WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

# EXPERIMENTAL STUDY ON THE BENDING PROPERTIES OF GLULAM MADE BY FAST-GROWING CHINESE FIR

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**ABSTRACT:** To facilitate rational utilization of China's abundant fast-growing forest resources, this study investigated the flexural performance of glulam fabricated from fast-growing Chinese fir (*Cunninghamia lanceolata*) using machine-graded laminations. Key findings include: (1) Transverse vibration method grading revealed that M22 and M18 strength classes collectively contributed to over 80% of total lamina production. (2) The glulam exhibited significantly reduced coefficients of variation in bending properties compared to raw laminations, with both lamina grade and lamination assembly configurations demonstrating statistically significant effects on mechanical performance. (3) The maximum achievable strength class reached $TC_T40$, with most specimens meeting $TC_T32$/$TC_{YD}32$ requirements. Notably, the derived design values for bending strength exceeded those specified in GB50005-2017 "Standard for Design of Timber Structures" for corresponding GLT grades.

**KEYWORDS:** Fast-growing Chinese fir; glulam; machine grading; full-scale testing; bending property

## 1 – INTRODUCTION

Modern timber structures have gained increasing attention due to their advantages in green sustainability, seismic resilience, and high prefabrication efficiency [1]. Despite the rapid development of timber construction in China, the domestic production of glulam has long relied on imported lamination from foreign sources [2]. Current national standards including GB 50005-2017 "Standard for Design of Timber Structures" and GB/T 50708-2012 "Technical Code for Glued Laminated Timber Structures" primarily specify softwood species of European and American origins as suitable raw materials, while domestic fast-growing timber species such as Chinese fir (*Cunninghamia lanceolata*) remain excluded from the approved list. This regulatory gap underscores the critical need for systematic investigation into the mechanical properties of glulam manufactured from domestic fast-growing Chinese fir.

Fast-growing plantation timber exhibits inherent limitations including lower density, dimensional instability, and significant variability in mechanical properties due to growth conditions and natural defects [3]. To ensure the structural reliability of Chinese fir glulam, grading of lamination becomes imperative [4]. Existing research [5] demonstrates that grading methods substantially affect timber classification outcomes, with machine grading showing superior reliability compared to visual grading. Advanced nondestructive techniques such as longitudinal stress wave testing and transverse vibration analysis have proven effective for efficient quality assessment [6,7].

Recent years have witnessed experimental investigations on glulam beams fabricated from fast-growing species including poplar [3,8], Chinese fir [9], and larch [10], yielding valuable insights into flexural performance. However, current glulam production predominantly utilizes ungraded or visually graded laminations, resulting in suboptimal material utilization efficiency and heightened performance variability. Furthermore, existing studies have not adequately addressed the critical influences of lamination with divergent mechanical properties and layup configurations on composite structural behavior. This investigation therefore focuses on experimental evaluation of flexural performance in glulam manufactured from machine-graded Chinese fir lamination, aiming to establish technical references for engineered applications of fir glulam.

## 2 – TEST DESIGN

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https://doi.org/10.52202/080513-0600

## 2.1 MACHINE GRADING OF CHINESE FIR LAMINATION

The fast-growing Chinese fir were harvested from Congjiang County, Guizhou Province, with approximately 30-year growth cycles and minimum diameter at breast height of 25 cm. Through sequential processing including cross-cutting, kiln drying, and surface planing, 1,937 sawn timber specimens were prepared. The specimens exhibited average moisture content of 14.4% and mean density of 390 kg/m³. Specimens were categorized into two dimensional groups based on cross-sectional width: 1,305 pieces measuring 40 mm × 150 mm, and 632 pieces of 40 mm × 85 mm configuration, all maintaining 4,000 mm length aligned with longitudinal grain direction.

Following GB/T 29895-2013 "Method for Determining Dynamic Modulus of Elasticity of Wood-Based Materials by Transverse Vibration", machine grading was conducted using a Metriguard Model 340 E-computer portable grading device. The transverse vibration dynamic modulus of elasticity (Et, in GPa) was determined through the following relationship:

$$E_{\mathrm{t}} = GL^3 f_1^2 \Big/ \left(Kbd^3\right) \qquad (1)$$

Where, $G$ is specimen weight (N), $L$ is span length (mm), $f_1$ is fundamental frequency (Hz), $K$ is constant ($1.83\times10^6$).

