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Published in:
European Journal of Wood and Wood Products

DOI:
[10.1007/s00107-025-02265-5](https://doi.org/10.1007/s00107-025-02265-5)

Published: 01/06/2025

Document Version
Publisher's PDF, also known as Version of record

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Please cite the original version:
Vafadar, F., Collins, S., & Fink, G. (2025). Bayesian modeling of finger joints' tensile and bending properties considering censored data. *European Journal of Wood and Wood Products*, 83(3), Article 110.
<https://doi.org/10.1007/s00107-025-02265-5>

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Bayesian modeling of finger joints' tensile and bending properties considering censored data

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Received: 24 January 2025 / Accepted: 23 April 2025
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Abstract

Finger joints (FJs) are longitudinal interlocking connections between timber boards commonly used in engineered wood products such as glued laminated timber beams. The mechanical properties of FJs, particularly tensile strength, are vital for the performance of such products; however, practical constraints often lead to testing FJs primarily in bending rather than tension. Therefore, it is crucial to investigate the relationship between tensile and bending strengths. The present study investigates this relationship using paired FJs. It further evaluates the predictability of FJ tensile and bending properties based on the dynamic modulus of elasticity of the connected timber boards. Tensile and bending tests were conducted, and censored data resulting from failures outside the FJs were handled using a hierarchical Bayesian linear regression method. The study proposes models to estimate FJ tensile strength from bending strength and to predict tensile and bending properties based on the dynamic modulus of elasticity of the connected timber boards. Model predictions are compared with experimental outcomes, indicating the effective integration of censored data. Results further show that excluding censored data underestimates FJ tensile and bending strength. The proposed Bayesian modeling procedure offers a means to connect failure modes with data types and appropriately address censored data. Such models can help to enhance quality control/production efficiency and the structural reliability of engineered wood products.

1 Introduction

Finger joints (FJs) are a fundamental woodworking technique used to connect two timber boards longitudinally. FJs are widely utilized in structural applications to fabricate endless lamellae that are used to produce engineered wood products, such as glued laminated timber (GLT) beams. The production process involves cutting the timber board cross-sections at an angle to generate finger-like protrusions that interlock. The joints are bonded using adhesive and pressure to establish a connection. For more detailed information

about the FJ production, it is referred to (e.g., Jakerst 1981; Prins 1982).

FJs significantly influence the mechanical properties of engineered wood products, particularly the bending strength of the GLT beams (Fink et al. 2015). The importance of FJ mechanical properties for the GLT beams properties is highlighted in Ehlbeck and Colling (1986), where the characteristic bending strength of GLT beams was estimated based on the characteristic tensile strength of FJs and timber boards. Despite the significant relevance of FJ tensile strength ($f_{t,j}$)¹ to GLT beam mechanical properties, practical considerations often lead to FJs being tested primarily in bending rather than tension. Therefore, it is crucial to investigate the relationship between $f_{t,j}$ and FJ bending strength ($f_{m,j}$).

To investigate the $f_{t,j}$ and $f_{m,j}$ relationship, the type of information obtained from experimental investigations should be adequately considered. In tensile and bending testing of the FJs, when the specimens fail within the FJs, $f_{t,j}$ and $f_{m,j}$ are directly observed from the tests (in this paper, such information is categorized as uncensored).

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¹ In this study, the subscript “j” is used to denote the mechanical properties specifically associated with the FJs, following the notation form for strength properties of FJs presented in EN 14080 (2013).

However, it is also common that specimens fail in the wood around the FJs or the testing apparatus. In these cases, although $f_{t,j}$ and $f_{m,j}$ are not directly captured, they may be assumed to be greater or equal to the observed strength values from the tests, i.e., $f_{t,j}$ and $f_{m,j} \geq$ observed strength values (in this paper, such information is categorized as censored).

The relationship between $f_{t,j}$ and $f_{m,j}$ has been investigated in limited literature. In a prior study (Larsen 1982), 300 FJs were fabricated, of which half of the specimens were tested in tension, and the other half were tested in bending. On average, a ratio of 0.62 between the tensile strength and bending strength of the specimens was reported based on the test results. The data analysis was performed by including all the data and treating them similarly regardless of failure mode, although it is the position of the current paper that not all experimental results represent the same type of information. Moreover, in a separate study (Görlacher et al. 1991), tensile and bending tests were performed on 700 FJs to investigate the ratio between the characteristic values (5th percentile which is denoted with subscript "k") of FJs tensile ($f_{t,j,k}$) and bending ($f_{m,j,k}$) strength. On average, a ratio of $f_{t,j,k}/f_{m,j,k} \approx 0.65$ was identified. Wherein, the data of the specimens with failures outside the FJs were excluded from analysis. The relationship between $f_{t,j,k}$ and $f_{m,j,k}$ is also addressed in the European standard EN 14080 (2013) for validation of the GLT beams strength classes. In general, investigations into the relationship between $f_{t,j}$ and $f_{m,j}$ have primarily focused on estimating their characteristic or mean strength ratios while excluding or misinterpreting censored data. This approach potentially biases results and limits the reliability of the findings. Furthermore, the predictability of $f_{t,j}$ based on $f_{m,j}$ while explicitly accounting for censorship effects in both strength properties has not been investigated in detail. Addressing this gap is vital for developing robust predictive models and enhancing the understanding of FJ mechanical behavior.

