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THE STATISTICAL VARIABILITY AND LENGTH EFFECTS IN THE TENSILE TRANSVERSE BEHAVIOR OF CLEAR TIMBER

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ABSTRACT: In this work, clear timber specimens of different lengths with a small cross-sectional area were cut in the transverse direction of timber boards and tested under tensile loading. Regularly positioned and randomly positioned specimens were cut from different timber boards. Local deformations in each specimen were measured during the tests and the mechanical behavior of specimens of different lengths was compared. Statistics and size effects concerning the elastic modulus and strength were studied. The transverse tensile behavior was approximately linear. The results show very significant variability in the transverse elastic modulus, as high as 1000% between some specimens. The transverse tensile strength decreases linearly with specimen length increase on logarithmic scales.

KEYWORDS: Clear wood, Transverse mechanical properties, Quasi-static loading, Length effect, Uncertainty

1 INTRODUCTION

The existence of variability in the mechanical properties of timber has long been recognized [1]. This variability is related to the age, original position of the timber within the tree, structural complexity and imperfections, load history during tree growth etc. [2]. As a consequence of this variability, the statistics of the mechanical properties of timber can change with specimen size [3].

The longitudinal mechanical properties of timber have been more intensively investigated compared to the transverse properties. This is primarily because of the common applications of timber for beams and truss elements where mainly longitudinal stresses develop. On the other hand, in some applications such as mechanical and adhesively-bonded timber joints, transverse properties, such as the transverse tensile strength of clear timber which is only a few percent of its longitudinal tensile strength [4], are of critical importance.

The mean strength of timber, in its brittle failure modes such as those under longitudinal and transverse tensile loadings, decreases as its volume increases, since the probability of the occurrence of a weakest material point with a lower strength value increases. This phenomenon is referred to as the size effect on strength. Several experimental works have been devoted to the effect of size on the transverse strength of clear timber [1, 5-9], mainly focusing on glued-laminated material. The classical Weibull size effect law (CWSEL) [10] is commonly used in the literature for modeling this effect [5,6,9]. Very few works in the literature have adopted other approaches to investigate the size effect in timber, especially in the transverse direction. In the case of transverse strength, Pedersen et al. [8] and Astrup et al. [9] conducted transverse tensile tests on bulk specimens with a double symmetry and observed a large size effect in the results. They developed a deterministic model for the size effect observed from experiments. This model was based on the consideration of stress inhomogeneity caused by the anisotropic nature of timber.

Previous experiments were mostly carried out on bulk cubic or glulam specimens in order to comply with the EN standard [11], which recommends a glued laminated timber composed of solid timber blocks as the testing specimen, while the size effect on the transverse strength of small clear specimens has not been investigated. Also, it is reported in [3] that no conclusive evidence has yet been found concerning the accuracy of probabilistic strength size effect theories, like the CWSEL. Compared to the uncertainty regarding strength, the effect of the high scatter in the timber elastic properties [12] on the response of timber structures has received less attention [3,4,13]. However, a spatially variable elastic field can lead to a different stress field, compared to the case of a uniform elastic modulus. This stress field results in a different failure probability when used with a failure function, compared to the case when the spatial variability is not included.

This work addresses the aforementioned shortcomings in the literature by performing quasi-static experiments on specimens cut in the transverse direction with different

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lengths and analyzing their mechanical behavior and failure types. In addition to the global displacement monitoring, the local deformations along the length of each specimen were measured. The mechanical behavior of specimens of different lengths cut in regular and random manners from different boards was studied. The statistics of the elastic modulus and strength as well as the effect of specimen length on these properties were examined. The accuracy of CWSEL for the transverse tensile strength of small clear specimens was also evaluated.

