WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

EXPERIMENTAL INVESTIGATION ON THE ROLLING SHEAR PROPERTIES OF TIMBER

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ABSTRACT: The rolling shear properties of timber are important for wood products with orthogonal layups, such as Cross Laminated Timber (CLT). In this study, rolling shear tests are conducted on silver birch timber board segments for the determination of rolling shear strength and stiffness. The test setup applied is an adaptation of the longitudinal shear tests setup described in the European standard EN 408 [6]. Although the standard method requires steel loading plates glued to the wooden shear test specimen, in this study birch-wood longitudinal elements are glued to the birch-wood rolling shear test specimens. The setup was investigated as part of a Master's thesis work [12]. For determination of the rolling shear modulus, optical point tracking is employed to measure deformations on the loading plates and on the rolling shear specimen. In addition, a physical extensometer is attached to the specimens. Results indicate that the use of wooden loading plates is suitable for rolling shear testing, and advantageous, compared to steel plates, due to ease of fabrication. However, the bond-surface quality is found to be influential. Strength properties are influenced by bond-surface failures, and the shear modulus is influenced by poor adhesion and adhesion shearing, when measuring deformations from the loading plates, rather than directly on the rolling shear specimen.

KEYWORDS: Rolling shear strength, modulus, solid wood, birch hardwood, *Betula pendula*

1 – INTRODUCTION

The rolling shear properties of timber are important for the ultimate and serviceability limit state design of crosswise oriented structural timber products. Rolling shear, referred to as shear stresses acting in planes perpendicular to the grain, is of particular importance in the design of cross laminated timber (CLT).

To assess the mechanical properties of timber, proper methods of mechanical testing are crucial. Although most timber properties are addressed by international test standards with well-defined configurations, rolling shear still lacks standardized procedures and methods. As a result, the literature reports on various testing techniques to measure rolling shear modulus and/or strength, using diverse approaches, e.g. [1, 3–5, 8, 13, 17].

Ideally, the test setup should replicate typical stress conditions and configurations expected in actual use cases, such as bending tests performed on full-scale CLT plates. However, to obtain material properties, a simplified test on a single timber specimen may be advantageous, as it avoids the complexity of full-scale testing with multiple timber elements and is less resource intensive. One such test is the so-called modified planar shear test, also known as the two-plate planar shear test. In the present study, it will be simply referred to as a rolling shear test. The rolling shear test method is an adaptation of the European standard EN 408 [6] procedure for testing longitudinal shear properties, whereby the shear test specimen is sandwiched between two plates that transfer a vertical compression force to shear forces on the specimen.

One detail of interest with such tests has been the use of steel loading plates versus wood loading plates to transfer the load to the test specimen, e.g. [5, 14]. Nero et al., 2022 [14] observed lower stiffness values for setups with wood loading plates, rather than steel, when relying on deformation measurements from the loading device. In addition, the conventional use of extensometers attached to the loading plates may be prone to error, regardless of the material of the loading plates. To avoid these errors, it is suggested to adopt non-contact deformation measurement techniques that can measure shear strains directly on the rolling shear specimens [14].

In the present study, silver birch solid wood is experimentally investigated to determine rolling shear strength and modulus. The test procedure further adapts the two-plate planar shear test, in which three birch timber board segments are glued together with orthogonal lay-up with the central crosswise segment being loaded in transverse shear. A point tracking system is used to measure shear deformations on the specimen and the load transfer plates, and an investigation of the benefits and challenges of testing with wood loading plates is further conducted.

Birch species is used because birch is hardwood with favorable mechanical properties and good potential for use in value-added timber products [2]. However, information on the mechanical properties and behavior of birch, especially rolling shear behavior, is lacking. Previous experimental studies on birch rolling shear properties include, e.g., [5, 11].

