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EXPERIMENTAL INVESTIGATION OF FINGER JOINTS UNDER TENSILE AND BENDING LOADS

Farid Vafadar[1], Steven Collins[2], Gerhard Fink[3]

ABSTRACT: Finger joints are commonly used to fabricate endless lamella for engineered wood products such as glued laminated timber beams. The finger joints' properties are important for the mechanical characteristics of glued laminated timber beams, particularly those fabricated from higher-strength-graded lamellas. In the present study, 120 spruce timber boards were used to fabricate finger joints. Each timber board was assessed for quality by measuring the eigenfrequency and the density before the finger joint fabrication. The timber boards were cut in half, and both sets were arranged in the same order and afterward fabricated to endless lamellas, such that the finger joints were fabricated from the same timber boards in both sets. On one set, the tensile strength and on the other one, the flatwise bending strength and stiffness were investigated. This paper presents a statistical summary of the finger joint tensile and bending test results and correlation analyses between the mechanical properties and the relevant quality assessment indicators. A significant relationship between the finger joint tensile and bending strength is observed. Furthermore, the dynamic modulus of elasticity is identified to be a useful indicator of finger joint strength and stiffness.

KEYWORDS: Spruce, finger joint, tensile experiments, bending experiments, correlation analysis

1 INTRODUCTION

A finger joint (FJ) is the longitudinal interlocked connection between two timber boards. It is broadly used in the wood industry to fabricate endless lamella, mainly to produce engineered wood products such as glued laminated timber (GLT) or cross-laminated timber. Particularly for GLT beams fabricated from higher strength graded timber boards, which are typically characterized by fewer and smaller knots, the mechanical properties of the beams are influenced by the properties of the FJs [1].

The mechanical properties of FJs were investigated in several studies. In [2], the relationship between tensile strength and flexural modulus of elasticity in the bending of FJs from spruce timber was investigated. In [3], experiments were reported on the bending and tensile strength of finger-jointed pine lamellas from ten GLT factories. The aim was to compare bending and tensile strengths. As a result, a relatively constant ratio between the mean values of the tensile and bending strengths was found, such that the tensile strength was about 60% of the bending strength. In [4], bending and tensile experiments were performed on 700 FJs to investigate the ratio between the characteristic value (5th percentile-Guassian distribution) of finger joints' tensile and bending strength. Overall, a ratio between the characteristic values of the tensile and bending strength of approx. 0.65 was identified. However, it should be noted that in [4], a reduced testing length was used, and specimens with failures outside the FJ were not considered for analysis.

The importance of FJ is also considered in the respective standard for GLT beam mechanical behavior (EN 14080 [5]), where the mechanical properties of FJs are addressed. According to [5], the strength class of a GLT beam is estimated based on the tensile properties of the used timber boards and the flat-wise-bending properties of the FJ. In this case, the required value of the characteristic strength for FJs tested in tension is $f_{t,0,j,k} = f_{m,j,k}/1.4$.

A few studies have also been carried out to identify the correlation between various strength and stiffness-related indicators and the FJ properties. For instance, in [6], the mechanical performance of structural finger joints was investigated in four-point bending. The results indicated a positive relationship between the density and the bending strength. In [7], the results of 40 FJ tensile experiments were used to develop a model to predict the tensile strength of FJ based on the dynamic modulus of elasticity (E_{dyn}) of the connected timber boards. Nonetheless, the literature in this direction is lacking, particularly for studies investigating the influence of indicators on the FJ mechanical properties.

In the present study, the relationships between the FJ tensile and bending properties on paired specimens and the influences of timber board indicators (stiffness and density) on the FJ mechanical properties are investigated.