The machine grading process generated $E_{\mathrm{t}}$ and density ($\rho$) datasets for all specimens. Specimens were classified into five grade classes (S, I, II, III, R) based on $E_{\mathrm{t}}$ and $\rho$ distributions. Quality control measures ensured the combined percentage of specimens in the highest and lowest grades remained below 10%, with detailed distribution presented in Table 1.

**Table 1 Results of machine grading**

| Grade class | $E_{\mathrm{t}}$/GPa | | $\rho$/(kg·m$^{-3}$) | | Number | Percentage /% |
|---|---|---|---|---|---|---|
| | Section | Mean | Section | Mean | | |
| S | ⩾11.2 | 12.84 | ⩾480 | 497 | 11 | 0.6 |
| I | [9.4,11.2) | 11.62 | [430,480) | 450 | 193 | 10.0 |
| II | [7.6,9.4) | 10.08 | [380,430) | 409 | 772 | 39.8 |
| III | [5.8,7.6) | 8.70 | [330,380) | 367 | 842 | 43.5 |
| R | <5.8 | 7.37 | <330 | 321 | 119 | 6.1 |

Conventional determination of wood strength properties through clear wood specimens fails to account for critical influencing factors including natural defects and size effects, potentially compromising the accuracy of strength predictions and structural safety. To address this methodological limitation, full-scale bending tests and longitudinal tensile tests were systematically conducted on fast-growing Chinese fir laminations. The tests measured flexural modulus of elasticity $E_{\mathrm{s}}$, bending strength $f_{\mathrm{m}}$, and longitudinal tensile strength $f_{\mathrm{t}}$. The test results are listed in Table 2. Comparative analysis with Table 1 reveals a linear correlation between the $E_{\mathrm{t}}$ and $E_{\mathrm{s}}$ in Chinese fir lamination. Furthermore, distinct differentiation in mechanical properties was demonstrated across all graded classes. To align with practical requirements for glulam manufacturing, lamination classification was conducted in accordance with GB/T 36407-2018 and GB/T 50708-2012, with comparative grading results systematically presented in Table 2. The data explicitly show direct correspondence between vibration grading results and standardized mechanical classifications. This correlation validates the efficacy of transverse vibration methodology in characterizing the mechanical behavior of Chinese fir lamination. Notably, the proposed nondestructive evaluation technique provides enhanced operational efficiency compared to conventional standardized grading protocols.

**Table 2 Mechanical properties of Chinese fir lamination**

| Grade class | $E_{\mathrm{s}}$ | | $f_{\mathrm{m}}$ | | $f_{\mathrm{t}}$ | | Grading method | |
|---|---|---|---|---|---|---|---|---|
| | Mean /MPa | COV/% | Mean /MPa | COV/% | Mean /MPa | COV/% | Stress | MOE |
| I | 12634 | 9.7 | 50.46 | 21.7 | 30.60 | 26.1 | M26 | $M_E$12 |
| II | 11641 | 10.2 | 47.67 | 21.5 | 24.47 | 26.1 | M22 | $M_E$11 |
| III | 10411 | 11.7 | 41.28 | 21.4 | 18.76 | 22.1 | M18 | $M_E$10 |

## 2.2 MACHINE GRADING OF CHINESE FIR LAMINATION

A total of 45 glulam specimens fabricated from Chinese fir were designed and prepared. The specimens featured cross-sectional dimensions of 140 mm × 240 mm and a length of 4,000 mm, with all specimens composed of seven-layer machine-graded laminations. Based on lay-up methods, the specimens were classified into two groups: homogeneous grade combination glulam (labeled T1–T3) and symmetric heterogeneous grade combination glulam (labeled Y1–Y3). Detailed specimen parameters are summarized in Table 3.

**Table 3 Parameters of specimens**

| Group | T1 | T2 | T3 | Y1 | Y2 | Y3 |
|---|---|---|---|---|---|---|
| Number | 5 | 15 | 5 | 5 | 5 | 10 |
| $\rho$/(kg·m$^{-3}$) | 439 | 403 | 369 | 403 | 377 | 386 |
| Lay-up methods | I<br>I<br>I<br>I<br>I<br>I<br>I | II<br>II<br>II<br>II<br>II<br>II<br>II | III<br>III<br>III<br>III<br>III<br>III<br>III | I<br>II<br>III<br>III<br>III<br>II<br>I | I<br>III<br>III<br>III<br>III<br>III<br>I | II<br>II<br>III<br>III<br>III<br>II<br>II |

In accordance with GB/T 50329-2012 Standard for Test Methods of Timber Structures [12], four-point bending tests were conducted on 45 glulam specimens to determine their static flexural elastic modulus and flexural strength. The test setup is illustrated in Fig. 1. To ensure pure bending conditions, the span-to-depth ratio (L/h) was maintained at 16. The test employed monotonic displacement control with a loading rate of 25 mm/min, achieving failure within the targeted duration of 1-3 minutes.