2 EXPERIMENTAL INVESTIGATION

Norway spruce wood was used for the specimen fabrication. Specimens were conditioned to 12% moisture content before testing following the ASTM standard D143-14. They were tested in the lab temperature of 22±3 C°. The specimens were cut following two different plans. In the first plan, each board was used for cutting specimens of a specific length, regularly distributed over the board. These boards are designated as regular boards (REB). In the second plan, specimens of different lengths were randomly positioned in each board. These are referred to as random boards (RAB). The typical boards used for specimens of different lengths are shown in Figs. 1a a, b and c. Specimens of 8mm, 32mm and 120mm nominal lengths were fabricated.

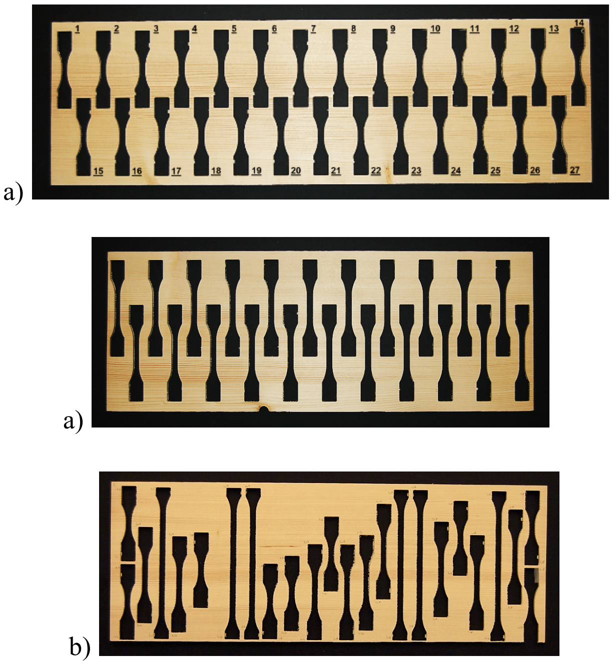

Figure 1: *a) A REB with 8mm specimens b) A REB with 32mm specimens c) a RAB with specimens of different lengths.*

Specimens with different lengths were fabricated by using a CNC machine. A cross-sectional area of 4×4 mm^2 was considered for all investigated specimens. Representative specimens are shown in Fig. 2a. The length of the middle zone (nominal length) can be 8, 32 and 120 mm. After conducting a number of preliminary experiments, 226 specimens were tested during the main program.

The following system is used to refer to the specimens in this study: TT-abc-16-de-fghi where TT refers to transverse tensile, 'abc' is the specimen length in mm (008, 032, 120), 16 is the cross-sectional area in mm2, the same for all specimens, and 'de' denotes the specimen ID number in each group of specimens with the same length. Finally, 'fghi' indicates the specific board.

A 5-kN walter+bai electromechanical testing machine was used for conducting the experiments. Quasi-static tensile tests were done in the displacement-control mode. Stroke rates of 1 mm/min for specimens with nominal lengths of 8 and 32 mm and a stroke rate of 2 mm/min for specimens with a nominal length of 120 mm were used on the basis of previous preliminary experiments so that the final failure occurred within 180±60 s throughout the whole testing program.

A video extensometry system composed of a 10-bit Sony XCLU1000 CCD connected to a Fujinon HF35SA-1, 35-mm f 1.4-22 lens with an accuracy of ±0.005 mm was used during the experiments to measure the axial deformation. Prior to the tests, black target dots of 1.1-mm diameter were applied on the specimens' surfaces. The distance between each two consecutive dots was 4 mm for all groups of specimens. A typical specimen of 32-mm length mounted in the testing rig is shown in Fig. 2b. The axial coordinates of the dots were recorded at a frequency of 5 Hz by the video extensometer throughout loading. Using the displacements of the first and last dots on each specimen, an overall strain for each nominal length was obtained. These data were used for calculating the effective elastic modulus for each specimen. Nominal axial stresses were calculated by using the load measurements and the initial cross-sectional areas.