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https://doi.org/10.52202/080513-0265

2 – EXPERIMENTAL INVESTIGATIONS

2.1 SPECIMENS

Silver birch timber from southern Finland is investigated. The dimensions of the rolling shear specimens are *w* x *t* x *l* = 120 x 30 x 100 mm^3. The specimens are cut from defect-free regions of timber boards. The timber boards were previously used in a separate study on the tensile mechanical properties of birch timber see Collins et al. [2]. In the previous study, the timber boards were tested in tension until failure. The specimens selected for the present study were obtained from regions outside the fractured regions of the tested timber boards. However, due to the large tensile forces applied, the prior stress (parallel to the grain) may have caused plastic deformations or damage that is not identified by visual inspection. To investigate the possible influence of prior tests, a separate smaller batch of tests were prepared from raw untested material. In total, 98 rolling shear tests were performed, of which 79 were of previously tested material and 19 of untested raw material[1].

According to the test results, when comparing the statistics of the previously tested and raw untested batches, no significant influence of prior tension tests was found. Therefore, implementing this sort of cascading testing regime to evaluate the mechanical properties of a sample material is deemed suitable, and the tested and untested batches are not further differentiated in this study.

The specimens are conditioned in a climate chamber at 20°C and 65% relative humidity, as described in EN 408 [6]. The density is determined from the mass and volume of each rolling shear specimen prior to gluing onto the loading plates. The annual ring pattern (cylindrical geometry of the concentric growth rings) of the specimen is randomly arranged in the setup, and images of the annual ring pattern are taken.

2.2 TEST SETUP

The rolling shear test setup is shown in Fig. 1. A focus of the study is on the setup and the advantages and challenges of using wooden loading plates to bring the load to the rolling shear specimen. The setup was investigated as part of a Master's thesis work in Jungerstam [12]. A vertical force *F* is applied to the longitudinal load transfer plates, which are glued to the birch rolling shear test specimen. The angle between the load direction and the specimen axis is 14°. This setup is an adaptation of the test configuration described in EN 408 [6] to determine longitudinal shear properties. A similar setup has also been applied for rolling shear tests in Ehrhart et al. [5] and Nero et al. [14]. However, in the present study the load transfer plates are made of birch wood (rather than steel plates as stipulated in EN 408 [6]). The rolling shear specimen, loaded in shear perpendicular to the grain, is glued to two loading plates, which are loaded parallel to the grain. Since birch has high longitudinal stiffness, the deformations that occur in the loading plate are investigated and compared to the rolling shear deformations of the test specimen.

1 Initially 80 specimens from previously tested material and 20 specimens from raw untested material were planned for testing but two specimens were removed due to poor fabrication quality.

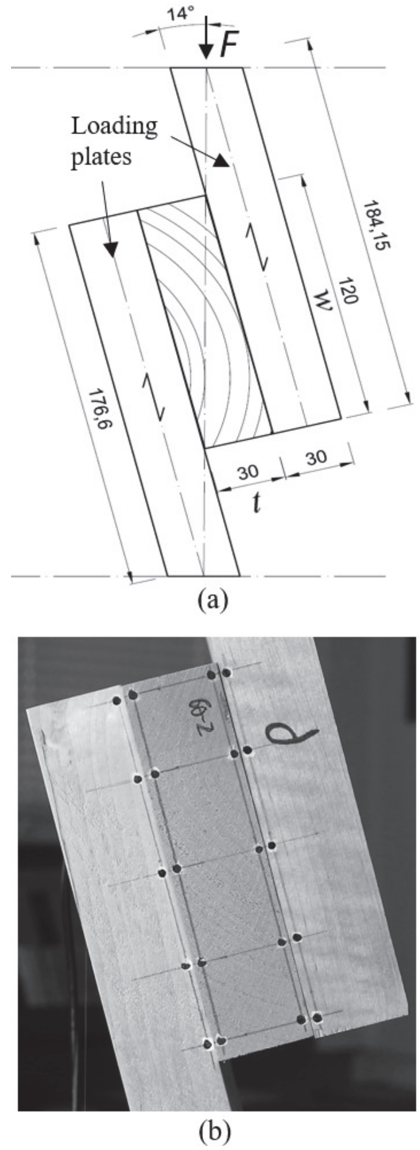

Figure 1: (a) Schematic of rolling shear test setup and dimensions (mm) and, (b) black and white point tracking points on the rolling shear specimen and load transfer plates.