[1] Farid Vafadar, Dept. of Civil Engineering, Aalto University, farid.vafadarestiar@aalto.fi
[2] Steven Collins, Dept. of Civil Engineering, Aalto University, steven.collins@aalto.fi
[3] Gerhard Fink, , Dept. of Civil Engineering, Aalto University, gerhard.fink@aalto.fi

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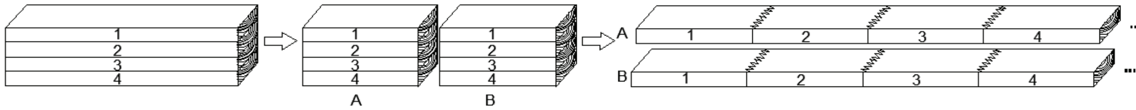

Figure 1: Schematic of the fabrication process of FJs

2 MATERIAL AND METHOD

2.1 SPECIMEN

Spruce timber boards (*w* x *t* = 125 x 50 mm with a length between 3800 mm and 4700 mm) were used to study the FJ tensile and bending mechanical properties. All timber boards were investigated for quality with a commercial grading device (Precigrader), which grades based on the timber board's E_{dyn} and measures the density. Based on the grader information, the boards were classified into R (rejected), T14, and T22 classes. The descriptive statistics of E_{dyn} for each class are mentioned in Table 1.

The timber boards were cut in half and finger-jointed into two equivalent sets of endless lamellas, according to Figure 1. Thus, the timber boards were arranged in the same order in both sets so that paired (tension and bending) FJs were fabricated. The two endless lamellas were cut into 8 m long segments to transport to the Aalto University testing laboratory. Then the FJs were cut out of each segment. Due to the cutting procedure (for transporting), some FJs could not be used for further testing. In total, 227 finger-jointed specimens (110 FJs for tension and 117 for bending test) were investigated, of which 98 were paired. The order of the timber boards was random, i.e., they were not grouped according to the strength grades[1]. The finger-jointed specimen groups were determined based on the class of the two connected timber boards (see Tables 2 and 3).

For the tensile and bending tests, the specimens were planed to the final dimensions of w x t x l = 115 x 45 x 1300 mm and w x t x l = 115 x 45 x 1000 mm, respectively. In the bending tests, eight specimens had a shorter span (distance between the supports) of 700 mm. All specimens were conditioned in a climate chamber at 20°C, with a relative humidity of 65%.

2.2 TENSILE TEST

The specimens were tested in tension according to EN 408 [8]. The test setup with failure at the FJ is shown in Figure 2. The test length clear of grips was 560 mm (> 9 x 45 mm) with 370 mm clamping length on each side. To secure the specimens in the grips while testing, lateral pressure was applied. However, 14 specimens slipped from the grips. Ten of these were re-clamped and tested for a second time to achieve failure, although it was not possible to test four FJs again because of damage at the clamping region. An actuator with a tensile capacity of 500 kN applied the force. A force control testing protocol with a 30 kN/min loading rate was used.

[1]Initially the study was planned to be performed with graded timber boards, although due to a technical error the boards were not sorted.

Table 1: *Descriptive statistics of E_{dyn} for the used timber boards*

Class	Mean value [MPa]	COV [-]	Range [MPa]
R	8795	0.06	< 9600
T14	10966	0.07	9600-12300
T22	13625	0.08	> 12300

Figure 2: FJ after failure in a tensile test

2.3 BENDING TEST

The bending experiments were performed according to EN 408 [8]. The test setup and a specimen during the test are shown in Figure 3. A universal testing machine with a capacity of 200 kN was used. The testing protocol was force control with a 2.5 kN/min loading rate. One linear variable differential transformer (LVDT) in the center of the specimen, at the bottom surface, was installed for global stiffness. For local deflection measurement, two LVDTs were installed on both side faces at the neutral axis and the FJ location. The average value of deflection was considered for local stiffness calculation. The LVDTs were removed from the specimens at an estimated 40% of the maximum force to prevent damage during failure.

2.4 VISUAL INSPECTION

After testing, the specimens were visually inspected. Following the approach presented in [9], the specimens were categorized into four groups according to their fracture pattern: Finger joint failure (FF), wood failure (WF), mixed failure (MF), and the slip of the grip without failure (S) which happened only in tensile tests.

The four specimens that slipped from the grips were considered slipped specimens (S). Conditions for classification are such that if at least two-thirds of the failed cross-section was within the finger joint (failure in adhesion and joint failure at fusion or net section), the specimen was categorized as finger joint failure (FF).