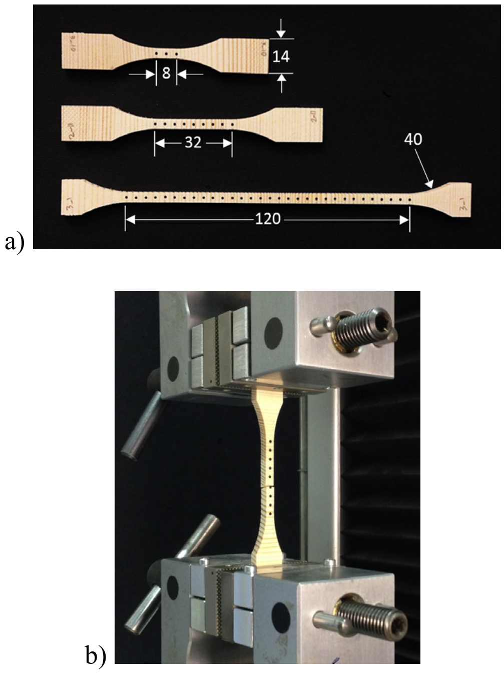

Figure 2: *a) Specimens b) Testing rig with a failed specimen.*

3 Mechanical behavior

Tensile stress-strain curves of the 8-mm, 32-mm and 120-mm-length specimens, cut from the REBs, are shown in Figs. 3-9. In the cases of boards with two rows of specimens, the curves in each row are indicated by a different color. Maximum and minimum strengths and strain to failure are indicated by vertical and horizontal dashed lines in each figure. The overall strains are used for plotting these curves; the average slope of each curve indicates the effective elastic modulus.

An almost linear stress-strain behavior is observed for most of the specimens. There is a high scatter in the effective elastic modulus, strength and strain to failure (overall strain) for each length. In a few cases, the maximum/minimum values of strength are associated with the maximum/minimum values of strain to failure, especially when the minimum strength in a board is relatively low.

Considering the specimens of 8-mm length, the results of the two rows from each board are not significantly different. The range of variation of strength and strain to failure is wider in the first board. The specimens from the first board have slightly higher strengths.

In the first board for specimens of 32-mm length, the specimens in the upper row exhibit higher moduli and strengths and lower strains to failure. However, the specimen behaviors in the two rows of the second board are not significantly different. As a result, the scatter in the mechanical properties is higher in the first board. Also, the first board is less stiff than the second board and exhibits lower strengths but higher strains to failure. In the specimens from the first board, higher moduli values are associated with higher strengths, which is not the case for the specimens from the second board. The range of variation in the strength is wider in the first board, mainly because of one specimen that happened to have a relatively low strength.

Regarding the specimens of 120-mm length, the specimens from the first board have lower moduli and strengths. The scatter in the effective elastic modulus and strain to failure is higher in the first board. However, the second board shows higher scatter in the strength. The strength is higher for the specimens from the third board than those from the second board, and higher for the specimens from the second board than those from the first board.

Specimens of 8-mm length exhibit a lower variability in their mechanical properties, since they represent mainly the variability of the transverse modulus in the longitudinal direction. The variability of the transverse modulus in the transverse direction of the boards can be better taken into account when specimens are longer. However, a size effect is still present with shorter specimens exhibiting higher strengths.

The experimental results for the mechanical properties of specimens of different lengths in the RABs are shown in Figs. 10-12. The mechanical behavior is almost linear, similar to the REBs. The strength consistently decreases with increasing specimen length. A detailed discussion regarding the size effect is provided in Section 4.

The mechanical properties of each specimen including the effective elastic modulus, the strength and the strain to failure as well as their maximum and minimum values in each board, along with density and failure type, are given in Tables 1-3. The failure types are discussed in Section 5. Those few specimen densities affected by a nearby knot (mainly in the tab of the specimen) are indicated by * and are excluded when examining the correlation between density and mechanical properties.