2.3 DETERMINATION OF SHEAR STRENGTH AND MODULUS

A vertical force is applied to the specimen using a universal testing machine and the force is recorded with a load cell. Deformations are measured using a point tracking system, which measures local displacements during testing. A video is captured during testing and an image correlation algorithm is later used to track displacements of individual points of interest, see Jaaranen et al. [10] for more information on the point tracking image correlation algorithm. Fig. 1 shows the black and white (high contrast) tracking points. They are placed on both the loading plates and the rolling shear specimen. In addition, a linear variable differential transformer (LVDT) is mounted on the opposite side of the test specimen to measure the shear displacement on the backside. The LVDT measures shear displacement

https://doi.org/10.52202/080513-0265

relative to the loading plates (i.e., rather than directly on the rolling shear specimen). The rolling shear moduli determined from these different measurement methods are compared.

The shear strength is calculated according to (1), where $F_{\text{max}} \cos(14°)$ is the shear component of the maximum imposed force and the shear area of the specimen is $w \cdot l$. The shear modulus is calculated according to (2), where dF/ds is the average inclination of the force-deformation curve within the linear elastic region, and t is the thickness of the specimen (Fig. 1).

$$f_{\text{v,r}} = \frac{F_{\text{max}} \cdot \cos(14°)}{w \cdot l} \tag{1}$$

$$G_{\text{v,r}} = \frac{dF \cdot \cos(14°)}{ds} \frac{t}{w \cdot l} \tag{2}$$

2.4 ADHESIVE

A pre-study on appropriate adhesives was conducted. Three adhesives were investigated: Polyvinyl acetate (PVAC), polyurethane, and a two-component epoxy. Polyurethane was deemed insufficient after four tests because of exclusive bond-surface failures at loads lower than expected, based on the literature. The PVAC adhesive achieved higher load values compared to polyurethane; however, failures were mainly in the bond-surface, suggesting that the rolling shear strength of the wood is higher than the bond-surface. Finally, tests with epoxy resulted in rolling shear failures that occur mainly in wood, at load levels similar to those in the literature, and thus it was selected as the appropriate adhesive to carry out the full series of tests.

3 – EXPERIMENTAL RESULTS AND DISCUSSION

3.1 ROLLING SHEAR STRENGTH

The use of birch wood as loading plates was found to be advantageous compared to steel plates because steel plates are in limited quantity. The limited quantity meant that laborious cleaning of the adhesive was required after each test using steel plates. For wooden loading plates, on the other hand, the material supply is more available and new loading plates could be fabricated for each test specimen, without the need for removal or cleaning after testing. This allowed more specimens to be tested, when using wood, resulting in a sample size of $n = 98$. In addition, rolling shear failures were observed in most tests, indicating that the use of longitudinal timber for loading plates was sufficient to determine rolling shear strength.

The rolling shear strength is determined from the maximum shear stress achieved during the tests, however, as is often the case when testing timber, there are certain caveats which concern the actual rolling shear strength of the specimens. According to the failure modes observed, most specimens failed due to rolling shear stresses, but in some cases failures occurred at the bond-surface between the plate and the specimen, or with a more complex fracture mode with mixed failures occurring in the rolling shear specimen and the bond-surface. In cases where it is obvious that the