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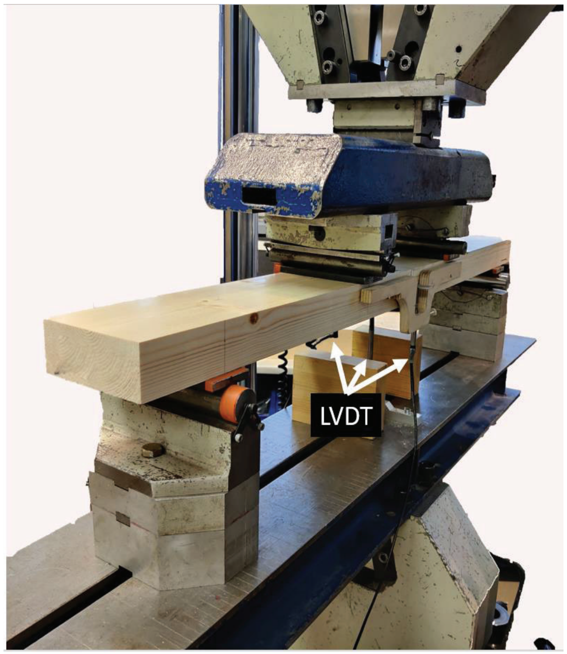

Figure 3: Flatwise four-point bending test setup and location of the linear variable differential transformer (LVDT)

Likewise, if two-thirds of the failed cross section was within a wood section, the specimen was considered with a wood failure (WF). All other specimens were defined as mixed failure (MF).

In addition to the failure type, the timber board in which the failure occurred was identified. It was targeted only for specimens where the failure could be allocated to a specific timber board. From the tensile and bending experiments, specimens are considered where at least two-thirds of the failed cross section was within one timber board. For the bending tests, the tension zone of the specimens was investigated. All other specimens, meaning specimens where the failure could not be directly allocated to one specific timber board, are not considered for related investigations.

3 RESULTS

The tensile and bending test results are summarised in Tables 2 and 3, respectively. Descriptive statistics of strength values are given for specimens with the same failure type and all FJs within each FJ group. In the latter case, the specimens with WF, MF, and S failures are considered censored from the perspective of FJ strength since the exact strength of the FJ is unknown, and only a lower bound is known; see [7] for more information. As a result, the tensile and bending strength of the FJs were calculated using equality data (FF) and censored data (WF, MF, S).

In this paper, it is distinguished between (a) the tensile and bending strength of tested specimens denoted with $f_{t,s}$ and $f_{m,s}$ and (b) the tensile and bending strength of FJ denoted with $f_{t,j}$ and $f_{m,j}$.

Table 2: *Expected values and coefficient of variations of tensile strength of FJ (calculated for all specimens considering censored data) and tensile strength of the specimens (categorized according to the failure type).*

FJ group (Based on the quality of the timber boards)	Failure type	n [-]	Tensile strength E(·) [Mpa]	COV [-]
R-T14	FF	4	20.9	0.10
	MF	3	22.8	0.23
	WF	7	18.3	0.29
All finger joints $f_{t,j}$	**-**	**14**	**25.3**	**0.18**
R-T22	FF	4	29.2	0.17
	MF	1	25.0	-
	WF	6	23.2	0.17
All finger joints $f_{t,j}$	**-**	**11**	**30.4**	**0.12**
T14-T14	FF	11	27.9	0.20
	MF	4	25.3	0.07
	WF	9	24.2	0.25
All finger joints $f_{t,j}$	**-**	**24**	**30.4**	**0.18**
T14-T22	FF	24	31.5	0.19
	MF	6	32.4	0.16
	WF	10	26.6	0.31
	S	1	36.3	-
All finger joints $f_{t,j}$	**-**	**41**	**34.2**	**0.20**
T22-T22	FF	14	33.1	0.14
	MF	2	32.4	0.16
	WF	1	38.5	-
	S	3	43.9	0.09
All finger joints $f_{t,j}$	**-**	**20**	**36.6**	**0.20**

About half of the specimens in the tensile experiments failed in the FJ (type FF). Slipped specimens have the highest mean tensile strength value. About 75% of the specimens in bending tests failed in the FJ (type FF).

