TECHNICAL REPORT

# ISO/TR 19623

First edition
2019-06

# Timber structures — Glued laminated timber — Assignment of glued laminated timber characteristic values from laminate properties

*Structures en bois — Bois lamellé-collé — Valeurs caractéristiques du bois lamellé-collé sur la base des propriétés des lamelles*



Reference number
ISO/TR 19623:2019(E)

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Published in Switzerland

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# Foreword

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This document was prepared by Technical Committee ISO/TC 165, *Timber structures*.

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# Introduction

This document was prepared in response to the growing interest in development of the strength and stiffness of structural glued laminated timber (glulam) from the characteristic values of lumber laminations.

Since its first introduction in 1890s, glulam has been used in timber construction for over 125 years with excellent track record of performance. Many countries around the world, which have experience in glulam construction, have various glulam production capabilities that are supported by methodologies or analytical models for development of glulam strength and stiffness from the characteristic values of lumber laminations. This document reviews methodologies from Europe, the USA, Australia/New Zealand, and Canada that have successfully demonstrated their acceptance through years of practice and end uses.

This document does not cover all methodologies around the world and is not intended to exclude other methodologies that can demonstrate their capabilities of correlating the analytical results with the actual product performance. This document will be updated with those additional methodologies when their documentation becomes available in the future.

This document promotes the understanding of the differences between methodologies as a first step toward an international harmonization in the process of assigning glulam characteristic values from laminate properties.



 

# Timber structures — Glued laminated timber — Assignment of glued laminated timber characteristic values from laminate properties

## 1 Scope

This document reviews the methodologies or analytical models that have been used to develop the strength and stiffness of structural glued laminated timber (glulam) from the characteristic properties of lumber laminations. The review is limited to the methodologies used in Europe, the USA, Australia/New Zealand, and Canada as they represent different fundamental philosophies in these areas. As a result, the methodologies are not intended to be combined unless there is clear understanding of the fundamental assumptions adopted by the respective methodologies.

NOTE Detailed assumptions used by the respective methodologies are available from the standards listed in the Bibliography.

## 2 Normative references

There are no normative references in this document.

## 3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

## 4 European methodologies

EN 14080 provides three different routes for producer to classify the glulam and all of them are related to properties in structural sizes. The glulam standard covers only properties related to nominal 12 % moisture content (in lamination, joint, and structural specimen tests, moisture content may be 12 ± 3 % without mandatory adjustments).

### 4.1 General

Mechanical resistance of glulam is intended to be determined from and declared:

— on the basis of geometrical data (e.g. cross-sectional sizes of laminations and layups) and material properties (strength, stiffness and density properties of laminations and strength properties of finger joints); or

— from tests.

#### 4.1.1 Timber

Timber is strength graded according to EN 14081-1.

### 4.1.2 Related material properties

The characteristic strength, stiffness and density properties of glulam are verified either:

a) from classifications from layups and lamination properties (this route is a direct result of the calculation procedure implemented in 4.3);

b) from calculations taking into account the cross-sectional layup and documented properties of boards and finger joints according to 4.3, or

c) from full scale tests according to 4.4.

The characteristic strength, stiffness and density properties may be declared by reference to a strength class according to Table 3 or 4 or to a manufacturer's specific strength class. For glulam having an asymmetrical layup, "ca" should be added to the class name, e.g. GL28 ca. The class name of resawn glulam is marked by "s", e.g. GL24 cs.

The characteristic bending strength should be valid for glulam with a depth $h$ of 600 mm and a lamination thickness of $t$ = 40 mm. If the lamination thickness is less than 40 mm, the bending strength may be multiplied by $k$ as given in Formula (1). For lamination thicknesses 40 mm < $t$ ≤ 45 mm, it is not necessary to take any strength modification into account.

$$k = \min \begin{cases} \left(\frac{40}{t}\right)^{0,1} \\ 1,05 \end{cases} \qquad (1)$$

where $t$ is the lamination thickness, in mm.

The characteristic tensile strength parallel to the grain should be valid for glulam with depth $h$ of 600 mm or width $b$ of 600 mm.

The characteristic tensile strength perpendicular to the grain should be valid for glulam with a stressed volume of 0,01 $m^3$.

The 5 %-fractile of a shear modulus or a modulus of elasticity should be estimated from the mean value by applying the ratio of $G_{g,k}/G_{g,mean}$ = 5/6 and $E_{0,g,k}/E_{0,g,mean}$ = 5/6, respectively.

For glulam members made of at least 10 laminations the product ($E_{0,g,k}$ $G_{g,k}$) may be increased by a factor $k$ = 1,40.

For rectangular glued laminated timber with depths in bending or widths in tension less than 600 mm, the characteristic values for $f_{m,k}$ and $f_{t,0,k}$ may be increased by the factor $k_h$ given by

$$k_h = \min \begin{cases} \left(\frac{600}{h}\right)^{0,1} \\ 1,1 \end{cases} \qquad (2)$$

where $h$ is the depth for bending members or width for tensile members, in mm.

## 4.2 Verification from classification of standardised beam lay-ups and lamination properties of glued laminated timber

### 4.2.1 Properties of the boards

The requirements of the boards given in Table 1 should be fulfilled. The essential material properties needed for the EN 14080 model are tension strength, modulus of elasticity, and density of the unjointed laminations and further finger joint tension or bending strength (see Table 1). Laminations up to T-class T18 can be graded visually according to several European grading standards and then assigned to T-classes, provided the respective classification reports on the basis of EN 384 exist. (issue of flatwise and edgewise bending needs to be addressed).

In case no information exists, the effort to group laminations based on tension tests according to EN 408 into a certain T-class (similar as for C class) is

— 40 specimens from 5 growth areas: no reduction in evaluation, based on mean of the 5 % quantiles of all 5 samples or 1,2 times of the sample with the lowest 5 % quantile (the lesser value is relevant)

— 40 specimens from 3 growth areas; penalization by factor of 0,89

— 40 specimens from 1 growth area; penalization by 0,77

**Table 1 — Characteristic strength and stiffness properties for T-classes in N/mm$^2$ and densities in kg/m$^3$ for boards or planks for glued laminated timber**

| T-class of boards[a] | $f_{t,0,l,k}$ | $E_{t,0,l,mean}$ | $\rho_{l,k}$ |
|---|---|---|---|
| T8 (C14) | 8 | 7 000 | 290 |
| T9 | 9 | 7 500 | 300 |
| T10 (C16) | 10 | 8 000 | 310 |
| T11 (C18) | 11 | 9 000 | 320 |
| T12 (C20) | 12 | 9 500 | 330 |
| T13 (C22) | 13 | 10 000 | 340 |
| T14 (C24) | 14 | 11 000 | 350 |
| T14,5 | 14,5 | 11 000 | 350 |
| T15 | 15 | 11 500 | 360 |
| T16 (C27) | 16 | 11 500 | 370 |
| T18 (C30) | 18 | 12 000 | 380 |
| T21 (C35) | 21 | 13 000 | 390 |
| T22 | 22 | 13 000 | 390 |
| T24 (C40) | 24 | 13 500 | 400 |
| T26 | 26 | 14 000 | 410 |
| T27 (C45) | 27 | 15 000 | 410 |
| T28 | 28 | 15 000 | 420 |
| T30 (C50) | 30 | 15 500 | 430 |

[a] The C-classes according to EN 338:2009 meet at least the required values of the respective T-classes.

#### 4.2.2 Strength of finger joints

The declared or necessary finger joint strength values depend on the different glulam classification approaches.

— For classification approach (A), fixed values need to be met.

— For classification/verification approach (B), i.e. the calculation method, values in a certain bandwidth can be declared.

The required characteristic values of the flatwise bending strength of finger joints $f_{m,j,k}$ in laminations for glulam classification approach (A) should be taken from Table 2 or 3. If the finger joints are tested in tension the required characteristic value of the tensile strength of finger joints should be taken as

$$f_{t,0,j,k} = f_{m,j,k} / 1,4 \quad (3)$$

### 4.2.3 Beam lay-up and strength class

Provided the beam lay-up is in accordance with Table 2 or 3, the glulam fulfils the requirements of a strength class given in Table 4 or 5.

The zones of the cross section are defined in Figure 1.

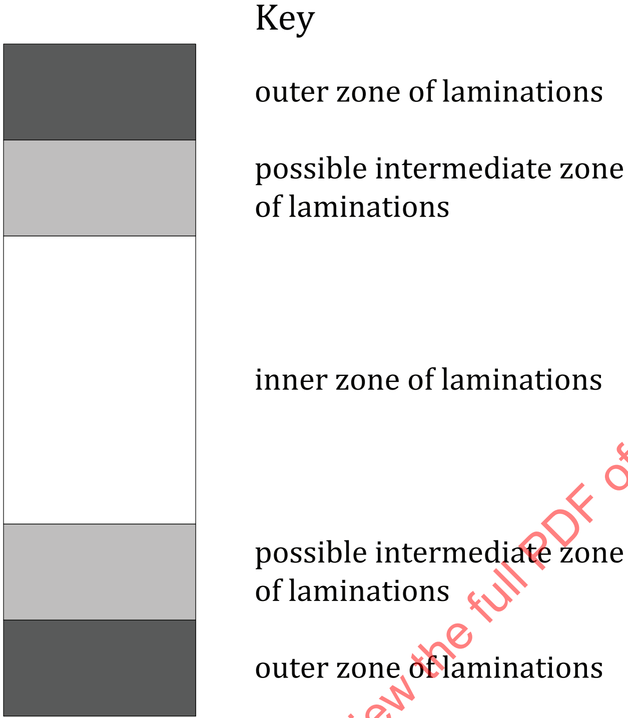


**Figure 1 — Example of a beam lay-up of combined glulam**

— For combined glulam, the outer zones of lamination grades (see Figure 1) should be at least the proportion given in Table 2, but at least two laminations for glulam with more than 10 laminations and at least one lamination for glulam with up to 10 laminations.