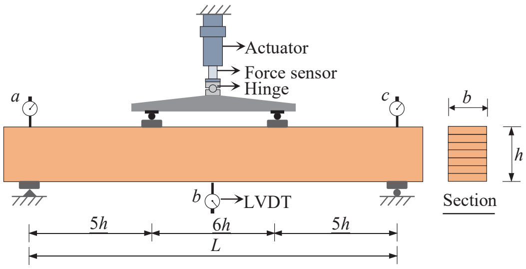



**Fig.1 Test setup**

The apparent flexural elastic modulus $E_m$ and $f_m$ of the specimens were calculated using the following equations:

$$E_m = \frac{u(3L^2 - 4u^2) \cdot \Delta F}{48I \cdot \Delta e} \quad (2)$$

$$f_m = \frac{F_{max} u}{2W} \quad (3)$$

where $u$ is the distance from the individual loading point to the support (mm), $I$ represents the cross-sectional moment of inertia (mm⁴), and $W$ denotes the section modulus (mm³).

## 3 – RESULTS AND DISCUSSION

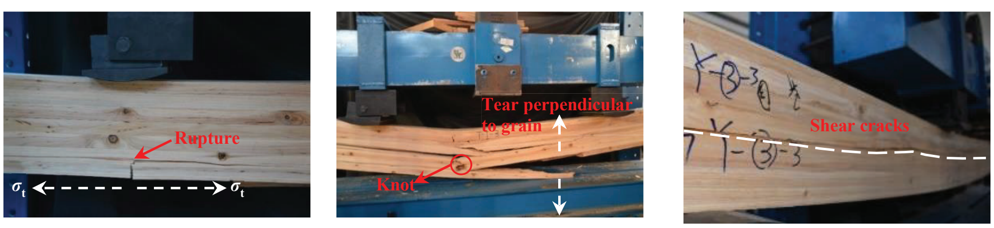
### 3.1 – FAILURE MODES

Figure 3 illustrates the typical failure modes of Chinese fir glulam. During initial loading stages, all specimens exhibited linear growth of mid-span deflection with increasing load. As loading progressed, bending deformation became progressively pronounced. Three distinct failure patterns emerged near peak load:

(a) For defect-free specimens, tensile fiber rupture initiated at mid-span or third-point regions of the outer tension lamination, accompanied by horizontal crack propagation, leading to abrupt load-bearing capacity loss characteristic of brittle failure (Fig. 2a).

(b) Specimens containing natural defects (knots or grain deviations) in the pure bending region demonstrated longitudinal splitting through transverse tensile failure at defect locations under stress concentration, resulting in similar brittle fracture patterns (Fig. 2b).

(c) A minority of GLT specimens (5.3%) failed through lamination shear splitting in intermediate layers under combined bending and shear stress (Fig. 2c).




(a) Tensile failure at outer laminas (b) Tensile failure at the knots (c) Shear failure at inner laminations

**Fig.2 Typical failure modes of glulam**

### 3.2 – LOAD-DEFLECTION CURVES

The load-deflection curves of the specimens are presented in Fig. 3. The bending process can be divided into elastic phase and failure phase, as most specimens exhibited abrupt brittle failure with only isolated cases showing limited elastoplastic behavior during later loading stages. As shown in Fig. 3, the T2 and T3 specimen groups demonstrated average load-bearing capacity reductions of approximately 15.4% and 43.5% respectively compared to T1 group, while Y2 and Y3 groups showed decreases of 0.08% and 9.15% relative to Y1 group. This indicates that the flexural capacity of glued laminated timber decreases with the reduction in grade quality of constituent laminations. Notably, the Y2 group exhibited an 18.4% reduction in average capacity compared to T1 group, but displayed a 44.3% increase relative to T3 group. Similar trends were observed in T2, T3 and Y3 groups, demonstrating that the flexural capacity of GLT is primarily governed by the performance of outer laminations. Higher-grade exterior laminations significantly enhance mechanical properties, thereby increasing the overall bending resistance of the composite structure.


