degree of process control. This also cannot be agreed. The process controls and the need for a plant manual are prescribed in AS/NZS1328.

Continuous and periodic monitoring It is also thought that there is no continuous and periodic monitoring of glulam properties. Glulam has continuous monitoring but not periodic monitoring in the form defined in AS/NZS 4490 which presents rules that were developed for sawn timber and envisage the continuous monitoring taking the form of machine stress grading. Under machine stress grading member stiffness is measured and this has only a loose relationship to strength which is what concerns capacity factors. Thus the need for some additional “periodic monitoring” to check that the strengths are still being met is, arguably, necessary. With glulam, the monitoring of finger strengths is a more direct measure of overall beam strength. Thus the need to undertake periodic monitoring is less pressing. GLTAA members also test 1 beam per month to determine both bending strength and stiffness in-house and have Monash test 3 per annum, although this is not an AS/NZS1328 requirement.

Overall it is difficult to avoid the conclusion that the capacity factors recommended in PN01.3700 are more appropriate.

Other references

Leicester, RH, (1999) Mud map to AS 4063, Unpublished paper presented to Committee TM/001 of Standards Australia.

Ravindra, MK, Galambos, TV, (1978)Load resistance factor design for steel, JStructDiv, ASCE, v104,ST9, Septemb