The mean value of local and global bending stiffness increases with the quality of the timber boards. The global stiffness mean values are lower than the local stiffness. In addition, it is noted that the local deflection data in four specimens and the global deflection of one specimen are missing due to measurement errors of the LVDTs.

General results concerning the tensile and bending tests indicate that the relative frequency of the specimens with FF failure type increases with the quality of the timber boards, particularly for tensile-loaded specimens. This is expected since, in higher-quality timber boards, there are (in general) fewer natural defects that may cause failure outside of the FJs.

4 CORRELATION ANALYSIS

4.1 MECHANICAL PROPERTIES

A scatter plot of the tensile and bending strength for all the paired specimens is shown in Figure 4. In total, 41 pairs failed within FJ in both the bending and the tensile tests. This case is classified as FF-FF. For illustrative reasons, the "Other" specimens are illustrated together, representing specimens in which a failure occurred outside the FJ in tension and/or bending. According to the scatter plot, the relationship is associated with a rather large scatter.

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***Table 3** Expected values and coefficient of variations of bending strength and stiffness (local and global). Bending strength of FJ (calculated for all specimens considering censored data) and bending strength of the specimens (categorized according to the failure type).*

FJ group (Based on the quality of the timber boards)	Failure type	Bending strength n [-]	Bending strength E(·) [Mpa]	Bending strength COV [-]	Local bending stiffness E_L n [-]	Local bending stiffness E_L E(E_L) [Mpa]	Local bending stiffness E_L COV [-]	Global bending stiffness E_G n [-]	Global bending stiffness E_G E(E_G) [Mpa]	Global bending stiffness E_G COV [-]
R-T14	FF	11	38.4	0.11						
	MF	3	40.7	0.11						
	WF	2	35.2	0.26						
All finger joints $f_{m,j}$	**-**	**16**	**40.2**	**0.12**	**15**	**9496**	**0.13**	**16**	**8524**	**0.15**
R-T22	FF	8	39.2	0.20						
	MF	2	30.4	0.06						
	WF	3	33.6	0.34						
All finger joints $f_{m,j}$	**-**	**13**	**41.0**	**0.18**	**13**	**9812**	**0.17**	**12**	**9294**	**0.14**
T14-T14	FF	23	42.4	0.18						
	MF	5	43.7	0.15						
	WF	3	44.8	0.17						
All finger joints $f_{m,j}$	**-**	**31**	**44.7**	**0.18**	**31**	**10147**	**0.16**	**31**	**9532**	**0.14**
T14-T22	FF	36	46.5	0.17						
	MF	5	46.9	0.19						
	WF	1	45.5	-						
All finger joints $f_{m,j}$	**-**	**42**	**47.6**	**0.17**	**40**	**11408**	**0.12**	**42**	**10666**	**0.12**
T22-T22	FF	11	53.5	0.11						
	MF	1	44.2	-						
	WF	3	54.1	0.08						
All finger joints $f_{m,j}$	**-**	**15**	**54.8**	**0.10**	**14**	**12348**	**0.19**	**15**	**12009**	**0.16**

Significant relationships are observed between the specimens' tensile and bending strength. The corresponding correlation coefficient for all paired specimens is $r(f_{t,s}, f_{m,s}) = 0.50$, and for the FF-FF case, the correlation is $r(f_{t,j}, f_{m,j}) = 0.48$.

Regarding the relationships between strength and stiffness, notable correlations are found between the bending strengths ($f_{m,s}$ and $f_{m,j}$) and local and global bending stiffness (E_L and E_G), with correlations of $r \approx 0.70$ for all relationships. However, the correlations between tensile strengths and local bending stiffness are lower: for all paired specimens, $r(f_{t,s}, E_L) = 0.44$, and for specimens with FF, $r(f_{t,j}, E_L) = 0.34$. Similar trends for the relationship between tensile strength and global bending stiffness are identified with $r(f_{t,s}, E_G) = 0.51$ (all paired specimens) and $r(f_{t,j}, E_G) = 0.33$ (specimens with FF).