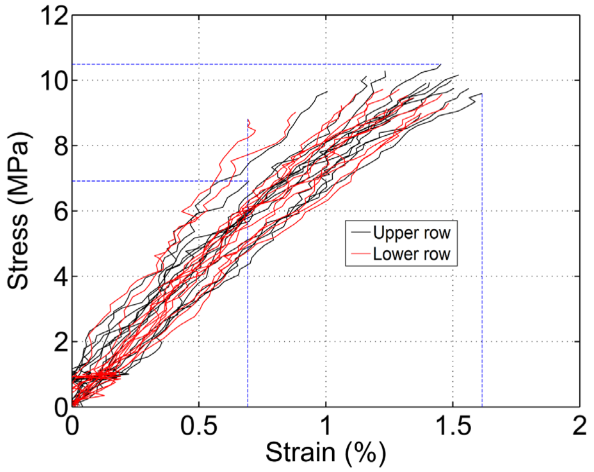

Figure 3: *Transverse tensile stress-strain curves of spruce wood for 8-mm specimens cut from REB1*

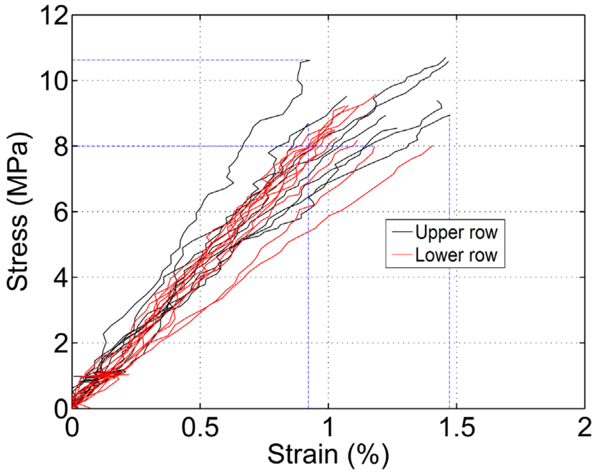

Figure 4: *Transverse tensile stress-strain curves of spruce wood for 8-mm specimens cut from REB2*