Beyond the FJ tensile-to-bending strength relationship, several studies have investigated the potential to predict FJ mechanical properties using other parameters. Studies have shown that the tensile strength of finger-jointed timber boards correlates with their flatwise bending stiffness, with a correlation coefficient of $r \approx 0.5$ (see, e.g., Heimeshoff and Gios 1980; Samson 1985,). Also, $f_{t,j}$ was estimated based on the tensile modulus of elasticity of the finger-jointed timber boards using linear regression analysis (Moody 1970; Ehlbeck et al. 1985). A correlation coefficient of $r \approx 0.5$ was found between $f_{t,j}$ and the modulus of elasticity. Moreover, studies on $f_{m,j}$ have highlighted a correlation to the dynamic bending modulus of elasticity (Frese and Blaß 2006; Stapf and Aicher 2011). The dynamic modulus of elasticity of the individual timber boards (E_{dyn}), particularly its minimum

value ($E_{dyn,min}$) in the FJs, was found to be correlated to $f_{t,j}$ and $f_{m,j}$ (see, e.g., Ehlbeck and Colling 1990; Fink et al. 2021; Vafadar et al. 2023). Despite these findings, the research has generally taken two approaches to data handling by either excluding test results from specimens failing outside the FJ or treating all test results equivalently, regardless of the failure mode. These approaches potentially bias the results, underscoring the need for an appropriate approach to data handling.

Therefore, the present paper addresses these potential shortcomings by 1) investigating the relationship between $f_{t,j}$ and $f_{m,j}$ based on the result of testing paired FJs and 2) evaluating the predictability of $f_{t,j}$, $f_{m,j}$, and the local bending stiffness ($E_{m,l}$) while accounting for censored data and the effect of censorship. The study builds on the findings of Vafadar et al. (2023), which presents experimental investigations of the FJs and correlation analysis between their tensile and bending mechanical properties and E_{dyn} .

Hierarchical Bayesian linear regression modeling is utilized in this study, accommodating censored data in both predictor and dependent variables. Consequently, incomplete information from test results can be effectively incorporated. An additional benefit of this approach is the inclusion of prior information, which hierarchically reflects initial beliefs about the parameters, enhancing the robustness of the model. Bayesian models of this nature have been applied in various studies (see, e.g., Groth et al. 2017, 2018).

2 Material, test setup and procedure

This section summarizes specimen description, tensile and bending test setups, and procedures. More detailed information about the fabrication of the finger-jointed specimens and the experimental investigations can be found in Vafadar et al. (2023).

2.1 Specimens

To produce the finger-jointed specimens, spruce timber boards sourced from southern Finland, with cross-sectional dimensions of $w \times t = 125 \times 50$ mm² and lengths ranging from $l = 3800$ mm to 4700 mm were used. The E_{dyn} of all timber boards was measured, based on eigenfrequency, with the commercial grading device Precigrader (Dynalyse).

To fabricate the finger-jointed specimens, each timber board was halved, and each segment was joined with a complementary half from another board to form endless lamellae. Specimens were then cut from the lamellae; however, some were excluded due to insufficient length for testing. A total of 227 FJs were produced, with 110 allocated for

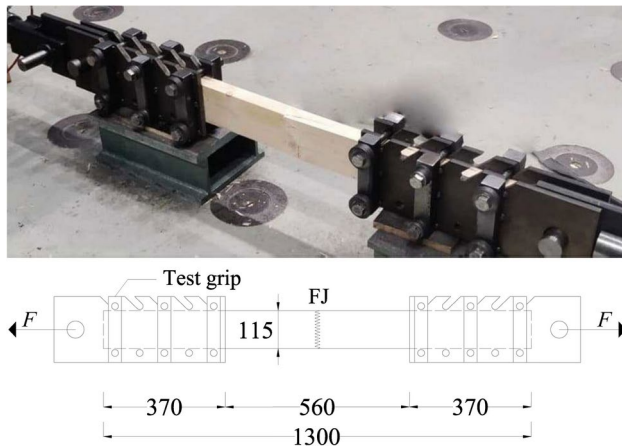


Fig. 1 Tensile test setup. The FJ is located in the middle of the specimen. Dimensions are in mm

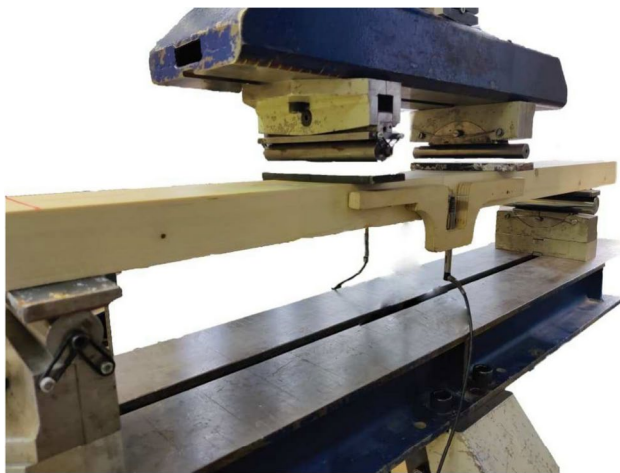


Fig. 2 Bending test setup. The FJ is located in the middle of the specimen. Dimensions are in mm

tensile testing and 117 for bending testing. After fabrication, the specimens were planed and cut to their final dimensions: $w \times t \times l = 115 \times 45 \times 1300 \text{ mm}^3$ for tensile tests and $w \times t \times l = 115 \times 45 \times 1000 \text{ mm}^3$ for bending tests.