4.2 MECHANICAL PROPERTIES VS. INDICATORS

Correlation analyses are made between the mechanical properties and selected strength and stiffness-related indicators. For the strength properties, the lower quality timber board of the connected timber boards is expected to influence the strength predominantly. Accordingly, the investigated parameters are the minimum characteristics: $E_{dyn,min}$, and ρ_{min}. Based on visual inspection, the timber board in which the failure occurred was identified for each specimen with FF. Of all the specimens tested in tension and bending with FF (57 tensile specimens and 89 bending specimens), 63% and 78% of specimens failed in the timber board with lower E_{dyn}, respectively.

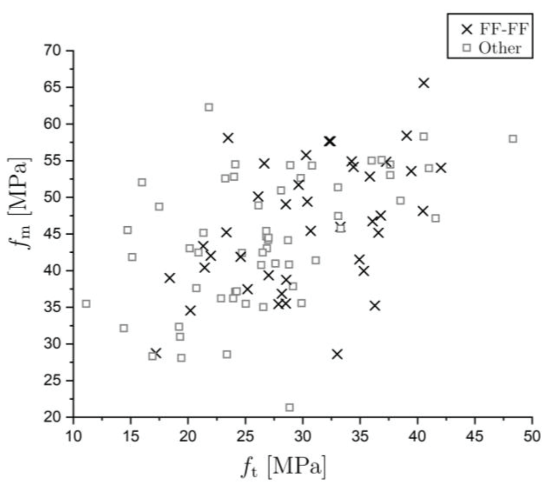

***Figure 4:** Scatter plot of all the paired FJs' bending strength versus tensile strength. FF-FF represents FJ failures in both paired bending and tension specimens.*

Further investigation showed that most failures within the stiffer boards were characterized by natural defects, such as knot clusters close to or within the FJs. Since the ρ_{min} and $E_{dyn,min}$ are highly correlated, similar results are expected when considering the minimum density. Therefore, results suggest that FJs fail more frequently within a lower-quality timber board.

A scatter plot of FJ tensile strength and $E_{dyn,min}$, and ρ_{min} are shown in Figure 5. For $E_{dyn,min}$, when all failure types are considered together, the correlation is apparent, and a significant correlation coefficient of $r(f_{t,s}, E_{dyn,min}) = 0.59$ is obtained.

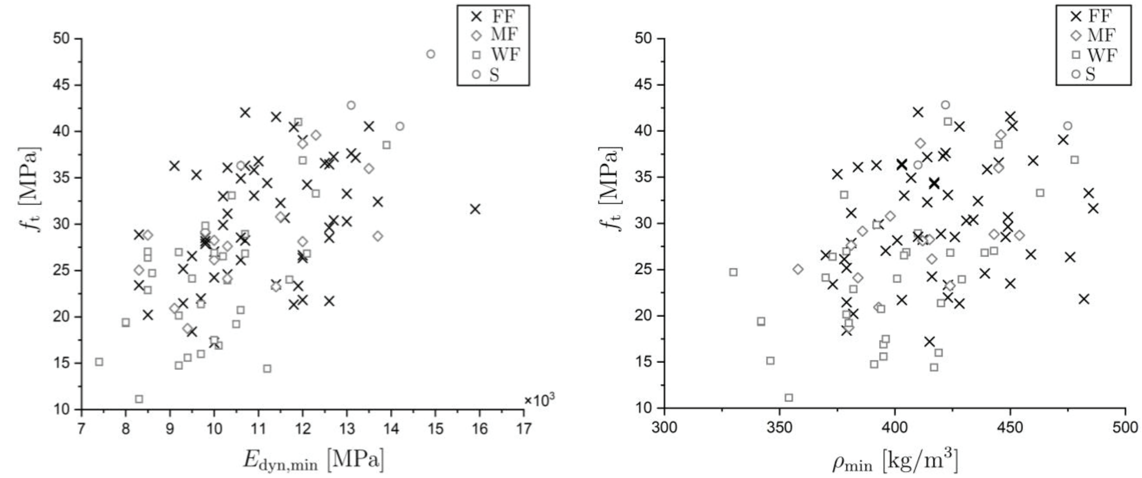

Figure 5: *Scatter plot of FJ tensile strength versus (left)* $E_{dyn,min}$ *(right)* ρ_{min} *of the connected boards.*