**Table 2 — Beam lay-up of combined glued laminated timber and minimum values for bending strength of finger joints in laminations in N/mm²**

| Glued laminated timber | Outer zones of laminations | | | Intermediate zones of laminations | | | Inner zone of laminations | | |
|---|---|---|---|---|---|---|---|---|---|
| Strength class | Strength class | Proportion [%] | $f_{m,j,k}$ [N/mm²] | Strength class | Proportion [%] | $f_{m,j,k}$ [N/mm²] | Strength class[a] | Proportion [%] | $f_{m,j,k}$ [N/mm²] |
| GL 20c | T13 | 2 × 33 | 21 | — | — | — | T8 | 34 | 18 |
| GL 22c | T13 | 2 × 33 | 26 | — | — | — | T8 | 34 | 18 |
| GL 24c | T14 | 2 × 33 | 31 | — | — | — | T9 | 34 | 19 |
| GL 26c | T16 | 2 × 33 | 34 | — | — | — | T11 | 34 | 22 |
| GL 28c | T18 | 2 × 25 | 37 | — | — | — | T14 | 50 | 28 |
| GL 28c | T21 | 2 × 17 | 36 | — | — | — | T14 | 66 | 26 |
| GL 28c | T21 | 2 × 17 | 38 | — | — | — | T13 | 66 | 25 |
| GL 28c | T21 | 2 × 25 | 35 | — | — | — | T11 | 50 | 22 |
| GL 28c | T21 | 2 × 20 | 35 | T14 | 2 × 20 | 28 | T11 | 20 | 22 |
| GL 28c | T22 | 2 × 20 | 35 | — | — | — | T13 | 60 | 25 |



 

**Table 2** *(continued)*

| Glued laminated timber | Outer zones of laminations | | | Intermediate zones of laminations | | | Inner zone of laminations | | |
|---|---|---|---|---|---|---|---|---|---|
| Strength class | Strength class | Proportion [%] | $f_{m,j,k}$ [N/mm²] | Strength class | Proportion [%] | $f_{m,j,k}$ [N/mm²] | Strength class[a] | Proportion [%] | $f_{m,j,k}$ [N/mm²] |
| GL 30c | T22 | 2 × 17 | 40 | — | — | — | T15 | 66 | 27 |
| GL 30c | T22 | 2 × 17 | 41 | — | — | — | T14 | 66 | 28 |
| GL 30c | T22 | 2 × 20 | 40 | T14 | 2 × 20 | 30 | T11 | 20 | 22 |
| GL 30c | T22 | 2 × 17 | 42 | T14 | 2 × 23 | 31 | T11 | 20 | 22 |
| GL 32c | T24 | 2 × 17 | 44 | — | — | — | T18 | 66 | 31 |
| GL 32c | T26 | 2 × 17 | 45 | — | — | — | T14 | 66 | 26 |
| GL 32c | T26 | 2 × 10 | 48 | T18 | 2 × 20 | 32 | T11 | 40 | 22 |



**Table 3 — Beam lay-up of homogeneous glued laminated timber and minimum values for bending strength of finger joints in laminations in N/mm²**

| Strength class glued laminated timber | Strength class laminations | $f_{m,j,k}$ |
|---|---|---|
| GL 20h | T10 | 25 |
| GL 20h | T11 | 22 |
| GL 22h | T13 | 25 |
| GL 24h | T14 | 30 |
| GL 26h | T16 | 33 |
| GL 28h | T18 | 36 |
| GL 30h | T21 | 38 |
| GL 30h | T22 | 37 |
| GL 32h | T24 | 41 |
| GL 32h | T26 | 38 |

**Table 4 — Characteristic strength and stiffness properties in N/mm² and densities in kg/m³ for combined glulam**

| Property[a] | Symbol | Glulam strength class | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | GL 20c | GL 22c | GL 24c | GL 26c | GL 28c | GL 30c | GL 32c |
| Bending strength | $f_{m,g,k}$ | 20 | 22 | 24 | 26 | 28 | 30 | 32 |
| Tensile strength | $f_{t,0,g,k}$ | 15 | 16 | 17 | 19 | 19,5 | 19,5 | 19,5 |
| | $f_{t,90,g,k}$ | 0,5 | | | | | | |
| Compression strength | $f_{c,0,g,k}$ | 18,5 | 20 | 21,5 | 23,5 | 24 | 24,5 | 24,5 |
| | $f_{c,90,g,k}$ | 2,5 | | | | | | |
| Shear strength (shear and torsion) | $f_{v,g,k}$ | 3,5 | | | | | | |
| Rolling shear strength | $f_{r,g,k}$ | 1,2 | | | | | | |
| Modulus of elasticity | $E_{0,g,mean}$ | 10 400 | 10 400 | 11 000 | 12 000 | 12 500 | 13 000 | 13 500 |
| | $E_{0,g,05}$ | 8 600 | 8 600 | 9 100 | 10 000 | 10 400 | 10 800 | 11 200 |
| | $E_{90,g,mean}$ | 300 | | | | | | |
| | $E_{90,g,05}$ | 250 | | | | | | |

[a] Properties given in this table have been calculated on the basis of the layups given in Table 2. If different layups for a certain strength class lead to different characteristic values the lowest values are given here.

[b] Calculated as the weighted mean of the densities of the different lamination zones.

**Table 4** *(continued)*

| Property[a] | Symbol | Glulam strength class | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | GL 20c | GL 22c | GL 24c | GL 26c | GL 28c | GL 30c | GL 32c |
| Shear-modulus | $G_{g,mean}$ | 650 | | | | | | |
| | $G_{g,05}$ | 540 | | | | | | |
| Rolling shear modulus | $G_{r,g,mean}$ | 65 | | | | | | |
| | $G_{r,g,05}$ | 54 | | | | | | |
| Density[b] | $\rho_{g,k}$ | 355 | 355 | 365 | 385 | 390 | 390 | 400 |
| | $\rho_{g,mean}$ | 390 | 390 | 400 | 420 | 420 | 430 | 440 |

[a] Properties given in this table have been calculated on the basis of the layups given in Table 2. If different layups for a certain strength class lead to different characteristic values the lowest values are given here.

[b] Calculated as the weighted mean of the densities of the different lamination zones.

**Table 5 — Characteristic strength and stiffness properties in N/mm² and densities in kg/m³ for homogeneous glulam**

| Property | Symbol | Glulam strength class | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | GL 20h | GL 22h | GL 24h | GL 26h | GL 28h | GL 30h | GL 32h |
| Bending strength | $f_{m,g,k}$ | 20 | 22 | 24 | 26 | 28 | 30 | 32 |
| Tensile strength | $f_{t,0,g,k}$ | 16 | 17,6 | 19,2 | 20,8 | 22,3 | 24 | 25,6 |
| | $f_{t,90,g,k}$ | 0,5 | | | | | | |
| Compression strength | $f_{c,0,g,k}$ | 20 | 22 | 24 | 26 | 28 | 30 | 32 |
| | $f_{c,90,g,k}$ | 2,5 | | | | | | |
| Shear strength (shear and torsion) | $f_{v,g,k}$ | 3,5 | | | | | | |
| Rolling shear strength | $f_{r,g,k}$ | 1,2 | | | | | | |
| Modulus of elasticity | $E_{0,g,mean}$ | 8 400 | 10 500 | 11 500 | 12 100 | 12 600 | 13 600 | 14 200 |
| | $E_{0,g,05}$ | 7 000 | 8 800 | 9 600 | 10 100 | 10 500 | 11 300 | 11 800 |
| | $E_{90,g,mean}$ | 300 | | | | | | |
| | $E_{90,g,05}$ | 250 | | | | | | |
| Shear modulus | $G_{g,mean}$ | 650 | | | | | | |
| | $G_{g,05}$ | 540 | | | | | | |
| Rolling shear modulus | $G_{r,g,mean}$ | 65 | | | | | | |
| | $G_{r,g,05}$ | 54 | | | | | | |
| Density | $\rho_{g,k}$ | 340 | 370 | 385 | 405 | 425 | 430 | 440 |
| | $\rho_{g,mean}$ | 370 | 410 | 420 | 445 | 460 | 480 | 490 |



## 4.3 Classification, verification according to method B from cross sectional layup and properties of boards and finger joints

### 4.3.1 Properties of the boards

If the boards comply with one of the relevant strength classes, the strength, stiffness and density properties may be taken from Table 1.

If the boards or planks do not comply with Table 1, the characteristic values of the tensile strength parallel to the grain $f_{t,0,l,k}$, the mean modulus of elasticity parallel to the grain $E_{t,0,l,mean}$ and the characteristic density $\rho_{l,k}$ should be derived from tests according to EN 408 and calculated in accordance with EN 384 as outlined in 4.2.1 (there also specimen numbers are given).

### 4.3.2 Strength of finger joints

The characteristic flat wise bending strength or tensile strength of the finger joints should be declared by the glulam manufacturer. The declared strength of finger joints should be verified by tests in accordance with Annex E of ISO 10983:2014 (30 specimens per species, grade, strength class) and evaluation according to EN 14358.

### 4.3.3 Determination of characteristic values for glued laminated timber

The strength and stiffness properties of homogeneous glulam should be determined from the strength and stiffness properties of the laminations using the formulae given in Table 6.

The characteristic bending strength, the characteristic tensile and compression strengths parallel to the grain, the mean modulus of elasticity and the characteristic density of a combined glulam should be determined from the respective values of the different lamination zones considered as homogeneous glulam by means of the elastic composite beam theory.

For combined glulam, the outer zones of lamination grades should be at least two laminations for glulam with more than 10 laminations and at least one lamination for glulam with up to 10 laminations.

The strength verification should be made at all relevant points of the cross section.