To compare FJs' tensile and bending mechanical properties 2×98 paired specimens were identified among the finger-jointed timber boards, where paired refers to specimens fabricated from the same original timber boards. For example, boards A and B are halved, and the pairs are the two specimens fabricated with A connected to B.

The FJs were produced according to the specifications outlined in EN 15497 (2014), with finger profiles characterized by a length of 15 mm, a pitch of 3.8 mm, and a cutter width of 0.42 mm. Melamine Formaldehyde adhesive was used in the bonding process. To promote uniform moisture content conditions, all specimens were conditioned in a climate chamber at 20°C , with a relative humidity of 65%.

2.2 Tensile and bending tests

Tensile and flat-wise four-point bending tests were performed on the specimens according to EN 408 (2012). The tensile test setup is shown in Fig. 1. The specimens were secured using clamps with a grip length of 370 mm, and the clear test length of the specimens was 560 mm with the FJs in the middle. The load was applied with the force control protocol at a rate of 30 kN/min.

In the bending tests, the span (distance between the supports) was 810 mm, as shown in Fig. 2. The loading protocol was force-controlled at a rate of 2.5 kN/min. The local deflections were measured by two linear variable differential transformers, each installed on the side of the test specimens at the FJ location.

3 Experimental results

The specimens were investigated visually after testing to identify the type of failure. Based on the specimen's fracture pattern, they are categorized into four groups. Examples of the failure types are shown in Fig. 3. The same failure classification is used in a prior related study, refer to Fink et al. (2018) for more information on the the classification details.

- Finger joint failure (FF): more than two-thirds of fractures are identified in the FJs areas.
- Mixed failure (MF): fracture is a combination of FJ and wood, with less than $2/3$ of the fracture in the FJ and less than $2/3$ of the fracture in the wood.
- Wood failure (WF): more than two-thirds of fractures are identified in the wood section.
- Slip from the grip (S). Note: it only happened in the tensile tests.

In the tensile tests, around half of the specimens (51%) failed in the FJs (type FF), 15% were MF, 30% were WF,

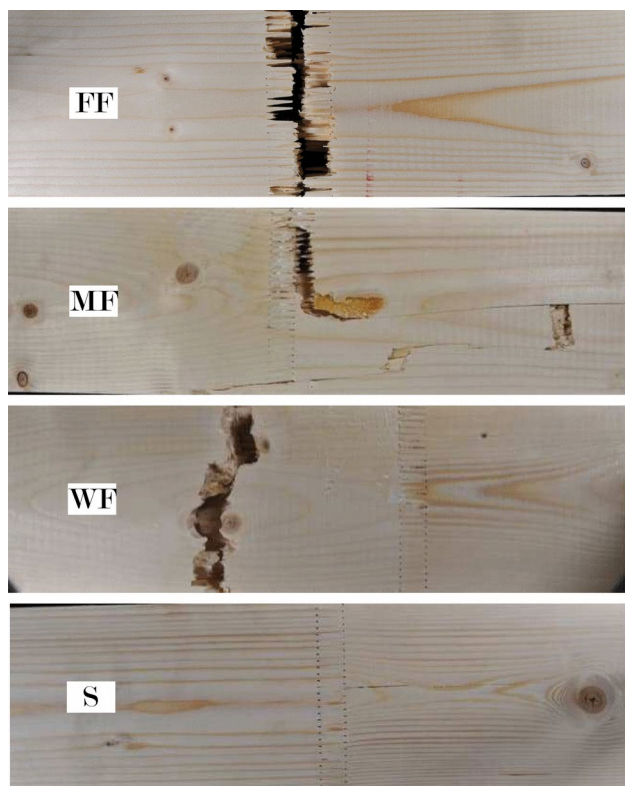


Fig. 3 Examples of typical failure types: Finger joint failure (FF), mixed failure (MF), wood failure (WF), and slipping from the tensile test grips (S)

and 4% slipped from the grips. The bending failure types were composed of 75% failed in the FJ (type FF), 14% were MF, and 11% were WF. Both MF and WF typically occur in the area of knots located outside the FJ. The number of specimens with MF and WF failure types in tensile tests is higher than in bending tests. This could be explained by the significantly larger length of the maximum tensile stresses compared to the length of the maximum bending stresses, which results in more local weak sections. A comprehensive description of FJ tensile and bending test results is mentioned in Vafadar et al. (2023).