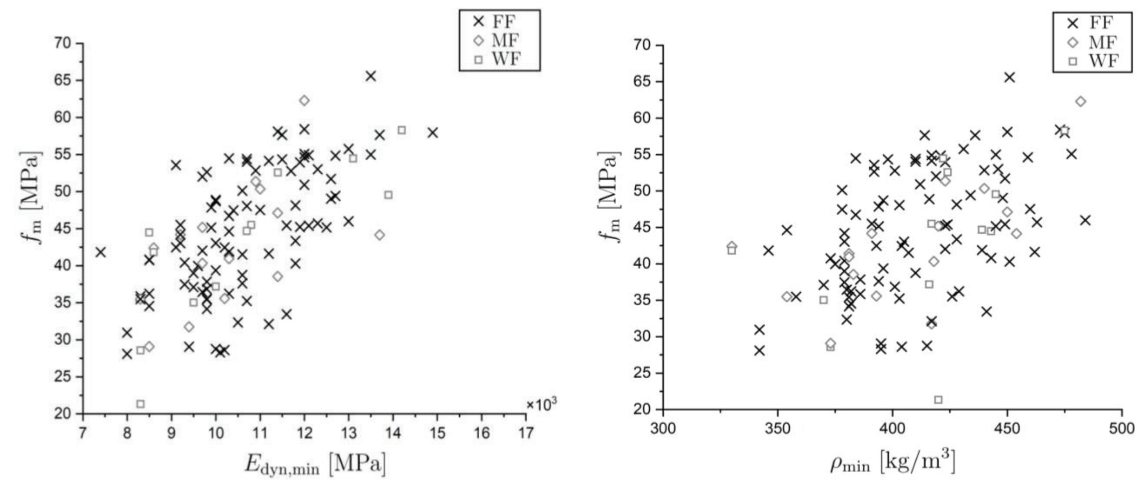

Figure 6: *Scatter plot of FJ bending strength versus (left)* $E_{dyn,min}$ *(right)* ρ_{min} *of the connected boards.*

However, for specimens with FF, the relationship between tensile strength and $E_{dyn,min}$ is comparatively lower: $r(f_{t,j}, E_{dyn,min}) = 0.36$. The reason for this difference may be related to the failure types: some of the strongest and stiffest specimens slipped from the testing grips (type S), and some of the weakest specimens failed outside the FJ (e.g., WF); both are not accounted for in the FF group. Therefore, the overall effect is a stronger correlation when all failure types are considered and a lower correlation when FF failure is considered individually. From the scatter plot, the influence of ρ_{min} on the tensile strength for specimens with FF is not unambiguous and associated with a rather large scatter. Overall, the influence of density on the tensile strength is minor. The correlation coefficient is $r(f_{t,s}, \rho_{min}) = 0.47$ and $r(f_{t,j}, \rho_{min}) = 0.20$. It is noted that a few specimens significantly influence this correlation coefficient, with WF having some very low values.

The scatter plot of the FJs bending strength versus the $E_{dyn,min,}$ and ρ_{min} are shown in Figure 6. Overall, the relationship between bending strength and $E_{dyn,min}$ is more significant than the tensile strength. The correlation coefficients are $r(f_{m,s}, E_{dyn,min}) = 0.64$ and for specimens with FF, $r(f_{m,j}, E_{dyn,min}) = 0.62$. In addition, an apparent influence of density on the bending strength is observed, although the scatter is relatively large. The correlation coefficients are $r(f_{m,s}, \rho_{min}) = 0.50$ and $r(f_{m,j}, \rho_{min}) = 0.48$.