**Table 6 — Characteristic strength and stiffness properties in N/mm² and densities in kg/m³ of homogeneous glued laminated timber**

| Property | | Characteristic values |
|---|---|---|
| Bending strength (N/mm²) | $f_{m,g,k}$ | The characteristic bending strength should be calculated using the following expression.<br>$$f_{m,g,k} = -2,2 + 2,5 f_{t,0,l,k}^{0,75} + 1,5 \left( \frac{f_{m,j,k}}{1,4} - f_{t,0,l,k} + 6 \right)^{0,65}$$<br>The expression should only be used for a characteristic flat wise bending strength of the finger joint in the range:<br>$1,4 f_{t,0,l,k} \leq f_{m,j,k} \leq 1,4 f_{t,0,l,k} + 12$<br>The formula is also applicable to glulam without finger joints provided $f_{m,j,k}$ is taken as:<br>$f_{m,j,k} = 1,4 f_{t,0,l,k} + 12$ |
| Tensile strength (N/mm²) | $f_{t,0,g,k}$ | The characteristic tensile strength should be taken as 80 % of the characteristic values of the bending strength $f_{m,g,k}$. |
| | $f_{t,90,g,k}$ | 0,5 |
| Compression strength (N/mm²) | $f_{c,0,g,k}$ | The characteristic compression strength should be taken as $f_{m,g,k}$ in N/mm² where $f_{m,g,k}$ is the characteristic bending strength of the glued laminated timber. |
| | $f_{c,90,g,k}$ | 2,5 |
| Shear strength (N/mm²) | $f_{v,g,k}$ | 3,5 |
| | $f_{r,g,k}$ | 1,2 |
| Modulus of elasticity (N/mm²) | $E_{0,g,mean}$ | The mean modulus of elasticity should be taken as $E_{0,g,mean} = 1,05\ E_{t,0,l,mean}$. |
| | $E_{90,g,mean}$ | 300 |
| Shear modulus (N/mm²) | $G_{g,mean}$ | 650 |
| | $G_{r,g,mean}$ | 65 |
| Density (kg/m³) | $\rho_{g,k}$ | $1,1\ \rho_{l,k}$ |
| | $\rho_{g,mean}$ | $\rho_{l,mean}$ |

Glulam may have an asymmetrical layup. In that case, the verification of the bending strength in the outer compressive zone may be disregarded if the followings conditions are met:

— the difference in nominal bending strength between the outer compressive zone and the adjacent zone of laminations (see Figure 1) does not exceed 8 N/mm$^2$;

— the ratio of the moduli of elasticity $E_{0,g,mean}$ of the outer tensile and compressive zone of laminations, respectively, does not exceed 1,25.

The density of a combined glulam should be taken as the weighted densities of the lamination zones estimated as the densities of homogeneous glulam according to Table 6.

## 4.4 Verifications from full scale tests with glulam

### 4.4.1 Properties of the boards

The characteristic values of the tensile strength parallel to the grain $f_{t,0,l,dc,k}$ or the bending strength $f_{m,l,dc,k}$, the mean modulus of elasticity parallel to the grain $E_{t,0,l,dc,mean}$ and the characteristic density $\rho_{l,dc,k}$ of the boards should be estimated and declared by tests according to Annex E of ISO 10983:2014.

### 4.4.2 Strength of finger joints

The characteristic flatwise bending strength of the finger joints $f_{m,j,dc,k}$ should be estimated and declared by tests according to Annex E of ISO 10983:2014.

The declared characteristic flatwise bending strength of the finger joints $f_{m,j,dc,k}$ should be not less than 1,4 $f_{t,0,j,dc,k}$.

### 4.4.3 Strength, stiffness and density properties of glulam derived from testing

#### 4.4.3.1 Combined glulam

Combined glulam should be assigned to one of the strength classes given in Table 4 or to any other manufacturer specific strength class if the characteristic bending strength parallel to the grain $f_{m,g,k}$, the mean modulus of elasticity parallel to the grain $E_{0,g,mean}$ and the characteristic density derived from full-scale tests according to Annex F of ISO 10983:2014 and the characteristic tensile strength $f_{t,0,g,k}$ and the compression strength $f_{c,0,g,k}$ parallel to the grain tested according to EN 408 and derived according to EN 14358 are not less than the declared values. Characteristic tensile strength $f_{t,0,g,k}$ and compression strength $f_{c,0,g,k}$ parallel to the grain may be taken as the values for the lamination zone having the lowest characteristic tensile strength parallel to the grain $f_{t,0,l,k}$.

The other strength and stiffness properties of a manufacturer specific strength class should be calculated using the expressions given in Table 6.

#### 4.4.3.2 Homogeneous glulam

Homogenous glulam should be assigned to one of the strength classes given in Table 5 or to any other manufacturer specific strength class if the characteristic bending strength parallel to the grain $f_{m,g,k}$, the mean modulus of elasticity parallel to the grain $E_{0,g,mean}$ and the characteristic density $\rho_{g,k}$ derived from full scale tests according to Annex F of ISO 10983:2014 are not less than the declared values.

The other strength and stiffness properties of a manufacturer specific strength class should be calculated using the formulae given in Table 6.

## 4.5 Resawn glulam

Glulam may be sawn perpendicular to the glue lines into 2 or 3 parts (resawn glulam).

Each part should have a minimum width $b_s$ of 38 mm and a maximum depth to width ratio of $h/b_s \leq 8$.



 

# 5 US methodologies

The US building codes require that all glulam be trademarked as being in conformance with ANSI A190.1, and Section 4.3.6 of ANSI A190.1 requires that grade combinations for glulam be developed in accordance with ASTM D3737, or should be obtained by performance testing and analysis in accordance with recognized standards, such as ASTM D7341. ANSI 117 provides many glulam lay-up combinations that were developed based on the methodologies reviewed in this clause.

## 5.1 General

Since glulam was a new product in the US, the US Forest Products Laboratory (FPL) in Madison, WI undertook a series of extensive tests on glulam arches beginning in 1934. These included tests of glulam to check for such factors as design formulas, working stresses and the effect on strength of curvature, end joints and knots and was reported in Reference [24]. With the great demand during World War II for heavy timbers, the development of glulam was greatly hastened and significant research was conducted in the areas of adhesives, lumber quality, and the testing of full-size laminated beams and columns to supplement and confirm the work reported in Reference [24]. This work was published in Reference [16] and formed the basis for the development of characteristic design stresses for glulam which is still used today.

The basic premise of Reference [16] is that the strength of glulam is dependent on the knot characteristics and their distribution in the glulam member. This led to the development of the "$I_K/I_G$" model that forms the basis for ASTM D3737. This standard has undergone numerous changes over the years including

a) incorporating provisions for using full-scale beams tests to determine bending and horizontal shear properties,

b) adding special provisions for tension laminations, and

c) introducing the volume effect factor.

In addition to being the basis for ASTM D3737, Reference [16] was also the predecessor of the manufacturing and fabrication requirements for glulam used today in the US. The first manufacturing standard for glulam was US. Department of Commerce Commercial Standard CS 253-63 published in 1963 and it was subsequently revised and published as Department of Commerce Standard PS 56-73. At the same time, it was also promulgated as ANSI A190.1-1973, which has been superseded by A190.1-1983, A190.1-1992, A190.1-2002, A190.1-2007, and ANSI A190.1-2017.

## 5.2 ASTM D3737

### 5.2.1 General

Since ASTM D3737 is relatively complicated, this document is focused on the determination of bending strengths for a glulam member loaded perpendicular to the wide face of laminations (called X-x-axis). The basic concept of ASTM D3737 is that clear wood strength properties and their expected variation for small clear, straight-grained specimens of green lumber based on ASTM D2555 can be used to develop stress index values for the various strength properties. For example, for a bending member loaded on the X-x-axis, the bending stress index can be determined by calculating the fifth percentile of modulus of rupture in accordance with ASTM D2555, multiplying by an appropriate adjustment factor and multiplying by 0,743 to adjust to a 300-mm deep, uniformly loaded simple beam with a 21:1 span-to-depth ratio. As an alternative, results of testing and analysis of large glulam beams of Douglas Fir-Larch, Southern Pine and Hem-Fir are also used to establish stress indexes.

These stress indexes are then multiplied by stress modification factors developed based on the effects of strength reducing characteristics of knots, slope of grain and density. For example, the bending stress modification factor for knots, ($SMF_{bx\ \mathrm{knots}}$) is given by Formula (4):

$$SMF_{bx\,\mathrm{knots}} = (1+3\frac{I_K}{I_G})(1-\frac{I_K}{I_G})^3(1-\frac{I_K}{2I_G}) \qquad (4)$$

### 5.2.2 $I_K/I_G$ analysis

The “$I_K/I_G$” analysis that forms the basis for ASTM D3737 is based on determining how strength reducing characteristics including knot sizes and slope of grain of the individual laminations and their distribution within the glulam member affect the overall strength of the finished glulam. The following definitions are used.

$I_k$ is the sum of the moments of inertia of the cross-sectional areas of all knots within 150 mm of a single cross section at the 99,5 percentile.

$I_g$ is the moment of inertia of the full of gross cross section.

Defining X-bar as the average of the sum of all knot sizes within any 300-mm length along the piece of lumber, h is the difference between the 99,5 percentile knot size and X-bar.

Thus, it is necessary to define the knot characteristics, X-bar and h, for all combinations of species and lumber grades to apply the “$I_K/I_G$” principles. Annex A6 of ASTM D3737 provides guidance on the determination of these knot dependent values. There are 8 types of knots that are measured and these are shown in Figure 2. Note that there is no knot type 8 by committee decision. All knots of 6 mm or greater are measured and the projected cross-sectional area for each knot type is determined.