For analysis of the test results, different types of information should be considered. The FJ tensile and bending strength data based on the failure types are categorized into uncensored and censored information. In the specimens in which the failure happened within FJs (FF failure type), the FJs tensile and bending strengths are equal to the observed strength values from the tests, meaning that $f_{t,j} = f_t$ and $f_{m,j} = f_m$. Thus, those data are considered as uncensored information. In contrast, specimens with MF, WF, and S failure types did not fail entirely within the FJs. In this case, the strength of the FJs would be equal to or greater than the observed strength values from the tests, i.e., $f_{t,j} \geq f_t$ and $f_{m,j} \geq f_m$. These data are considered censored

Table 1 Data types of FJ tensile and bending strengths of the paired FJs

Case	$f_{t,j}$	$f_{m,j}$	n
1	Uncensored	Uncensored	34
2	Uncensored	Censored	10
3	Censored	Uncensored	44
4	Censored	Censored	10

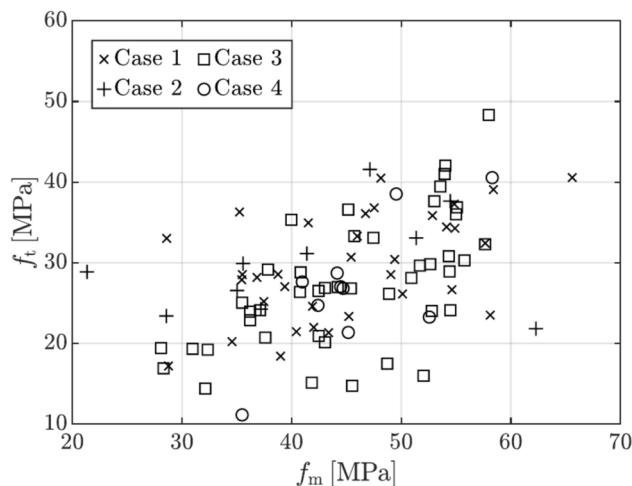


Fig. 4 Tensile strength (f_t) and bending strength (f_m) of the paired specimens. Different cases, according to the type of information, are denoted with specific signs; for the explanation of each case, see Table 1

information since the exact strength values of the FJs are unknown. Regarding the stiffness properties, the local bending stiffnesses ($E_{m,l}$) of the specimens were directly observed from the experiments and considered uncensored.

For investigating the relationship between $f_{t,j}$ and $f_{m,j}$, based on the type of information of the test results, the data are classified into four cases, described in Table 1, which are shown in Fig. 4.

To analyze the relationships between $f_{t,j}$, $f_{m,j}$, and $E_{m,l}$ with E_{dyn} , the findings from a prior study (Vafadar et al. 2023) serve as a foundation. The earlier research revealed significant correlations between $f_{t,j}$ and $f_{m,j}$ with the minimum E_{dyn} of the two connected timber boards in the FJs ($E_{dyn,min}$), as well as between $E_{m,l}$ and the mean value of E_{dyn} of the connected timber boards in the FJs ($E_{dyn,mean}$). Building on these insights, scatter plots are shown in Fig. 5 to illustrate the relationships. The plots depict the tensile and bending strengths, along with the local bending stiffness of the specimens, as functions of $E_{dyn,min}$ and $E_{dyn,mean}$. Censored data points are distinctly marked.

For proper statistical representations of the strengths and associated models, these different types of information must be appropriately considered.

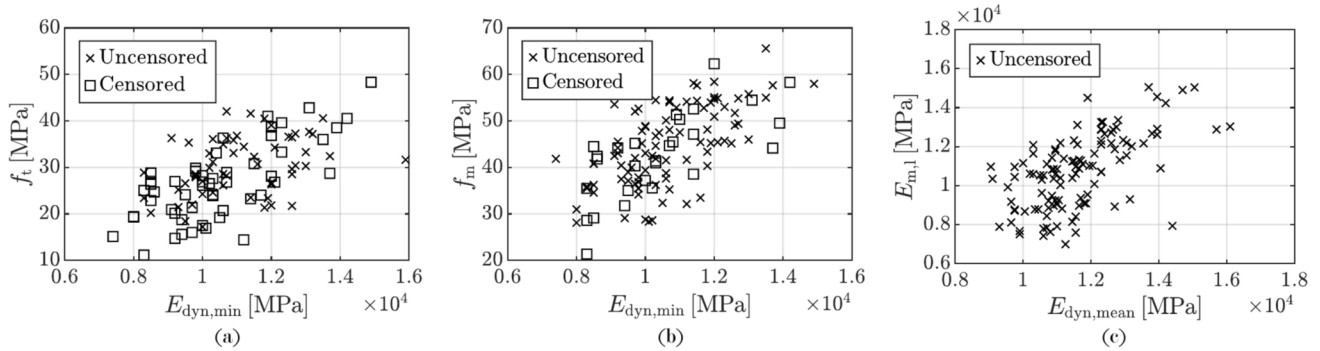


Fig. 5 **a, b** Tensile strength (f_t) and bending strength (f_m) of the specimens based on the minimum dynamic modulus of elasticity of the connected timber boards ($E_{dyn,min}$). **c** Local bending stiffness of the finger-jointed timber boards ($E_{m,l}$) based on the mean value of dynamic

modulus of elasticity of the connected timbee boards ($E_{dyn,mean}$). The uncensored and censored information types are denoted with specific signs