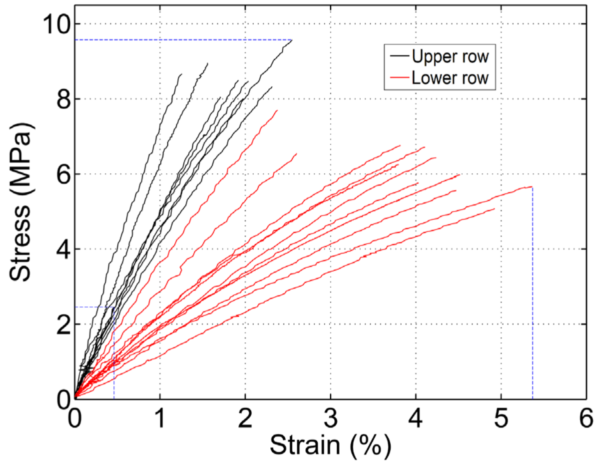

__Figure 5:__ Transverse tensile stress-strain curves of spruce wood for 32-mm specimens cut from REB1

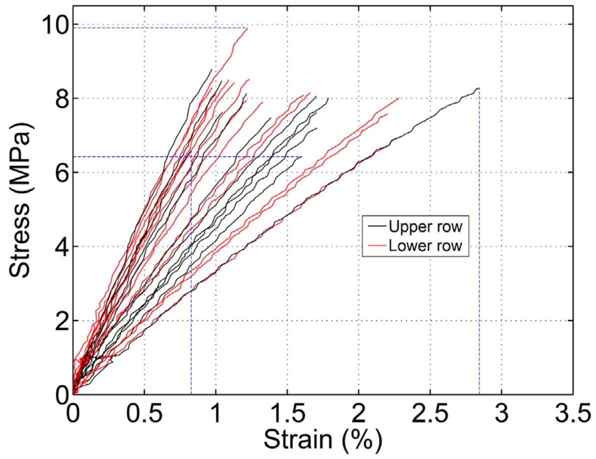

__Figure 6:__ Transverse tensile stress-strain curves of spruce wood for 32-mm specimens cut from REB2

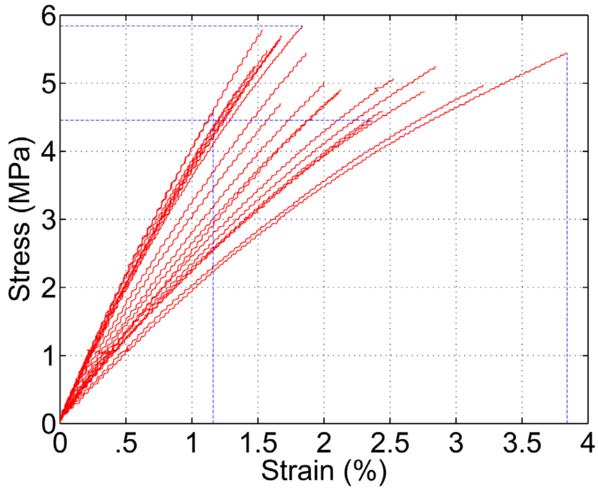

__Figure 7:__ Transverse tensile stress-strain curves of spruce wood for 120-mm specimens cut from REB1

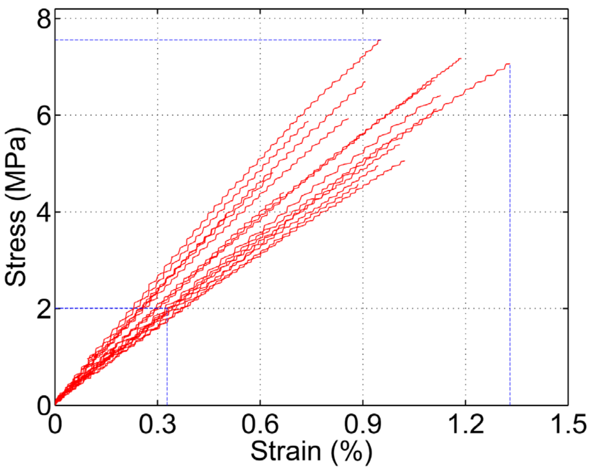

__Figure 8:__ Transverse tensile stress-strain curves of spruce wood for 120-mm specimens cut from REB2

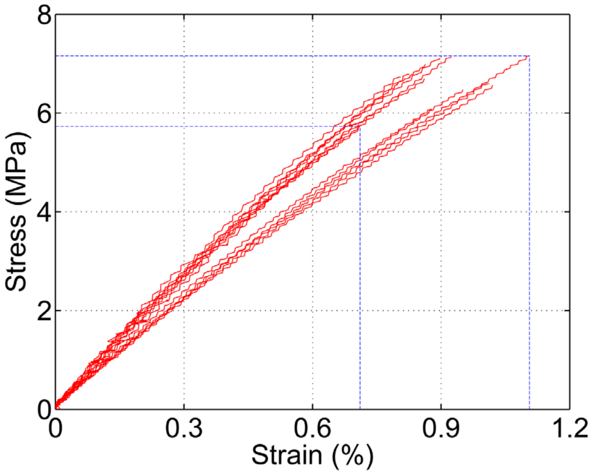

__Figure 9:__ Transverse tensile stress-strain curves of spruce wood for 120-mm specimens cut from REB3

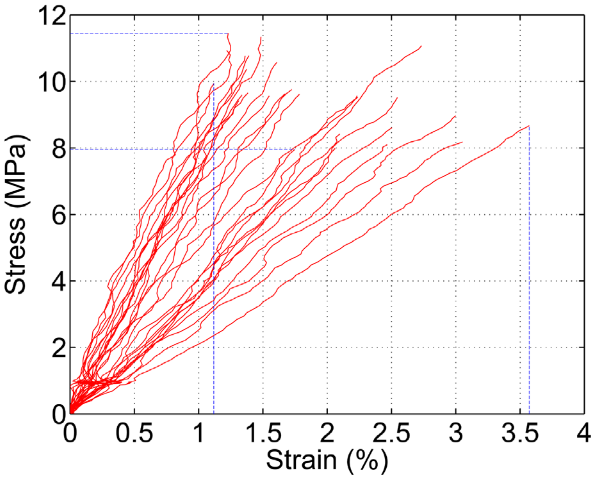

__Figure 10:__ Transverse tensile stress-strain curves of spruce wood for 8-mm specimens cut from RABs

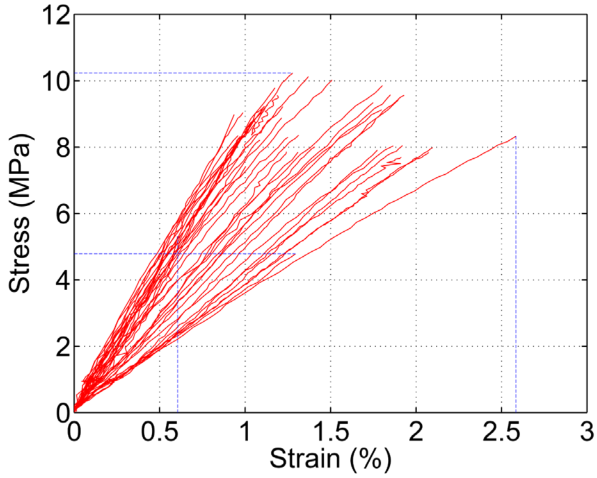

Figure 11: *Transverse tensile stress-strain curves of spruce wood for 32-mm specimens cut from RABs*

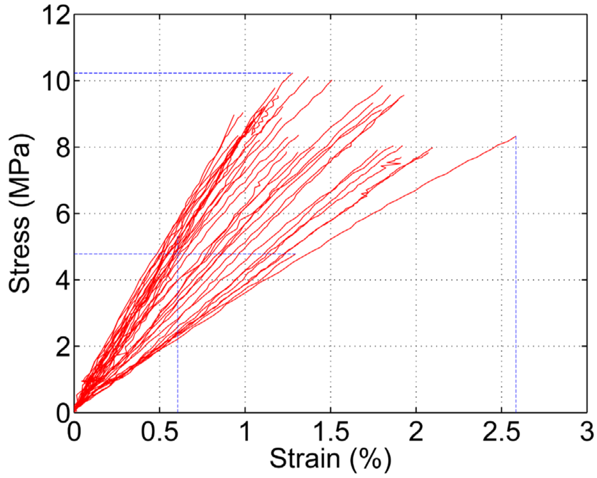

Figure 12: *Transverse tensile stress-strain curves of spruce wood for 120-mm specimens cut from RABs*

4 Statistics of properties and length effects

4.1 Statistics of effective transverse elastic modulus

The statistics of the effective elastic modulus for the three specimen lengths, cut from the REBs and RABs, are given in Table 1. First, test results for specimens cut from the REBs are considered. It can be seen that the mean value for specimens of 8-mm length is considerably higher than those for 32-mm- and 120-mm-length specimens; however, the standard deviation (SD) is lower. Consequently, the coefficient of variation (COV) for the 8-mm-length specimens is also much lower. This is because the elastic moduli values of the 8-mm-length specimens mainly represent the scatter in the transverse elastic modulus along the longitudinal paths from which they were cut. This is also true for the mean value of the modulus for the 8-mm-length specimens from the REBs. However, in the case of the 32-mm- and 120-mm-length specimens, a wider range in the transverse direction is covered and therefore the variability of the transverse elastic modulus in the transverse direction can be appropriately investigated.

Considering the RABs, the mean value of the modulus slightly increases from 8-mm to 32- mm-length specimens and then decreases for 120-mm-length specimens, indicating that the mean value does not change significantly as size changes. On the other hand, the COV decreases consistently as specimen lengths increase.