Any linear regression routine that determines the parameters of the regression line and the value of the 99,5 percentile can be used to emulate the procedure of plotting the sum of knots cumulative frequency data on arithmetical probability paper and drawing a straight line through the data, which was the method used in Reference [16]. The underlying assumption for using this procedure is that an analysis, which handles the knot data as normally distributed, is satisfactory.

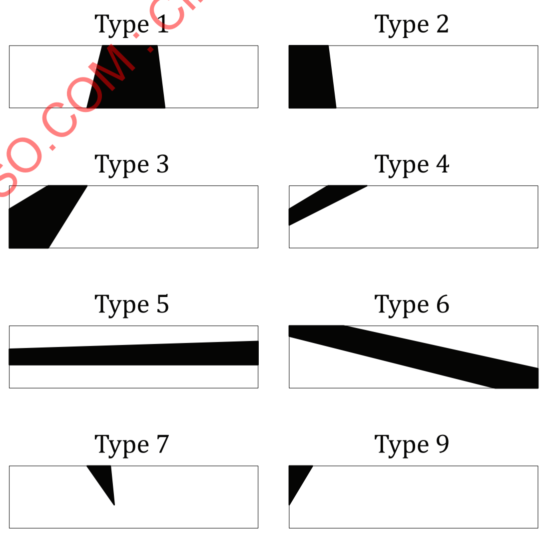


**Figure 2 — Knot types for used in $I_K/I_G$ model**

The following steps summarize the provisions of Annex A4 of ASTM D3737 to determine the bending strength ($F_{bx}$) for horizontally laminated beams assuming the use of several zones based on different grades and or species of laminating lumber throughout depth of the member. This can be used for symmetric layups or for unsymmetrical layups such as shown in Figure 3. The grade combination in

Figure 3 for a six-zone beam also shows that different species as well as different lumber grades can be intermixed.

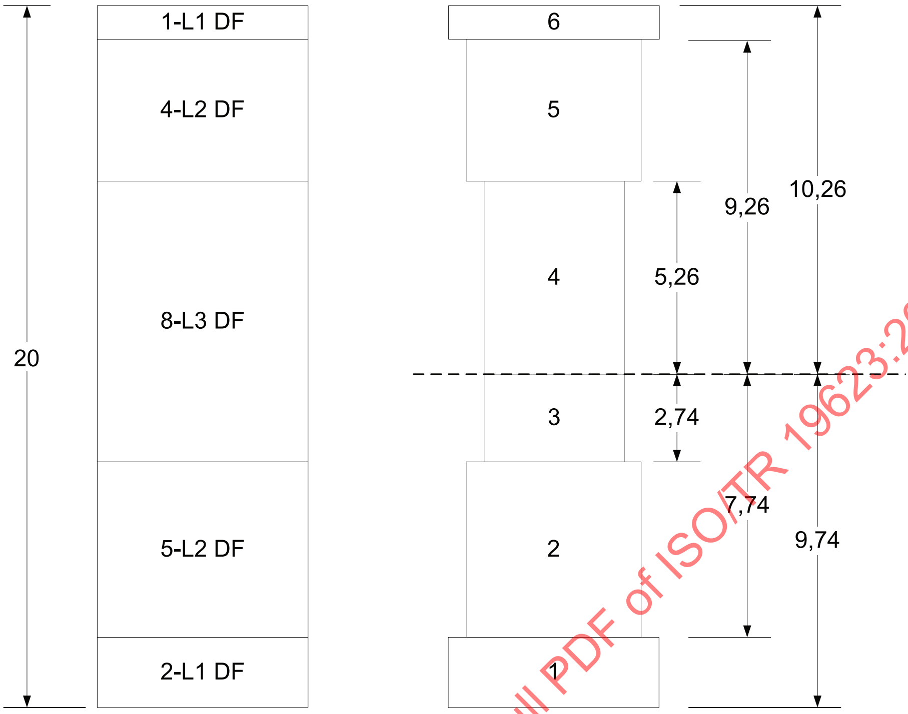


**Figure 3 — Grade combination and transformed section**

1) The location of the neutral axis of the transformed section is determined using Formula (5), and the distance from the neutral axis to the edges of each grade zone in the beam is determined using Formulae (6) and (7).

$$\bar{y} = \frac{\sum_{j=1}^{n_1} \left[ \frac{E_j}{2} \left( y_j^2 - y_{(j-1)}^2 \right) \right]}{\sum_{j=1}^{n_1} \left[ E_j \left( y_j - y_{(j-1)} \right) \right]} \tag{5}$$

where

$\bar{y}$ is the distance from bottom of beam to neutral axis;

$E_j$ is the long span modulus of elasticity for $j$th zone;

$y_j$ is the distance from bottom of beam to top of $j$th zone;

$y_{(j-1)}$ is the distance from bottom of beam to bottom of $j$th zone;

$n_1$ is the total number of zones in beam.

$$N_j = \left( y_j - \bar{y} \right) \tag{6}$$

$$N_{(j-1)} = \left( y_{(j-1)} - \bar{y} \right) \tag{7}$$

where

$N_j$ is the distance from neutral axis to upper edge of *j*th zone;

$N_{(j-1)}$ is the distance from neutral axis to lower edge of *j*th zone.

2) The transformed moment of inertia for each zone about the neutral axis is calculated using Formula (8), and the moment of inertia of the transformed section is calculated using Formula (9).

$$I_j = b\left(\frac{E_j}{E_T}\right)\frac{\left(N_j^3 - N_{(j-1)}^3\right)}{3} \tag{8}$$

where

$I_j$ is the transformed moment of inertia of *j*th lam about neutral axis;

$E_T$ is the modulus of elasticity of transformed section;

$b$ is the un-transformed width of laminations.

$$I_T = \sum_{j=1}^{n_1} I_j \tag{9}$$

where $I_T$ transformed moment of inertia of the section.

3) The moment of inertia of the un-transformed (gross) section is calculated using Formula (10).

$$I_g = \frac{bD^3}{12} \tag{10}$$

where

$I_g$ is the gross moment of inertia of the section;

$D$ is the depth of the section.

4) An $I_K/I_G$ ratio is calculated for each zone using Formula (11).

$$\left(\frac{I_k}{I_g}\right)_j = \frac{\sum_{i=1}^{j}\left(x_i\left(\frac{E_i}{E_j}\right)(O_i)\right) + \sqrt{\sum_{i=1}^{j}\left(h_i^2\left(\frac{E_i}{E_j}\right)^2(P_i)\right)}}{2d_j^3} \tag{11}$$

where

$x_j$ is the average knot size, expressed in decimal fraction of width, for the grade of lamination in the $j$th zone;

$h_j$ is the difference between the 99,5 percentile and average knot size, expressed in decimal fraction of the width, for the grade of lamination in the $j$th zone;

$d_j$ is the distance between the outermost edge of the $j$th zone and the neutral axis.

5) The stress modification factor for knots, $SMF_{bx\,\text{knots}\,j}$, is calculated for each zone using Formula (12).

$$SMF_{bx\ \text{knots}\ j} = \left[ \left(1+3\left(\frac{I_k}{I_g}\right)_j\right)\left(1-\left(\frac{I_k}{I_g}\right)_j\right)^3 \left(1-\left(\frac{I_k}{2I_g}\right)_j\right) \right] \geq SR_{bx\ \min\ j} \tag{12}$$

6) The stress modification factor for slope of grain, $SMF_{bx\,\text{SOG}\,j}$, is determined for each zone based on tabulated data for slope of grain values from 1:4 to 1:20 given in Table 4 of ASTM D3737.

7) The stress modification factor for each zone is determined using Formula (13).

$$SMF_{bx\ j} = \min\left\{SMF_{bx\ \text{knots}\ j}, SMF_{bx\,\text{SOG}\ j}\right\} \tag{13}$$

8) The maximum stress permitted on each zone, $F_{\max,\,j}$, is calculated using Formula (14).

$$F_{\max,j} = K\left(BSI_j\right)\left(SMF_{bx\ j}\right) \tag{14}$$

where

$F_{\max,\,j}$ is the maximum stress allowed at outer edge of $j$th zone;

$BSI_j$ is the bending strength index of laminations in $j$th zone;

$SMF_{bx\,j}$ is the strength ratio for bending = Min($SR_{bx\ \text{knots}}$, $SR_{bx\ \text{SOG}}$);

$K$ = 1,4 for flexural compression;

= 1,0 for flexural tension.

9) The apparent outer fibre stress on the beam corresponding to $F_{\max,\,j}$ for each zone is calculated using Formula (15).

$$\sigma_{\text{apparent},j} = F_{\max,j}\left(\frac{D/2}{d_j}\right)\left(\frac{E_T}{E_j}\right)\left(\frac{I_T}{I_g}\right) \tag{15}$$

10) The allowable flexural design stress ($F_{bx}$) is determined using Formula (16).

$$F_{bx} = \min\left\{\sigma_{\text{apparent},j}\right\}(TL) \tag{16}$$

where

*TL* is the tension lamination factor;

= 1,0 if tension laminations meeting the requirements of section 4.3 of ASTM D3737 are used;

= 0,85 if tension laminations meeting the requirements of section 4.3 of ASTM D3737 are not used and $d \leq 380$ mm;

= 0,75 if tension laminations meeting the requirements of section 4.3 of ASTM D3737 are not used and $d > 380$ mm.

11) The required strength ratio of the tension lamination ($SR_{TL}$) is calculated using Formula (17), and the tension lamination grading requirements of section 4.3 of ASTM D3737 are determined, if a tension lamination factor of 1,0 is used in Formula (14).

$$SR_{TL} = \frac{F_{bx}\left(\frac{2d_{TL}}{D}\right)\left(\frac{E_{TL}}{E_T}\right)\left(\frac{I_g}{I_T}\right)}{BSI_{TL}} \tag{17}$$

where

$d_{TL}$ is the distance from neutral axis to the outer edge of the *TL*;

$E_{TL}$ is the long-span modulus of elasticity of the lumber in the outermost tension zone;

$BSI_{TL}$ is the bending stress index of the lumber in the outermost tension zone.