4 Bayesian linear regression modeling

Bayesian linear regression models are developed considering the types of information obtained from the experimental results. The general form of the model is given in Eq. (1).

$$Y = \beta_0 + \beta_1 X + \varepsilon \tag{1}$$

Where Y is the vector of the dependent variable, here, FJ tensile or bending mechanical properties, and X is the vector of the predictor. Regression coefficients β_0 and β_1 are the model parameters, and ε is the error term, which is assumed to be normally distributed around the regression model $\varepsilon \sim N(0, \sigma_\varepsilon^2)$ in which σ_ε is the standard deviation for the error term.

A Bayesian hierarchical model is used to estimate the regression parameters (see, e.g., Carlin and Louis (2008) for more information about the method). The posterior distribution for the parameters, i.e., $P(\beta, \sigma_\varepsilon | X, Y)$ is proportional to the joint distribution as described in the following expression (Eq. (2)).

$$\begin{aligned}
 P(\beta, \sigma_\varepsilon | X, Y) \propto & N(\mu | \theta_\mu, \sigma_\mu^2) \times IG(\sigma_X^2 | a, b) \\
 & \times N(\beta | \mu_\beta, V_\beta) \times IG(\sigma_\varepsilon^2 | c, d) \\
 & \times N(\mu_\beta | \mu^*, K) \times IW(V_\beta | \Psi, \nu) \\
 & \times \prod_{i \in UC_X} N(x_i | \mu, \sigma_X^2) \\
 & \times \prod_{i \in C_X} \left(1 - \Phi\left(\frac{x_i - \mu}{\sigma_X}\right) \right) \\
 & \times \prod_{i \in UC_Y} N(y_i | \beta_0 + \beta_1 x_i, \sigma_\varepsilon^2) \\
 & \times \prod_{i \in C_Y} \left(1 - \Phi\left(\frac{y_i - (\beta_0 + \beta_1 x_i)}{\sigma_\varepsilon}\right) \right)
 \end{aligned} \tag{2}$$

The joint distribution for Y and X considering the censored data in both vectors is presented. The joint distribution includes prior distributions encapsulating initial beliefs about the coefficients and the likelihood functions representing the probability of observing the data, given those coefficients. The priors are updated into posterior distributions through Bayes' theorem, capturing the refined understanding of parameters after considering the observed data.

The dependent variable Y , is assumed to be normally distributed i.e., $Y \sim N(\beta_0 + \beta_1 X, \sigma_\varepsilon^2)$, where $\beta_0 + \beta_1 X$ is the expected value. A bivariate normal prior for $\beta = (\beta_0, \beta_1)$ is assumed i.e., $\beta \sim N(\mu_\beta, V_\beta)$, where μ_β is the mean values vector and V_β is the variance-covariance matrix (2×2). It is assumed that μ_β follows a bivariate normal distribution $\mu_\beta \sim N(\mu^*, K)$ where μ^* is the vector of the mean values and K is the variance-covariance matrix (2×2). V_β follows an inverse-Wishart distribution, i.e., $V_\beta \sim IW(\Psi, \nu)$ in which Ψ is the scale matrix (2×2) and ν is the degree of freedom. Moreover, the assumption is that σ_ε^2 follows an inverse gamma distribution $IG(c, d)$ with the shape parameter c and the rate parameter d . Φ is the cumulative standard normal distribution function.

Regarding the predictor X , according to the probabilistic model code (JCSS 2006), the strength properties of structural timber follow a lognormal distribution. To facilitate modeling and simplify the analysis, the natural logarithm of the strength properties is applied as a transformation, resulting in a variable (X) that is normally distributed, i.e., $X \sim N(\mu, \sigma_X^2)$. Similarly, stiffness properties are reported by JCSS (2006) to follow a lognormal distribution. Since stiffness properties are directly used as predictors without transformation, they are assumed to maintain their lognormal distribution, i.e., $X \sim Lognormal(\mu, \sigma_X^2)$, where μ is the mean value and σ_X^2 is the variance. For the hierarchical modeling, it is assumed that μ is normally distributed $\mu \sim N(\theta_\mu, \sigma_\mu^2)$. Accordingly, it is assumed that σ_X^2 follows

Table 2 Prior information for the model parameters to predict FJ tensile strength ($f_{t,j}$), FJ bending strength ($f_{m,j}$), and finger jointed timber boards local bending stiffness ($E_{m,1}$)

θ_μ	σ_μ^2	a, b, c, d	μ^*	K	Ψ	ν
0	10^2	0.01	[0 0]	$\begin{bmatrix} 10^2 & 0 \\ 0 & 10^2 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	2

an inverse gamma distribution $IG(a, b)$, with the shape parameter a and the rate parameter b .