https://doi.org/10.52202/080513-0600

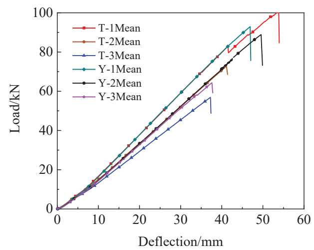



**Fig.3 Load-deflection curves of specimens**

## 3.3 – MODULUS OF ELASTICITY AND BENDING STRENGTH

As demonstrated in Table 4, both the modulus of elasticity $E_m$ and bending strength $f_m$ progressively decreased across specimen groups T1–T3 and Y1–Y3, revealing distinct mechanical performance gradients in Chinese fir glulam fabricated with machine-graded laminations. The T3 group exhibited significantly lower $E_m$ and $f_m$ values compared to other groups. When replacing its surface or outer laminations with Grade I/II Chinese fir laminations, the flexural elastic modulus increased by 15.4–37.5%, accompanied by 32.6–45.5% enhancement in flexural strength. Due to Chinese fir's rapid growth cycle and small stem diameters (see Table 1), high-grade laminations account for less than 20% of total production, while medium-low grade laminations constitute over 80%. The proposed heterogeneous-grade GLT assemblies demonstrated economically viable solutions — by strategically combining laminations of varying mechanical grades, comparable mechanical performance to medium-high grade homogeneous GLT was maintained, while significantly improving material utilization efficiency.

**Table 4 Modulus of elasticity and bending strength**

| Group | $E_m$ Mean /MPa | $E_m$ COV /% | $f_m$ Mean /MPa | $f_m$ COV /% | Group | $E_m$ Mean /MPa | $E_m$ COV /% | $f_m$ Mean /MPa | $f_m$ COV /% |
|---|---|---|---|---|---|---|---|---|---|
| T1 | 13211 | 4.40 | 53.23 | 8.51 | Y1 | 12760 | 7.04 | 46.50 | 8.94 |
| T2 | 11083 | 9.75 | 44.98 | 14.93 | Y2 | 11458 | 4.71 | 40.20 | 7.52 |
| T3 | 9608 | 3.62 | 29.87 | 14.71 | Y3 | 11422 | 5.98 | 39.61 | 18.57 |

## 3.4 – CHARACTERISTIC BENDING STRENGTH

Typically, the strength of glued laminated timber follows a log-normal distribution, while its elastic modulus follows a normal distribution [14]. Due to the small sample size of each group in this study, the characteristic bending strength $f_{mk}$ and characteristic modulus of elastic $E_k$ of Chinese fir glulam were determined according to the parameters specified in the European standard EN 14358 "Timber structures—Calculation and verification of characteristic values".

$$E_k = E_m - k_s s_E \tag{4}$$

$$f_{mk} = \exp(f_m - k_s s_f) \tag{5}$$

$$f_m = \frac{1}{n}\sum_{i=1}^{n} \ln f_i \, , \tag{6}$$

$$E_m = \frac{1}{n}\sum_{i=1}^{n} E_i \tag{7}$$

$$s_f = \max\begin{cases} \sqrt{\dfrac{1}{n-1}\sum_{i=1}^{n}(\ln f_i - f_m)^2} \\ 0.05 \end{cases} \tag{8}$$

$$s_E = \max\begin{cases} \sqrt{\dfrac{1}{n-1}\sum_{i=1}^{n}(E_i - E_m)^2} \\ 0.05E_m \end{cases} \tag{9}$$

where $s_E$ and $s_f$ are the standard deviations of the bending strength and modulus of elastic of the specimens, respectively; $k_s$ is the characteristic coefficient, whose value depends on the number of specimens $n$: 2.46 when $n$=5, 2.10 when $n$=10, and 1.99 when $n$=15.

The calculated characteristic bending strength and modulus of elastic values of glulam are listed in Table 5. Both characteristic bending strength and modulus of elastic decrease with the reduction of lamination grades. Compared to T3 group, T1 and T2 groups exhibit 110.1% and 62.1% increases in characteristic bending strength, respectively, with corresponding modulus of elastic improvements of 37.5% and 4.8%. However, Y1, Y2, and Y3 groups show 81.8%, 62.3%, and 27.7% enhancements in characteristic bending strength, respectively, accompanied by 25.2%, 19.2%, and 18.5% increases in modulus of elastic. These results demonstrate that upgrading the grade of outer laminations significantly improves overall mechanical performance.