Since this analysis is calculation intensive, computer software programs have been developed to facilitate calculations. By knowing the knot characteristics of X-bar and h, any combination of grades and species can be input into the computer model and the resulting design properties for that grade combination are generated. It is important to note that this calculation methodology, although dating back to the 1950s, has been verified by thousands of full-size beam tests by the industry, government research laboratory, and universities. While more sophisticated probabilistic models have also been developed over the years, they yield essentially the same results as ASTM D3737 and require much more complicated material property inputs and thus did not achieve widespread acceptance in the US.

It is also important to note that countries exporting glulam into the US need to complete this analysis to develop their claimed design properties before the glulam can be accepted under the US building codes.

## 5.3 Tension laminations

As noted in steps 10 and 11 in 5.2.2, the term “tension lamination” has been introduced. The results of full-size beam tests reported in References [13] and [14] yielded an empirical relationship between the size of knots in the tension zone and bending strength that was adopted into ASTM D3737 in the early 1980s. This relationship dictates that special grading considerations be applied to the laminations used in the outer 10 % of the beam depth on the tension side. This tension side may exist on the top or bottom of the beam, or both, depending upon loading and support conditions. If horizontally laminated timbers are manufactured without applying these special tension lamination-grading considerations, the bending strength should be reduced by multiplying the calculated strength by 0,85 if the beam depth is 380 mm or less or by 0,75 if the beam depth exceeds 380 mm.

The special grading provisions for maximum permissible knot characteristics in tension laminations based on the $SR_{TL}$ calculated in accordance with Formula (17) depend on the location in the beam depth (i.e. the outer 5 % of the beam depth and the next inner 5 % of the depth), and the actual beam depth (i.e. 4 laminations to 125 mm, 125 mm to 380 cm, and greater than 380 mm).

## 5.4 Volume factor

Traditionally, the design properties generated in accordance with ASTM D3737 for bending stress were further adjusted by a size factor, $C_F = (12/d)^{1/9}$, which is similar to the European requirements for establishing flexural design properties for a depth of 300 mm and adjusting them for other depths. However, research involving full-size beams with a large range in sizes conducted by the US glulam industry in the late 1980s and reported in reference 15 led to the adoption of the volume effect factor, $C_V$, in ASTM D3737 in the early 1990s. This was also adopted by the US codes as a required design adjustment factor for glulam.

This research demonstrated that the flexural strength of glulam beams is not only affected by the depth of the member but also by its width and length. Therefore, for horizontally laminated bending members, the bending stress determined in accordance with ASTM D3737 needs to be adjusted for sizes greater than the standard size beam (as defined in Formula (18)) by multiplying by the volume effect factor, $C_V$, shown in Formula (18):

$$C_V = \left(\frac{130}{w}\right)^{\frac{1}{x}} \left(\frac{305}{d}\right)^{\frac{1}{x}} \left(\frac{6\,400}{L}\right)^{\frac{1}{x}} \leq 1{,}0 \tag{18}$$

where

- $d$ is the beam depth, in mm;
- $w$ is the beam width, in mm;
- $L$ is the length of beam between points of zero moment, in mm;
- $x$ is the exponent determined by procedures outlined in Annex A8 of ASTM D3737.

The standard beam is assumed to be uniformly loaded and is defined as having a depth of 305 mm, a width of 130 mm and a length of 6 400 mm. It is noted that for Western species in the US, the exponent “$x$” is 10 and for Southern pine the exponent is 20. For other species, including imported species, the exponent “$x$” is used to establish and to publish flexural design properties in accordance with US building codes.

## 5.5 Other glulam properties

The procedures discussed in 5.2 to 5.4 address the bending strength when the load is applied perpendicular to the wide face of laminations (X-x-axis). The glulam modulus of elasticity in this orientation is determined from a transformed-section analysis based on the long-span E of each laminating lumber within the glulam cross section and further multiplied by a factor of 0,95 to account for shear deformation. On the other hand, when the glulam in loaded parallel to the wide face of laminations (Y-y-axis), the glulam modulus of elasticity in this orientation is determined from the average long-span E of each laminating lumber within the glulam cross section and further multiplied by a factor of 0,95 to account for shear deformation. The glulam axial modulus of elasticity is calculated in the same manner as the glulam modulus of elasticity in the Y-y-axis except that the 0,95 factor does not apply.

The other glulam properties can also be determined from the properties of laminating lumber. For example, the glulam horizontal shear and compression perpendicular to grain properties in the X-X direction is assigned based on the shear strength of the core laminations and the compressive strength perpendicular to grain of the outermost lamination, respectively. On the other hand, the glulam tensile strength parallel to grain is conservatively determined based on the lowest tensile strength of all laminating lumber grades within the glulam cross section. The tensile strength of each laminating lumber grade is assumed to be 5/8 of the bending strength of the lumber grade. However, full-scale tests are always permitted as an alternative to the analytical approach mentioned in 5.2.2, provided that the full-scale tests are conducted in accordance with a recognized national or international standard.

## 5.6 ANSI A190.1

While ASTM D3737 focuses on the lumber properties as they influence design properties, it is acknowledged that an equally important consideration is the strength of the end joints, particularly in highly stressed tension zones of members. ANSI A190.1 requires that all end joints be qualified using a full-size tension test with a gauge length of 600 mm. The requirement is that the 5 % tolerance limit with 75 % confidence should exceed 1,67 times the qualification stress level (QSL) using 2 × 6 lumber. For bending members, the QSL is defined as the characteristic bending strength of the glulam combination divided by 2,1 based on normal duration of loading and dry service conditions.

As an example, for a glulam bending member having a characteristic bending strength of 34,8 MPa, the characteristic end joint qualification in tension is 34,8/2,1 × 1,67 = 27,6 MPa. The difference between the beam bending strength of 34,8 MPa and the end joint tensile strength of 27,6 MPa, i.e. the ratio of 1,67/2,1 is due to the difference between the relatively low tensile strength and the relatively high bending strength of wood, and the laminating effect (i.e. defect dispersion) of end joints in a glulam beam. For a member with a characteristic bending strength of 43,4 MPa, the requirement is 43,4/2,1 × 1,67 = 34,5 MPa. Qualification tests are required for all combinations of species, adhesives and treatments used by any manufacturer. ANSI A190.1 also sets for the requirements for daily full-size tension tests to confirm the quality of the end joints.

The premise for the 1,67 factor is based on full-scale beam tests with the end joint strength being equivalent to the tension lamination quality. In other words, it is expected that the end joints are as strong as the lumber with which the end joints are manufactured. Thus, in a test of 100 beams, it is hypothesized that 50 would fail at an end joint and 50 would fail due to some lumber strength-reducing characteristic and this has been generally confirmed by the large magnitude of full-scale beam tests conducted in the US. The factor of 2,1 is a ratio between the characteristic bending or tensile strength and the allowable bending or tensile stress used in the US.

## 5.7 Performance-based standard

As previously noted, a provision was added to ANSI A190.1 to permit the development of characteristic values for grade combinations using performance testing as an alternate to the provisions of ASTM D3737. Similarly, Table 2 of ASTM D3737 provides bending stress index values based on full-size beam tests. The values in Table 2 of ASTM D3737 are based on beams designed using these values and tested in accordance with ASTM D198 yielding bending strength values such that the lower 5th percentile will exceed the characteristic bending strength with 75 % confidence. Analysis of test data assumed a lognormal distribution but there were no definitive sample preparation and sampling requirements.

To provide a performance-based method, ASTM D7341, was developed. Guidelines are given for:

a) testing individual structural glued laminated timber layups (with no modelling),

b) testing individual glulam combinations (with limited modelling), and for

c) validating models used to predict characteristic values.

The sample size to be evaluated is based on which of these conditions are being evaluated. ASTM D7341 is limited to procedures for establishing characteristic bending properties (modulus of rupture and modulus of elasticity) although some of the principles for sampling and analysis presented may be applicable to other properties. The characteristic value is defined as a test statistic from which design values can be derived by the application of appropriate adjustment factors. For glulam bending strength, this characteristic value is typically a 5th percentile estimate with 75 % confidence. For deformation-based properties, such as modulus of elasticity, this value is represented by the average value.



 

## 6 Australian/New Zealand methodologies

Under recently developed AS/NZS methodologies, the structural characteristics of glulam in bending can be determined by computational methods or by full-scale testing in 4-point bending according to AS/NZS 4063.1 and evaluation to AS/NZS 4063.2. These standards are practically identical to ISO 8375 and ISO 12122-1. Two computational procedures are provided:

a) a direct method based on an extension of failure theories developed by Weibull (1939) and extended by Bohannan (1966) that is appropriate for balanced homogeneous glulam and balanced composite glulam,

b) Monte Carlo simulation that deals with balanced (homogeneous and composite) and unbalanced composite glulam.

Both computational methods envision a glulam beam made up as an assemblage of bonded, finger jointed lamination pairs (see Figure 4) and utilize their tension strength as the strength parameter for determination of glulam beam strength. The reason for pursuing this approach is as follows.

— It requires no specific to a strength class system such as followed in EN 14080 while, at the same time, can reference one.

— It can be manufacturer specific or industry broad if manufacturers conform to prescriptive requirements related to location of finger joints relative to knots.

Weibull provided the risks of rupture of rectangular prismatic elements loaded in uniform tension and bending moment with the notion that failure ultimately requires tension rupture. For the present purposes, the tension data are taken as applicable to a bonded lamination pair of length $a$, breadth $b$, and thickness $2t$, where $t$ is the lamination thickness used to form a glulam assembly. Bohannan extended the original Weibull bending formula so that it applied to the form of bending moment that is used as a standard in ISO for determining beam strengths. This undertaken as 4-point bending over length $L = 3a = 18Nt$, where $a$ retains the bonded tension test length definition and $N$ is the number of laminations in the glulam beam assembly.