$UC_Y = \{i : y_i \text{ are uncensored}\}$ and $C_Y = \{i : y_i \text{ are censored}\}$ are the sets of indices for which y_i , i.e., the tensile and bending mechanical properties of FJs, are uncensored and censored, respectively. The same definition applies to UC_X and C_X that are the set of indices in which x_i as the predictors are uncensored and censored.

Weak prior information for the models' parameters is assigned and described in Table 2. The posterior distributions of the model parameters are evaluated using Markov Chain Monte Carlo (MCMC) methods, e.g., Gibbs sampling (see, Geman and Geman (1984) for information about the sampling method and Gelfand et al. (1992) which describes the application of the method for the censored data).

The expected values of censored data are estimated using sampling methods. In MCMC sampling, censored observations were treated as latent variables and iteratively sampled alongside the model parameters. The posterior samples of these latent variables were then used to calculate their expected values. After the 20, 000 initial iterations for burn-in, an additional 40, 000 MCMC iterations were run to model the FJ tensile and bending mechanical properties. The statistical analyses were performed using the RJAGS package in RStudio (Plummer et al. 2023).

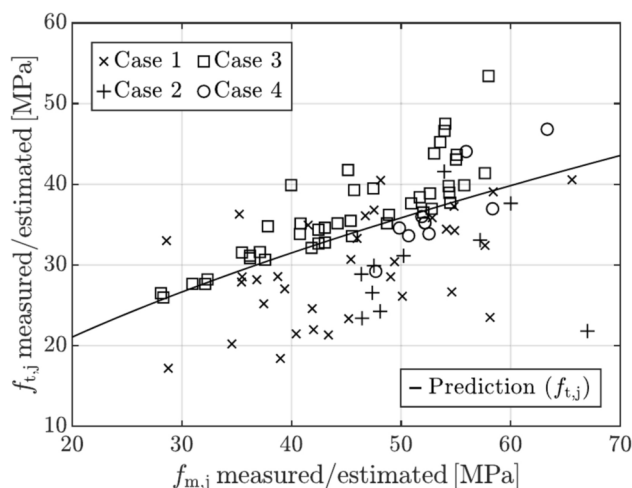


Fig. 6 Measured or estimated values of FJ tensile strength ($f_{t,j}$) based on measured or estimated values of FJ bending strength ($f_{m,j}$) along the prediction model. Different cases, according to the type of information, are denoted with specific signs; for the explanation of each case, see Table 1

5 Prediction of $f_{t,j}$ based on $f_{m,j}$

FJ tensile strength ($f_{t,j}$) could be predicted based on the FJ bending strength ($f_{m,j}$) using the test results of the paired FJs. The descriptive statistics of the model parameters are summarized in Table 3. The intercept (β_0) and the slope (β_1) are highly correlated ($r \approx -1$). The coefficient of variation (COV) of the model parameters is estimated. β_0 varies more compared to β_1 and σ_ϵ , indicating larger uncertainty of the parameter.

The prediction model and the expected strength values of the censored information are estimated using the sampling method and are shown in Fig. 6. In Case 1, where both data vectors are uncensored, their values remain unchanged. For Cases 2, 3, and 4, the expected strength values of the censored data are estimated; for the description of each case, see Table 1. In Case 2, where only $f_{m,j}$ is censored, the

Table 3 Descriptive statistics of the FJ tensile and bending mechanical properties prediction models' parameters

Model	Parameter	Mean value	COV
$\ln(f_{t,j}) = \beta_0 + \beta_1 \ln(f_{m,j}) + \epsilon$	β_0	1.31	0.39
	β_1	0.58	0.23
	σ_ϵ	0.24	0.10
$\ln(f_{t,j}) = \beta_0 + \beta_1 E_{dyn,min} + \epsilon$	β_0	2.86	0.06
	β_1	5.58×10^{-5}	0.28
	σ_ϵ	0.22	0.09
$\ln(f_{m,j}) = \beta_0 + \beta_1 E_{dyn,min} + \epsilon$	β_0	2.98	0.04
	β_1	7.77×10^{-5}	0.14
	σ_ϵ	0.16	0.07
$\ln(E_{m,1}) = \beta_0 + \beta_1 E_{dyn,mean} + \epsilon$	β_0	8.42	0.01
	β_1	7.24×10^{-5}	0.14
	σ_ϵ	0.15	0.06

expected strength values of the censored data shifted to the right, meaning that the $f_{m,j}$ of those specimens are expected to be higher than observed strength values, which is aligned with the definition of the censored data. In Case 3, with $f_{t,j}$ being censored, the expected strength values of the censored data shifted upward. In Case 4, where both $f_{t,j}$ and $f_{m,j}$ were censored, the estimated expected strength values resulted in shifts to the right and upward compared to the observed strength values.

The assumption of normally distributed error terms is tested by analyzing the residuals, i.e., the difference between the measured or expected values of the FJ tensile and bending strength and the predicted values from the models. The residuals are randomly distributed around negligible mean values (close to zero) across the model with constant variance, confirming that the assumption of homoscedasticity holds.

The predicted FJ tensile strengths based on FJ bending strengths are compared to measured or estimated FJ tensile strengths, yielding a correlation coefficient of $r \approx 0.5$. As discussed, the paired FJs are fabricated from the same timber boards. However, the variation in fabrication quality and natural irregularity of the timber boards may affect the model's prediction accuracy and the relationship between the FJ tensile and bending strength.