For engineering applications of fast-growing Chinese fir glulam, Table 5 compares the lay-up grade class and actual grade class according to GB/T 26899-2022 Structural glued laminated timber. All groups except T3 achieve actual grade class equal to or higher than their lay-up grade class, and most specimens meet $TC_T32$ ($TC_{YD}32$) strength class requirements. The results demonstrate that Chinese fir laminations graded by the transverse vibration method can produce glulam that meets the mechanical performance requirements for glulam assembly. This confirms that domestically fast-growing Chinese fir serves as a suitable species for glulam.

**Table 5 Characteristic values of bending strength and calculated values for elastic modulus of glulams**

| Group | $f_{mk}$/MPa | $E_k$/MPa | | Lay-up grade | Strength grade |
|---|---|---|---|---|---|
| | | Mean | Standard | | |
| T1 | 42.79 | 13211 | 11586 | $TC_T36$ | $TC_T40$ |
| T2 | 33.01 | 11083 | 8932 | $TC_T32$ | $TC_T32$ |
| T3 | 20.37 | 9608 | 8426 | $TC_T28$ | $TC_T20$ |
| Y1 | 37.03 | 12760 | 10548 | $TC_{YD}28$ | $TC_{YD}36$ |
| Y2 | 33.07 | 11458 | 10048 | $TC_{YD}24$ | $TC_{YD}32$ |
| Y3 | 26.01 | 11422 | 9987 | $TC_{YD}24$ | $TC_{YD}24$ |

### 3.5 – DESIGN VALUE OF BENDING STRENGTH

According to the reliability analysis method for wood design parameters [15], the design value of bending strength $f_{md}$ of fast-growing Chinese fir glulam can be determined by the following equation:

$$f_{md} = \frac{f_{mk} K_{Q3}}{\gamma_R} \qquad (10)$$

Where, $K_{Q3}$ represents the load duration effect coefficient, taken as 0.72, $\gamma_R$ denotes the resistance partial factor.

The calculated design value of bending strength of glulam are presented in Table 6. Compared with the design value of bending strength specified for comparable-grade glulam in GB50005-2017, the proposed values for Chinese-fir glulam in this study demonstrate conservative values with systematically higher magnitudes. This indicates that Chinese-fir glulam with rational lay-up configurations possesses sufficient margin of safety in bending resistance, confirming its suitability for practical engineering applications.

**Table 7 Design values of bending strength of glulams**

| | T-1 | T-2 | T-3 | Y-1 | Y-2 | Y-3 |
|---|---|---|---|---|---|---|
| $f_{md,test}$/MPa | 29.5 | 23.0 | 14.2 | 25.8 | 22.9 | 17.9 |
| $f_{md,GB50005}$/MPa | 27.9 | 22.3 | — | 19.5 | 22.3 | 16.7 |

## 6 – CONCLUSION

1) The machine grading method based on the transverse vibration modulus of elasticity can effectively and distinctly differentiate the mechanical properties of domestic China fir laminates. Specifically, laminations with strength grades M22 and M18 collectively account for over 80% of the total, demonstrating the method's efficiency in classifying fast-growing timber resources.
2) The lay-up configuration of laminations significantly influences the flexural performance of fast-growing Chinese fir glulam. Experimental results reveal that strategically enhancing the grade of outer-layer laminations in glulam fabrication leads to substantial improvements in bending resistance characteristics, providing an optimized approach for structural applications.
3) Strength classification analysis indicates that homogeneous combinations of fast-growing Chinese fir glulam achieve standardized grades ranging from $TC_T20$ to $TC_T40$ based on modulus of elasticity and bending strength criteria, and heterogeneous combinations attain grades between $TC_{YD}24$ and $TC_{YD}36$. These compliance ranges with national specifications confirm the technical feasibility of utilizing fast-grown domestic China fir in engineered wood product manufacturing.
4) Reliability theory-based calculations establish that all the design values of bending strength for fast-growing Chinese fir glulam exceed the corresponding grade requirements specified in GB50005-2017 "Standard for Design of Timber Structures". This theoretical verification provides crucial design references and validates the engineering applicability of ast-growing Chinese fir glulam in load-bearing structures.

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