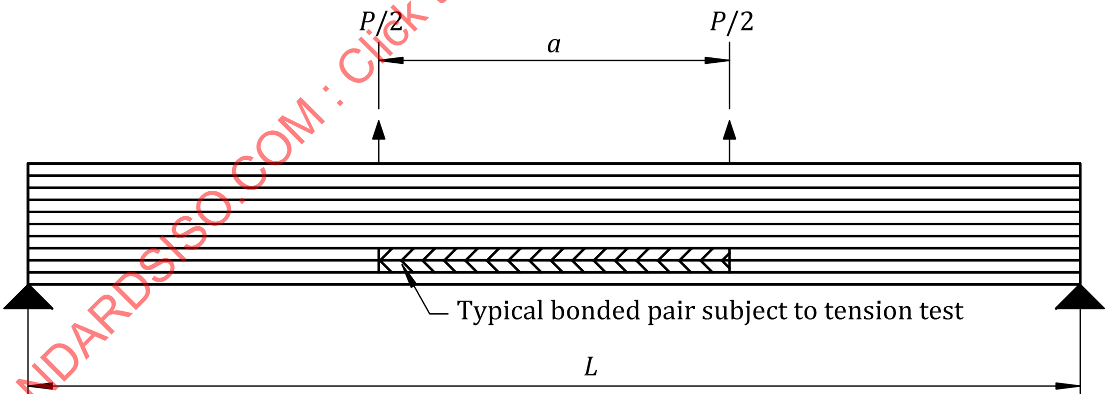


**Figure 4 — Model used for deriving characteristic glulam strength from bonded pair tension tests**

### 6.1 Direct method

#### 6.1.1 Tension tests of bonded lamination pairs

The bonded pair tension test subjects the specimen to uniform tension so that, according to Weibull (1939), the risk of rupture, $B$, at tension stress $f_{t,bp}^{\beta}$ is given by

$$B = kvf_{t,bp}^{\beta} \tag{19}$$

$$v = 2abt \tag{20}$$

where $k$ is a material strength parameter determined on the basis of volume $v$ = 2$abt$.

The 5th percentile tension strength is given by

$$f_{t,bp,05} = \left(-\ln(1-0{,}05)/kv\right)^{1/\beta} = \left(0{,}051\ 29/kv\right)^{1/\beta} \tag{21}$$

### 6.1.2 Major axis bending strength of glulam assemblies

Bohannan (1996) extended an earlier analysis by Weibull (1939) that gave the risk of rupture for a solid homogeneous timber beam loaded as shown in Figure 4 as

$$B = \frac{(Lbd)k}{2(\beta+1)^2}\left(1+\frac{a}{L}\beta\right)f_{max}^{\beta} = \frac{v_{beam}k}{2(\beta+1)^2}\left(1+\frac{a}{L}\beta\right)f_{max}^{\beta} \tag{22}$$

where

$f_{max}$ is the extreme fibre stress;

$L$ is the overall beam length;

$v_{beam}$ is the volume of glulam assembly.

It is evident in both Weibull and Bohannan papers that considerable difficulty exists in assigning a value to the material parameter, $k$, and separating it from the volume effect, $v_{beam}$, since the two quantities appear as a product and are commonly replaced by $f_0$ (=1/$kv$) but even the determination of $f_0$ presents problems. Herein, glulam is treated as an assembly of bonded lamination pairs having tension strengths as measured in the tension test, and 2$abtk$ is treated as an equivalent $f_0$. Peterson and Noziska (1973) noted that, while bonded tension pairs had sharply higher tension strengths relative to single laminations, no further increase in strengths were observed for bonded triples and greater combinations so that bonded pairs provide a good assessment of tension strengths in the outer laminations. Bonded pairs within a glulam assembly are not strictly in uniform tension approaching such a condition which suggests replacing $f_{max}$ with $f_P$ or the stress at the first bondline from the extreme tension fibre. This point is referred to as P. With ($LBd$) replaced by (3$abNt$) and $L/a$ = 3, Formula (22) becomes:

$$B = \frac{N(2abt)k}{4(\beta+1)^2}\frac{L}{a}\left(1+\frac{a}{L}\beta\right)f_P^{\beta} = \frac{3Nvk}{4(\beta+1)^2}\left(1+\frac{\beta}{3}\right)f_P^{\beta} \tag{23}$$

The 5th percentile strength expressed in terms of the stress at the point $P$ becomes

$$f_{b,GL,05,P} = \left(\frac{4(\beta+1)^2}{3Nkv(1+\beta/3)}\right)^{1/\beta} 0{,}051\ 29^{1/\beta} \tag{24}$$

Corresponding to this stress, there exists a higher stress, $f_{b,GL,05}$, on extreme tension fibre given by

$$f_{b,GL,05} = f_{b,GL,05,p}\left(Nt/2/(Nt/2-t)\right) = f_{b,GL,05,p}\left(N/(N-2)\right) \tag{25}$$

Formula (25) can be written in terms of the extreme fibre stress as

$$\sigma_{b,GL,05} = \frac{N}{N-2}\left(\frac{4(\beta+1)^2}{3Nkv(1+\beta/3)}\right)^{1/\beta} 0{,}051\ 29^{1/\beta} \quad (26)$$

The implications of this replacement are dealt with later in 6.1.4, but it makes little difference for standard depth beams (300 mm for AS/NZS and US, and 600 mm for EN) and even shallow beams are not substantially affected by what might seem to be an artifice.

### 6.1.3 Ratio of glulam beam bending to bonded lamination pair tension strength

The ratio of the glulam beam assembly strength in bending to the tension strength of the bonded pair is given in Formula (27).

$$\frac{f_{b,GL,05}}{f_{t,bp,05}} = \left(\frac{N}{N-2}\right)\left(\frac{4(\beta+1)^2}{3N(1+\beta/3)}\right)^{1/\beta} \quad (27)$$

### 6.1.4 Comparison of glulam assembly bending strength between EN 14080 and Formula (27) values

#### 6.1.4.1 EN 14080 values

EN 14080 contains data that allow glulam assembly bending strengths to be linked to single lamination tension strengths, $f_{t,0,l,k}$ using EN 14080 notation. The tension data embeds the effects of knot and sloping grain reinforcement built into bonded pair test data so that the ratio $\sigma_{b,GL,05}/\sigma_{t,bp,05}$ prediction given by Formula (27) can only be compared with the EN 14080 ratios for higher grade material that is relatively knot and sloping grain free. For GL20h to GL30h, the higher ratios reflect a larger reinforcement levels. It is assumed that the use of T26 laminations to make GL 32h is the closest approach to the bonded pair test data and produces a ratio of 1,23. See Table 7. It is noted that EN 14080 takes a standard glulam beam as having a depth of 600 mm and a lamination thickness in the range 40 mm < $t$ ≤ 45 mm fixing the number of laminations at $N$ = 15 – 40 mm × 15 = 600 mm.

**Table 7 — EN14080 ratio of glulam assembly bending strength values to lamination tension strengths at 5th percentile level**

| GL Grade | 20h | 20h | 22h | 24h | 26h | 28h | 30h | 30h | 32h | 32h |
|---|---|---|---|---|---|---|---|---|---|---|
| $f_{b,GL,05}$ (MPa) | 20 | 20 | 22 | 24 | 26 | 28 | 30 | 30 | 32 | 32 |
| $f_{t,05}$ (MPa) | 10 | 11 | 13 | 14 | 16 | 18 | 21 | 22 | 24 | 26 |
| $\frac{f_{b,GL,05}}{f_{t,05}}$ | 2,00 | 1,82 | 1,69 | 1,71 | 1,63 | 1,56 | 1,43 | 1,36 | 1,33 | 1,23 |

#### 6.1.4.2 Formula (27) values

Assembled glulam members have a coefficient of variation that approximates 0,15 corresponding to a Weibull distribution $\beta$ parameter of 0,128 ($\beta$ = 0,989 5$V^{1,077\ 6}$). Two tables are constructed, Tables 8 and 9. In Table 8, lamination thickness is 40 mm and so that the ratio of 1,25 according to Formula (27) should be compared with 1,23 for Table 7. Table 9 reflects the AS/NZS standard depth of 300 mm made up of 10 × 300 mm laminations where a higher factor of 1,43 is applicable. Table 7 applies to a standard depth of 320 mm and a 40 mm lamination thickness gives a ratio of 1,57.