Table 1: *Statistics concerning the effective transverse modulus*

Property	Length (mm)	Mean (MPa)	COV (%)
Effective modulus in REBs	8	787.0	14.65
	32	464.3	49.90
	120	513.8	44.06
Effective modulus in RABs	8	574.7	35.24
	32	655.9	28.54
	120	581.8	20.53

4.2 Statistics of transverse tensile strength

The statistics of strength are given in Table 2 for specimens cut from both the random and the regular boards. The mean strength decreases with increasing length in all cases. Concerning the variability in the REBs, the COV of the 8-mm-length specimens is considerably lower than the other COVs. Similar to the case of the elastic modulus, this is because the COV of the 8-mm-length specimens from the REBs mainly represents the variability of the transverse tensile strength in the longitudinal direction. Considering the specimens of each length from the RABs, the COVs are similar, as shown in Table 2. However a sound conclusion cannot be drawn for the specimens cut from the REBs, since each specimen group (different lengths) comes from a different board and the COV is therefore increased as it includes the variability resulting from different boards.

According to the classical Weibull size effect law (CWSEL), the strength changes linearly with specimen size on the logarithmic scale. The slope of this line depends only on the shape factor of the corresponding Weibull distribution. In turn, this shape factor is only a function of COV. Therefore, using each three COVs from the RABs, the COVs of the strength data for specimens of 8-, 32- and 120-mm lengths were calculated and used to obtain an average value for the line slope. This slope, equal to -0.095, was used to fit a line to the experimental data, labeled as CWSEL in Fig. 13. The variability between the different boards is also shown in this figure as the mean values of strength obtained for each one of the RABs per specimen length is also indicated by solid symbols. This figure shows the experimental data on the logarithmic scale. It is seen that this line can well describe the size effect on the transverse strength of clear timber. The R-squared value for the fitting line is 0.972. This result is in contrast to the case of the longitudinal tensile strength, recently shown in [14].

It should be noted that the above analysis is not carried out for specimens from the REBs since specimens of different sizes are cut from different boards and, as shown in Fig. 13, variability between boards can affect the resulting average strengths.

Table 2: *Statistics concerning the transverse strength*

Property	**Length (mm)**	**Mean (MPa)**	**COV (%)**
Strength in REBs	8	9.41	8.18
	32	7.57	17.57
	120	5.63	19.01
Strength in RABs	8	9.71	10.88
	32	8.68	13.43
	120	7.79	10.49

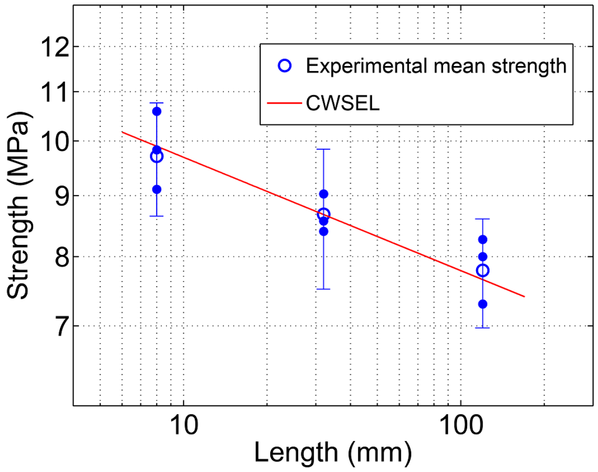

Figure 13: *Evaluation of accuracy of CWSEL against experimental data. Each hollow circle shows mean strength values for specimens of specific lengths cut from RABs. Solid circles show strength mean values in individual boards for specimens of specific lengths.*

5 Specimen failures

Four types of fracture were observed in the specimens, as shown in Fig. 14: 1) Earlywood 2) Earlywood-latewood 3) Growth ring border 4) Crossing growth rings. In the first type, failure happens mostly in the earlywood radial bonds which are stronger than tangential bonds and the failure plane is approximately perpendicular to the loading direction, leading to higher strength values for this failure type. The second type failure occurs in both earlywood and latewood. The failure plane is often not perpendicular to the loading direction, so the shear forces also participate in the failure. The failure path is a mixture of radial and tangential bonds, with the radial bonds constituting the larger part. In the third type, failure occurs in the radial bonds between earlywood and latewood, and the failure plane is not perpendicular to the loading direction, therefore shear forces are also acting on the failure plane. In the fourth type, the failure plane is approximately perpendicular to the loading direction. Consequently, with higher grain angles, the fracture path is a mixture of radial and tangential bonds in this failure type, which causes the strength to be lower than the previous types. The statistics of strength of all specimens from the REBs and the RABs, grouped according to their failure types, are given in Table 3.