The current regression model is based on including all the uncensored and censored data. If only uncensored data were used adopting the same modeling method, FJ tensile strength would be underestimated (approx. 15% for $f_{m,j} = 45$). This means that excluding censored data results in underestimating the FJ tensile strength in the prediction model, which aligns with the findings of previous literature (Fink et al. 2018). Moreover, this suggests that the tensile-to-bending strength ratio ($f_{t,j,k}/f_{m,j,k}$) reported in prior studies may be underestimated, as censored data in those studies were excluded. Further research is needed to reassess these historical test results.

6 Prediction of $f_{t,j}$, $f_{m,j}$, $E_{m,l}$ based on E_{dyn}

The tensile and bending strengths of FJs ($f_{t,j}$ and $f_{m,j}$) are predicted using the $E_{dyn,min}$, which is selected as the model predictor. This choice is based on correlation analysis in a prior related study (Vafadar et al. 2023), which demonstrated a stronger correlation between $f_{t,j}$ and $f_{m,j}$ and $E_{dyn,min}$ compared to other timber boards indicators, such as density. Similarly, the local bending stiffness of finger-jointed timber boards ($E_{m,l}$) is predicted using the mean value of dynamic modulus of elasticity of the connected timber boards ($E_{dyn,mean}$). $E_{dyn,mean}$ is chosen as the regression model predictor because it showed greater relevance to $E_{m,l}$ than $E_{dyn,min}$ (Vafadar et al. 2023). The descriptive statistics of the models' parameters are summarized in Table 3. Figure 7 illustrates these relationships along with the expected strength values of the censored data. The variation in model parameters for FJ bending strength is generally smaller than for FJ tensile strength.

The FJ tensile strength prediction model based on $E_{dyn,min}$ is compared to the model developed in Fink et al. (2021), where 40 FJs were tested in tension to predict FJ tensile strength based on $E_{dyn,min}$. The specimens in Fink et al. (2021) were shorter, and the loading rate was higher (specimens failed within 5 s) than those in the present study. However, in both studies, around half of the data were censored. To handle the censored data appropriately in Fink et al. (2021), the Maximum Likelihood Method (MLM) was used to estimate the expected values of the model parameters considering censored data; see also Collins and Fink (2022) for another example of applying the MLM method in timber engineering for regression modeling with censored data. Thus, to compare the two studies properly, the expected values of the model parameters in the present paper were also estimated using the MLM, and the same results were obtained.

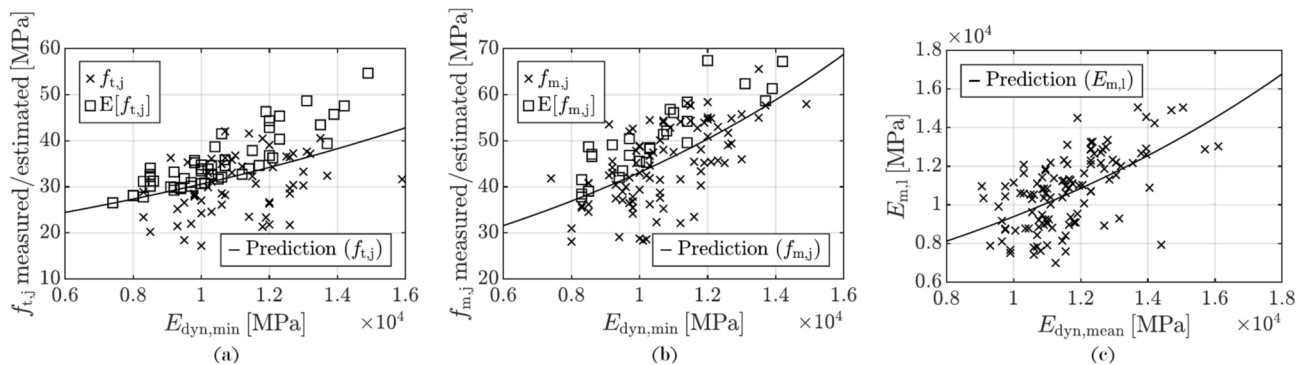


Fig. 7 a, b FJ tensile strength ($f_{t,j}$), FJ bending strength ($f_{m,j}$), along with the expected values ($E[.]$) of the censored data and prediction models based on minimum dynamic modulus of elasticity of the connected timber boards ($E_{dyn,min}$). c Local bending stiffness of the fin-

ger-jointed timber boards ($E_{m,l}$) and its prediction model based on the mean value of dynamic modulus of elasticity of the connected timber boards ($E_{dyn,mean}$)