**Table 8 — Values of ratio $f_{b,GL,05}/f_{t,bp,05}$ for a range of coefficient of variation values from Formula (27) (Depth = $N$ × 40 mm)**

| $N$ | $V$ | 0,10 | 0,15 | 0,20 |
|---|---|---|---|---|
| | Depth | Ratio $\sigma_{b,GL,05}/\sigma_{t,bp,05}$ | | |
| 4 | 160 | 2,45 | 2,57 | 2,67 |
| 8 | 320 | 1,54 | 1,57 | 1,57 |
| 15 | 600 | 1,26 | 1,25 | 1,22 |
| 32 | 1 280 | 1,10 | 1,05 | 0,99 |

**Table 9 — Estimates of ratio $f_{b,GL,05}/f_{t,bp,05}$ based on Formula (27) (Depth = $N$ × 30 mm)**

| $N$ | $V$ | 0,10 | 0,15 | 0,20 |
|---|---|---|---|---|
| | Depth | Ratio $\sigma_{b,GL,05}/\sigma_{t,bp,05}$ | | |
| 4 | 120 | 2,45 | 2,57 | 2,67 |
| 10 | 300 | 1,42 | 1,43 | 1,42 |
| 20 | 600 | 1,19 | 1,16 | 1,12 |
| 32 | 960 | 1,10 | 1,05 | 0,99 |

### 6.1.5 Depth and volume effects

The effect of beam size is based on Formula (24). According to Bohannan and others, breadth is not a significant parameter given that it is not involved in cascading forms of failure, where rupture over a small zone, immediately leads to rupture elsewhere without any assignable cause. Under the standard load condition, $a = L/3 = 6d = 6Nt$ with $t$, $\beta$, $k$ all identical so that both $a$ and $d$ depend on the number of laminations and lamination thickness. Depth and length size effects are taken to depend on these two variables only with $b$ being identical or simply not involved. A ratio is formed of the prediction at an arbitrary depth and at the standard depth that results in most terms cancelling.

$$\frac{f_{b,GL,05,p}}{f_{b,GL,05,p,\text{std}}} = \left(\frac{a_{\text{std}} d_{\text{std}}}{ad}\right)^{1/\beta} = \left(\frac{a_{\text{std}}}{a}\right)^{1/\beta} \left(\frac{d_{\text{std}}}{d}\right)^{1/\beta} \left(\frac{b}{b}\right)^{1/\beta} \tag{28}$$

Taking a standard lamination thickness as 30 mm (AS/NZS) and a standard depth as 300 mm $N_{\text{std}}$ is 10, but with (USA/Europe), 40 mm lamination thickness $N_{\text{std}}$ is 15 for a 600 mm reference depth beam. The term $1/\beta$ is in the range 0,128 ($V$ = 0,15) to 0,175 ($V$ = 0,20), but it is noted that $1/\beta$ = 0,082 8 for $V$ = 0,10 so that the index is sensitive in the range $V$ = 0,10 to 0,15 and any real-life test data can fit a range of $V$ values and appear plausible. The probability for failure to be simultaneously possible is given by multiplying the individual probabilities so that the effect of volume change on beam strength can be stated as

$$C_{\text{vol}} = \left(v_{\text{beam,std}} / v_{\text{beam}}\right)^{0,128} \tag{29}$$

### 6.1.6 Minor axis properties in bending also known as vertical glulam

The rupture of glulam in bending about its minor axis involves a different mechanism to its rupture about the major axis. Major failure involves the outer laminations being predominantly stressed in tension, whereas about the minor axis, all laminations are stressed in bending to approximately the same stress or, more accurately, the same deformation with stiffer laminations restricting the more flexible and presumably weaker ones. AS/NZS 1328 refers to a factor provided in AS 1720.1 known commonly as the parallel support factor and designated by the symbol $k_9$ given in Table 10.



 

**Table 10 — Values of $k_9$ extracted from AS 1720.1**

| Number of laminations ($N$) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 or more |
|---|---|---|---|---|---|---|---|---|---|---|
| $k_9$ | 1,00 | 1,14 | 1,20 | 1,24 | 1,26 | 1,28 | 1,30 | 1,31 | 1,32 | 1,33 |

### 6.1.7 Tension strength

Tension strengths in AS/NZS 1328 are set for both standard and custom glulam equal to the tension strength of the bonded pair. This approach is consistent with the Peter and Noziska (1973) observation that tension strengths at the 5th percentile level of bonded pairs are substantially higher than the tension strengths of single laminations, but that no further increases are seen with 3 or more bonded laminations. This principle is supported by the provisions of AS 1720.1 that does not support the use of $k_9$ modification factor in computing tension capacities although presumably it could do so for up to a factor of 1,14 if only two pieces were bonded.

### 6.1.8 Shear strength

Shear strengths are associated with the lamination grade that is used in the inner parts of a glulam member. For standard GL strength classes made from two different lamination grades, the simple expedient has been adopted of reducing the values by one stress grade. This simplification is applied only in the case of softwoods as there is insufficient scope in the choice of available strength grades to apply the principle to hardwood glulam.

### 6.1.9 Framework of AS/NZS 1328

AS/NZS 1328 is an omnibus standard in which the basic requirements are contained in the main body of the document, and technical details and test methods are outlined in appendices (annexes in ISO terminology).

## 6.2 AS/NZS 1328

### 6.2.1 Standard lamination requirements

#### 6.2.1.1 Feedstock for standard laminations

Standard lamination feedstock is required to be chosen as stated in Table 7 and thus meet the requirements for the stress grades of sawn timber given in AS 1720.1 or NZS 3603. In the case of standard laminations, this is achieved by compliance with one of the following:

a) AS/NZS 1748 for machine graded wood (MGP grades),

b) AS 2082 for visually graded hardwood,

c) AS 2858 for visually graded softwood,

d) AS 3519 for proof graded softwood and hardwood.

Wood-based laminating materials not listed in Table 7, such as laminated veneer lumber or other unspecified timber grades not covered by an AS, AS/NZS or NZS standard are deemed to be custom laminations. This allows a manufacturer to use in-house grading methods. See 6.2.2 for more details.

#### 6.2.1.2 Lamination tension strengths, finger joint strength in bending and finger joint location

The lamination tension strengths cited in Table 11 are based on the testing of bonded pairs containing finger joints and they exceed the tension strengths cited for the strength class of sawn timber cited in AS 1720.1. The values of tension strength given in Table 11 are valid only if the corresponding characteristic finger joint strength in bending, $\sigma_{b,fj}$, in bending are met. These strengths have been predetermined but under manufacturing conditions in which the finger joints are no closer than three knot diameters from any knot. See Figure 5. The finger joint strength is later used as an indicator property for factory production control. Failure to meet either condition means that a manufacturer is using custom laminations where other constraints apply.

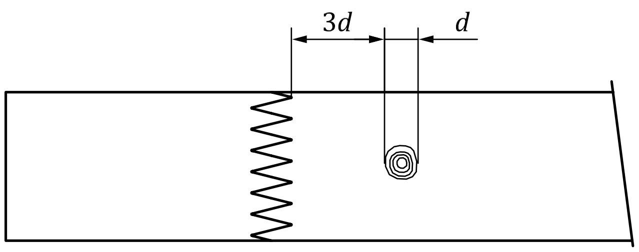


**Figure 5 — Location of finger joints relative to knots**

**Table 11 — Standard lamination grade designations, Lx, the stress grade of laminating feedstock, lamination tension strengths, $f'_{t,lam}$, elastic modulus, $E_{mean}$, and required finger joint strength in bending, $f'_{b,fj}$, after testing and evaluation to Appendix B of AS/NZS 1328:2017**

| Lamination grade | Stress grade laminating stock | Lamination bonded pair tension strength $f'_{t,lam}$ (MPa) | Mean elastic modulus $E_{mean}$ (MPa) | Characteristic finger joint bending strength $f'_{b,fj}$ (MPa) | Joint strength group |
|---|---|---|---|---|---|
| L8 | SG8 (NZ only) | 13,5 | 8 000 | 24 | JD5 |
| L10 | MGP10 | 15,0 | 10 000 | 25 | JD4 |
| L12 | MGP12 | 18,0 | 12 500 | 34 | JD4 |
| L13 | F17 | 21,0 | 13 300 | 41 | JD4 |
| L15 | MGP15 | 24,0 | 15 200 | 45 | JD4 |
| L17 | A17 | 28,0 | 16 000 | 50 | JD3 |
| L18 | F27 | 32,0 | 18 500 | 56 | JD2 |

#### 6.2.1.3 Determining lamination tension strengths of bonded pairs and recent test data

The procedure for obtaining the tension strengths is defined in AS/NZS 1328:2017, Appendix A. It is discussed in detail in in 6.2.2.3. Some test data observed in a recent series of tests are given in Tables 12 and 13. No bonded pair tension data are available for L8, L13 and L18. The *E* values were measured ultrasonically.

**Table 12 — Test data for bonded pairs of finger jointed laminations L10 and L12**

| | Radiata Pine MGP10/L10 | | | Radiata Pine MGP12/L12 | | |
|---|---|---|---|---|---|---|
| Test length (mm) | 3 200 | 3 200 | 2 600 | 3 200 | 3 200 | 2 600 |
| Size (mm × mm) | 65 × 40 | 65 × 40 | 65 × 80 | 66 × 42 | 66 × 42 | 65 × 83 |
| Finger joint | No | 2 minimum | 2 per lam | No | 2 minimum | 2 per lam |
| Number test pieces | 31 | 30 | 30 | 48 | 50 | 50 |
| CoV | 0,43 | 0,19 | 0,14 | 0,45 | 0,35 | 0,19 |
| $f_{t,bp,05}$ (MPa) | 13,8 | 13,5 | 19,4 | 12,7 | 13,7 | 19,0 |
| *E* (MPa) | 12 100 | 12 300 | 12 200 | 12 700 | 12 700 | 12 800 |

**Table 13 — Test data for bonded pairs of finger jointed laminations L15 and L17**

| | Slash Pine MGP15/L15 | | | Vic Ash A17/L17 | | |
|---|---|---|---|---|---|---|
| Test length (mm) | 3 200 | 3 200 | 2 600 | 3 200 | 3 200 | 2 600 |
| Size (mm × mm) | 66 × 32 | 66 × 32 | 65 × 63 | 66 × 32 | 66 × 32 | 65 × 33 |
| Finger joint | No | 2 minimum | 2 per lam | No | 2 minimum | 2 per lam |
| Number test pieces | 49 | 48 | 49 | 49 | 47 | 50 |
| CoV | 0,3 | 0,28 | 0,20 | 0,30 | 0,28 | 0,19 |
| $f_{t,bp,05}$ (MPa) | 22,9 | 21,1 | 26,3 | 28,3 | 21,2 | 33,9 |
| $E$ (MPa) | 17 500 | 17 700 | 17 700 | 17 600 | 17 600 | 17 800 |

### 6.2.2 Custom lamination requirements

#### 6.2.2.1 Feedstock for custom laminations

The feedstock for custom laminations must come from feedstock for which a full suite of characteristic properties is available by the same processes required of stress graded sawn timber used under AS 1720.1 or NZS 3603. This is not an easy pathway in that the standard strength classes have been the subject of industry wide initial type testing and are the basic foundation for AS 1720.1 and NZS 3603. Any manufacturer deciding to operate outside that system needs to establish a stress grading system and then to undertake the bonded pair tension testing as a further exercise in addition to setting the finger joint strengths necessary to achieve the tension strengths. For laminations composed of visually graded softwood or laminated veneer lumber characteristic properties may be taken from one of the following, but the bonded pair tension testing is an additional requirement:

a) AS 2858 for visually graded softwoods;

b) laminated veneer lumber that has been assigned characteristic properties by use of AS/NZS 4357.3 and AS/NZS 4357.4.