The relationships between the local bending stiffness (considered more relevant to FJ, compared to global stiffness) and the indicators are presented in Figure 7. The mean values of the indicators ($E_{dyn,mean,}$ ρ_{mean}) are, in this case, considered to be the relevant characteristics. The corresponding correlation coefficient between E_L and $E_{dyn,mean}$ is $r = 0.59$. However, E_G and $E_{dyn,mean}$ has a higher correlation with $r = 0.67$. The correlation between E_L and ρ_{mean} is $r = 0.42$. A similar correlation is found between E_G and ρ_{mean} ($r = 0.43$). These results suggest that the $E_{dyn,mean,}$ and ρ_{mean} are related to FJ bending stiffness, with $E_{dyn,mean}$ being an important indicator.

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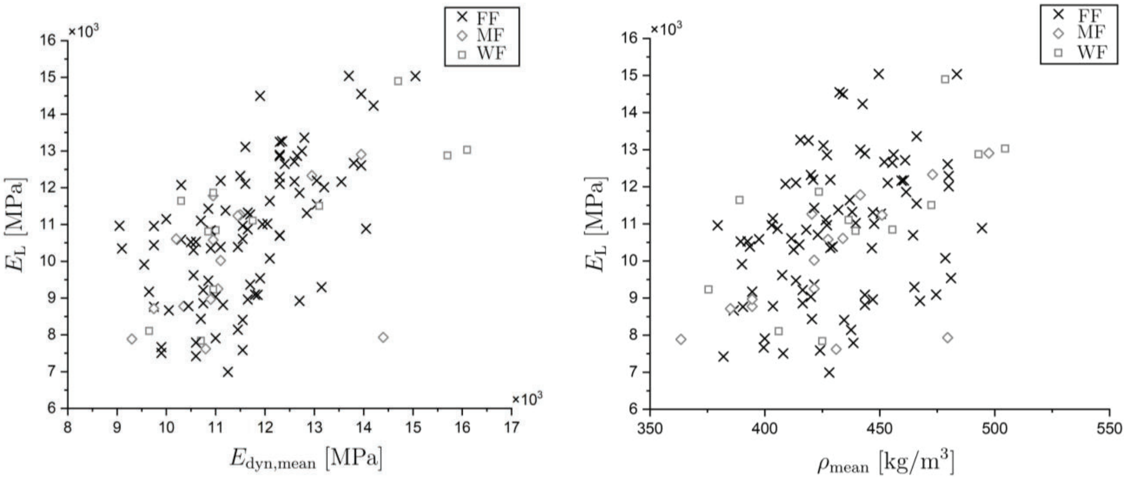

Figure 7: *Scatter plot of FJ local bending stiffness versus (left)* $E_{dyn,mean}$ *(right)* ρ_{mean} *of the connected boards.*

5 CONCLUSION AND OUTLOOK

The tensile and bending mechanical properties of finger joints are investigated. Overall, 227 finger-jointed specimens in five quality groups were tested in tension and bending. The statistical properties of the test results are presented along with a correlation analysis for the relationships between FJ tensile and bending mechanical properties and their relationship to non-destructive indicators. Results indicate:

- On average, the bending strength of finger joints is stronger than tensile strength.
- A significant relationship is identified between the FJ tensile and bending strength with a correlation coefficient of approximately 0.5.
- The mean value of the FJ tensile and bending mechanical properties increases with the quality of the joined timber boards.
- The connected boards' minimum dynamic modulus of elasticity significantly correlates with the FJ tensile and bending strength. The minimum density is also correlated, although to a lesser extent due to a rather large scatter.
- The mean value of the dynamic modulus of elasticity of the jointed boards correlates with the FJ bending stiffness properties.

This research contributes knowledge on the mechanical properties and behavior of finger joints. In addition, it will serve as the base for the development of material models, incorporating the relationship between FJ bending and tensile properties and relevant non-destructive strength and stiffness indicators.

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