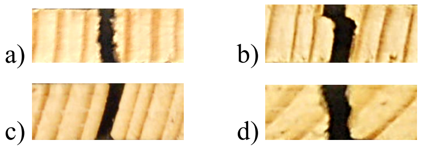

Figure 14: *Different failure types observed in specimens: a) Earlywood failure b) Earlywood-border failure c) Growth ring border failure d) Crossing growth ring failure. Vertical dimension is 4mm (specimen width). Load is applied in horizontal direction.*

Table 3: *Statistics of strength for all specimens when grouped according to failure types and statistics of local elastic modulus at failure zone*

Failure type	Number of specimens	Strength (MPa)	Local modulus (MPa)
1	134	8.85±1.26	634.1±246.1
2	42	7.42±1.58	614.1±284.9
3	32	6.34±1.71	546.2±308.6
4	15	5.50±1.77	179.0±119.0

In order to investigate whether or not the above classification also implies a significant difference between the mean strengths of the four groups, an analysis of variance (ANOVA), at a significance level of 5%, was performed. The null hypothesis states that samples in different data sets are taken from the same population. In this procedure, the variability of the means of data sets around the grand mean (between-set), which is the mean of all the raw data, is compared to the variability of the raw data around their respective means (within-set). By dividing the “between-set” variability by the “within-set” variability, an F-value is obtained which, along with the number of data sets and sample sizes, can be used for the estimation of the p-value from the F-distribution. The lower the p-value, the lower the probability that the raw data in the data sets are taken from the same population. Information regarding the calculation of the p-value is given in [15,16]. A p-value of 1.11e-16, which is far less than 0.05, was obtained for the examined pool of data sets, suggesting that one or more data sets were significantly different from the others. To identify the sets with significantly different mean values, the Scheffe's test [17] was used. The results of this test are given in Table 4. Any comparison whose associated p-value is less than 0.05 indicates a significant difference between the related data set mean values. All the estimated p-values, except the p-value of the pair 3 and 4, which is 3.21e-1, are less than 0.05. All comparisons, except that between the third and the fourth groups, show that specimen groups with different failure types have statistically significantly different mean strengths. Although the difference between the mean strength values of the third and fourth groups is similar to the differences between the first and second, or second and third groups, the limited fourth group sample size may have masked the significant statistical difference between these groups.

Table 4: *Results of Scheffe's test for two-by-two comparisons between failure types*

Pair	P-value
1 vs 2	1.51e-6
1 vs 3	1.13e-14
1 vs 4	8.67e-14
2 vs 3	1.71e-2
2 vs 4	2.56e-4
3 vs 4	3.21e-1

6 CONCLUSIONS

In this study, an experimental campaign consisted of transverse tensile quasi-static experiments on specimens of different lengths made of spruce wood was conducted. A total number of 226 valid experimental results were obtained. The cross-sectional area was the same for all specimens and reasonably small, so as to exclude the effect of the variability of the properties in the cross section. The nominal length of specimens varied from 8 mm to 120 mm in order to investigate the size effect on the mechanical properties. The following main conclusions were drawn:

- A plan with randomly positioned specimens is more appropriate for cutting specimens from a timber board, since the randomness in the mechanical properties is better captured.
- A highly significant variability was observed in the transverse tensile elastic modulus of clear spruce wood. COV of elastic modulus and mean value of the transverse strength are reduced as length increases.
- The CWSEL is sufficiently accurate for modeling the size effect on the transverse tensile strength of clear timber. This is in contrast to the case of longitudinal tensile strength, as shown in a previous study.
- Four types of failure were observed in the specimens. The strengths were higher when the grain angle was lower.

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