#### 6.2.2.2 Finger joint strength in bending about the minor axis in custom laminations

As stated in 6.2.2.1, custom laminations containing finger joints need to have a finger joint strength that does not adversely affect the characteristic lamination tension strength. An appendix is available that sets out the test methodology used to establish the required value.

#### 6.2.2.3 Determining lamination tension strengths of bonded pairs

The methodology for determining the tension strengths of the bonded pairs is detailed in Appendix A of AS/NZS 1328 and is undertaken over a test length of 1 800 mm, this being one-third of the span of a 'standard' glulam member. A standard depth for a glulam beam of 300 mm has been adopted in AS/NZS 1328 so that the standard test span for a member in bending according to AS/NZS 4364 and ISO 8375 is $18d = 18 \times 300$ mm = 5 400 mm. The elastic modulus is established by ultrasonic methods so that it can be correlated with a tension strength value. The procedure leads to the following values:

a) characteristic (mean) elastic modulus, $E_{mean}$, and its coefficient of variation, $V_E$,

b) characteristic tension strength, $f'_{t,lam}$, and its coefficient of variation, $V_{ft}$,

c) the Pearson correlation coefficient between, $f_{t,lam}$ and $E$.

The Pearson correlation coefficient is not specifically required unless the manufacturer chooses to use correlated values in a Monte Carlo simulation as described in AS/NZS 1328:2017, Section 4. In any event, the correlation between $f_{t,lam}$ and $E$ is negligible within a strength class in spite of the fact that it forms the basis for machine stress grading. It is a simple statistical fact that narrowing the range of $E$

values to sort pieces does not correspondingly narrow the range of strengths observed. Procedures are available to correlate, if desired.

### 6.2.3 Standard glulam and glued structural timber

#### 6.2.3.1 Characteristic strength and stiffness

Standard glulam of depth 300 mm and glued structural timber that is derived from standard laminations and with known minimum finger joint strengths can have glulam properties assigned to it as follows.

a) When composed of the lay-up details prescribed in Table 14, they may be deemed to have the set of characteristic properties equal those given in Table 15.

b) When composed of lay-up details other than those prescribed in Table 14, they may have the characteristic properties equal to those given in Table 15, subject to verification according to AS/NZS 1328:2017, Appendix B.

The purpose of b) is to allow a manufacturer to use a mixture of strength classes to achieve an end result. Typically, in New Zealand, L12 laminations are combined with L8 laminations to produce a GL10 glulam beam. See Reference [25]. The proportion of inner to outer laminations is determined by the formula $p^3 = (E_{\text{outers}} - E_{\text{GLgrade}})/(E_{\text{outers}} - E_{\text{inners}})$ and taking the specific case $p^3 = (12{,}7 - 10)/(12{,}7 - 8) = 0{,}57$ or $p = 0{,}83$ so that, for a beam with 20 laminations, $20 \times 0{,}83 \approx 16$ of the 20 laminations can be L8 and the 2 outers L12. But this results in a lowering of tension and shear strengths; the bending strength is not affected. The verification is carried out by one of the three following methods.

a) Test of the assembled glulam beam at the standard depth in bending and tension in accordance with ISO 8375.

b) Direct method outlined in 6.3.2 and 6.3.3 for balanced homogeneous and composite glulam.

c) A Monte Carlo simulation outlined in 6.3.2 and 6.3.4 for balanced and composite glulam and for unbalanced glulam.

**Table 14 — Lamination grade (Lx) for standard glulam grade (GLy) with laminations randomly distributed throughout the member cross-section**

| Standard GL grade (GLy) | Lamination derivative grade | Lamination grade (Lx) |
|---|---|---|
| GL8 | SG8 (NZ only) | L8 |
| GL10 | MGP10 | L10 |
| GL12 | MGP12 | L12 |
| GL13 | F17 | L13 |
| GL15 | MGP15 | L15 |
| GL17 | A17 | L17 |
| GL18 | F27 | L18 |

**Table 15 — Characteristic properties of standard glulam grades at depth 300 mm**

| Property | Glulam stress grade | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Symbol | GL8 | GL10 | GL12 | GL13 | GL15 | GL17 | GL18 |
| Bending strength (MPa) | $f_{b,GL,05}$ | 19 | 22 | 25 | 33 | 36 | 40 | 45 |
| h = homogeneous grades, c = composite grades | | | | | | | | |



 

**Table 15** *(continued)*

| Property | Glulam stress grade | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Symbol | GL8 | GL10 | GL12 | GL13 | GL15 | GL17 | GL18 |
| Tensile strength (MPa) | $f_{t,GL,05}$ | | | | | | | |
| | h | 12 | 13 | 18 | 21 | 24 | 28 | 32 |
| | c | 12 | 12 | 13 | 18 | 21 | 24 | — |
| | $f_{t,90,GL,05}$ | 0,5 | | | | | | |
| Compression strength (MPa) | $f_{c,GL,05}$ | 19 | 20 | 27 | 31 | 36 | 40 | 45 |
| | $f_{c,90,GL,05}$ | 2,5 | | | | | | |
| Shear strength (MPa) | $f_{s,GL,05}$ | 3,7 | 3,7 | 3,7 | 4,1 | 4,1 | 4,5 | 5,0 |
| Modulus of elasticity (MPa) | $E_{mean}$ | 8 000 | 10 000 | 12 500 | 13 300 | 15 200 | 16 700 | 18 500 |
| Joint group | The joint strength group should correspond to the lamination having the minimum tension strength given in Table 9. | | | | | | | |
| h = homogeneous grades, c = composite grades | | | | | | | | |

### 6.2.4 Custom glulam and glued structural timber

#### 6.2.4.1 Characteristic structural strength and stiffness

Custom glulam of depth 300 mm and glued structural timber can be deemed to have properties determined in accordance with the details set out in Table 16.

**Table 16 — Custom glulam grade characteristic values**

| Property | Symbol | Manufacturer's product description |
|---|---|---|
| Bending strength (MPa) | $f_{b,GL,05}$ | Testing and evaluation according to AS/NZS 4063.1 and AS/NZS 4063.2 (Method 1) or by computation (Method 2); see 6.3.1. |
| Tensile strength (MPa) | $f_{t,GL,05}$ | Testing and evaluation according to AS/NZS 4063.1 and AS/NZS 4063.2 (Method 1) or by computation (Method 2); see 6.3.2 and 6.3.3, or 6.3.2 and 6.3.4 |
| | $f_{t,90,GL,05}$ | 0,5 or establish custom properties |
| Compression strength (MPa) | $f_{c,GL,05}$ | Equal to bending strength |
| | $f_{c,90,GL,05}$ | 1,5 or establish custom properties |
| Shear strength (MPa) | $f_{s,GL,05}$ | Equal to shear strength of inner laminations determined according to AS/NZS 4063.1 and AS/NZS 4063.2 |
| Modulus of elasticity (MPa) | $E_{mean}$ | Testing and evaluation according to AS/NZS 4063.1 and AS/NZS 4063.2 (Method 1) or by computation (Method 2) |
| Joint group | *JDx* | As specified by the manufacturer or determined by AS 1649 |

NOTE For verification of this requirement refer to AS/NZS 1328.

## 6.3 AS/NZS 1328:2017, Appendix B

### 6.3.1 Determination of glulam major axis bending strength by computation

This section provides the general principles for determining glulam bending strength and stiffness of standard and custom glulam. The direct method can be based on a simple spreadsheet computation but access to suitable software is required for Monte Carlo simulation.

### 6.3.2 Beam bending stiffness $(EI)_c$

Both methods require the computation of composite beam bending stiffness values (see Figure 6).

a) transformed axial stiffness

$$(EA)_c = bt\sum_{i=1}^{N} E_i$$

b) transformed first moment of area relative to the lower tension face

$$(EQ)_c = bt\sum_{i=1}^{N} E_i \left(i - \frac{1}{2}\right)t$$

c) neutral axis position, $\bar{y}$, relative to the lower tension face

$$\bar{y} = (EQ)_c / (EA)_c$$

d) transformed bending stiffness

$$(EI)_c = bt\sum_{i=1}^{N} E_i \left[\left(i - \frac{1}{2}\right)t\right]^2 + \frac{1}{12}bt^3\sum_{i=1}^{N} E_i - (EA)_c\,\bar{y}^2$$

where

$E_i$ is the elastic modulus of the $i^{\text{th}}$ lamination;

$N$ is the number of laminations.

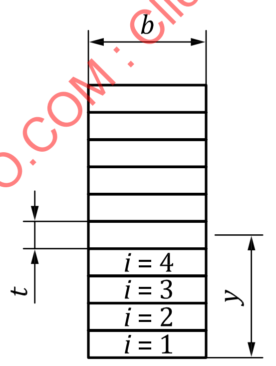


**Figure 6 — Parameters used to determine section stiffness in bending using transformed section theory**



### 6.3.3 Direct method for major axis bending and effective stiffness

a) Computation of the value of $(EI)_c$ and $\bar{y}$ as described in 5.3.2.

b) Computation of the elastic modulus in bending as

$$E = 12(EI)_c / b(Nt)^3$$

c) Computation of the characteristic bending strength as

 