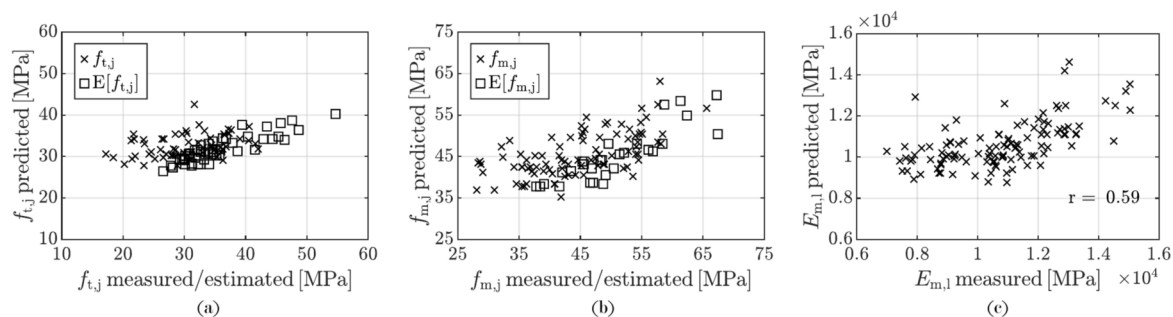


Fig. 8 **a, b** Predicted FJ tensile strength ($f_{t,j}$) and predicted FJ bending strength ($f_{m,j}$) versus measured or estimated expected values ($E[\cdot]$) of the censored data. **c** Predicted local bending stiffness of the finger-jointed timber boards ($E_{m,l}$) and the measured values from the tests

The variation in model parameters reported in Fink et al. (2021) is more significant than that observed in the current study, likely due to the smaller sample size in the previous research (40 specimens compared to 110 in the current study). Additionally, the previous model predicts higher FJ tensile strengths than the current model. This discrepancy may result from the higher loading rate and/or differences in fabrication quality. In particular, the potential influence of the production on the FJ quality is important for modeling engineered wood products.

The prediction accuracy of the FJ tensile and FJ bending strength models based on $E_{dyn,min}$ is investigated by comparing the predicted strength values to the measured or expected strength values. The scatter plots are shown in Fig. 8. A correlation coefficient of $r \approx 0.5$ and $r \approx 0.6$ between the predicted $f_{t,j}$ and $f_{m,j}$ and measured or estimated FJ tensile and bending strength are obtained, respectively. Considering naturally occurring defects near or within FJs and variations in fabrication quality may improve prediction accuracy for both tensile and bending strengths.

The $E_{m,l}$ prediction model is validated by comparing predicted and measured values, yielding a correlation coefficient of $r \approx 0.6$; see Fig. 8c. This confirms that $E_{dyn,mean}$ from the connected timber boards is a reliable predictor of the local bending stiffness of the finger-jointed timber boards.

7 Conclusion and outlook

This study investigates the relationship between FJs' tensile and bending mechanical properties, offering a foundation for prediction models. The study provides tools for estimating mechanical properties in engineered wood products by connecting failure modes to data types and using hierarchical Bayesian linear regression modeling to address censored data.

In total, 110 tension and 117 bending tests were conducted on the finger-jointed timber boards, with 98 paired

specimens. In tensile and bending testing of the FJs, censored data frequently arose when failures occurred outside the FJs, leaving the actual FJ strength partially observed. Censored data were handled appropriately using Bayesian modeling to mitigate biases in strength predictions. This approach accounted for censorship in dependent and predictor variables.

A regression model to predict $f_{t,j}$ based on $f_{m,j}$, addressing the relationship between FJ tensile strength and FJ bending strength, is proposed. The findings demonstrate that excluding censored data results in an underestimation of FJ tensile and bending strength, implying that prior studies may have underestimated tensile-to-bending strength ratios. Moreover, although FJ tensile strength is critical for the mechanical modeling of engineered wood products such as GLT beams, for practical reasons, FJs are being tested mainly in bending rather than tension. The proposed model offers an approach for estimating FJ tensile strength based on FJ bending strength.

Furthermore, the study explored the FJ tensile and bending strength predictability using $E_{dyn,min}$. According to the results, $E_{dyn,min}$ is a reliable predictor for FJ tensile and bending strength, with greater accuracy observed for predicting FJ bending strength. Additionally, the study examined the relationship between the local bending stiffness of finger-jointed timber boards and $E_{dyn,mean}$. Results show that $E_{dyn,mean}$ effectively predicts the local bending stiffness.

In this study, the dynamic modulus of elasticity, representing the average properties of timber boards, is used as the primary predictor for estimating FJ tensile and bending properties. Since FJs are primarily fabricated at the ends of timber boards, future research could improve models' accuracy by incorporating other variables related to end-grain characteristics and local material properties, such as growth ring characteristics and local density. Expanding Bayesian inference to address censorship comprehensively across all variables will further improve modeling capabilities. These

advancements will contribute to more reliable assessments and optimized performance of engineered wood products.

Acknowledgements This research has been conducted with funding from the Research Council of Finland (previously known as the Academy of Finland) with decision no. 13334004. The authors thank Versowood Group Oy company for their support and cooperation during specimen fabrication and transportation.

Author Contributions FV: Writing—review and editing, Writing—original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Steven Collins: Writing—review and editing, Methodology, Conceptualization. GF: Writing—review and editing, Supervision, Methodology, Project administration, Funding acquisition, Conceptualization.

Funding Open Access funding provided by Aalto University.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no Conflict of interest.

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