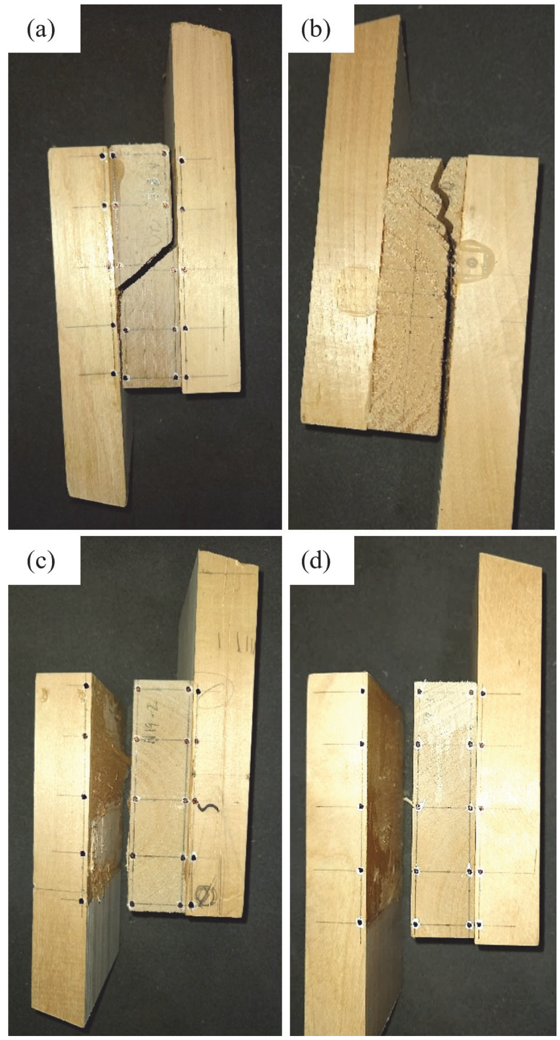

Figure 2: Different failure modes from the rolling shear tests showing failures in the rolling shear specimen (a & b) and along the bond-surface (c & d). Images from Jungerstam 2023 [12].

bond-surface failed prior to the rolling shear specimen, it can be reasoned that the rolling shear strength is actually higher than the value obtained from the maximum load of the test. However, in mixed failures, with partial failure in the bond-surface and in the rolling shear specimen, there is ambiguity regarding the ”true” rolling shear strength. Fig. 2 shows examples of different failure modes, in which it can be argued how well the test results provide a measure of the ”true” rolling sher strength. While Fig. 2(a,b) show fracturing of the rolling shear specimen, Fig. 2(c,d) show fractures along the bond-surface with varying amounts of the fracture occurring in wood and adhesive. The question is how best to consider these different forms of information when determining the strength of a specimen or the strength properties of a group (sample) of specimens.

One way to consider such different forms of strength information is with statistical techniques that apply the concept of censored data. Censored data means a value that is only partially observed due to a cutoff or threshold. In this case, the threshold is the value of maximum load

https://doi.org/10.52202/080513-0265

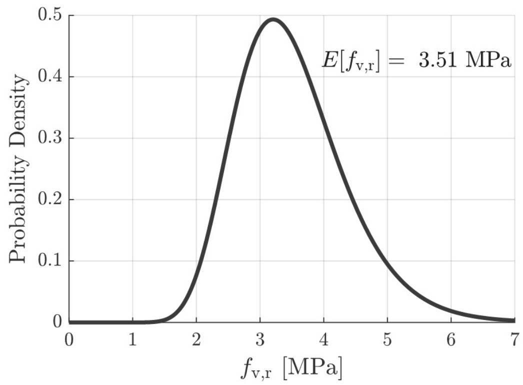

Figure 3: Lognormal distribution of the rolling shear strength, with censored data considered. E is the expected value.

obtained when the specimen failed in ways that may be distinguished as a fault/limitation of the setup, i.e., non-rolling-shear failures. The use of statistical methods that consider censored information in timber engineering can be found in literature, e.g., [2, 7, 15, 16]. Such methods aim to consider that the "true" value is greater than the observed value, by means of statistical methods to estimate the strength properties of the overall sample.

In this study, data are classified as censored when failures occur mainly in the bond-surface, and fracturing of the adhesive constitutes at least 3/4 of the total fracture surface. In that case, the strength of the rolling shear specimen is assumed to be greater than or equal to the maximum shear stress obtained in the test. The censoring condition is defined on the basis of visual inspections of all failed specimens. With this censoring condition, 24 of the 98 test results are considered censored.

Fig. 3 shows the distribution of the rolling shear strengths, considering censoring in the analysis. The probability distribution of the sample is fitted to the data using the maximum likelihood method with censored data; see, e.g., [9]. The expected value is $E[f_{\mathrm{v,r}}] = 3.51$ MPa with coefficient of variation $CV[f_{\mathrm{v,r}}] = 0.25$. As the censoring condition applied is subjective, the results are accompanied by additional uncertainty. It is therefore important to develop tests methods that reduce such uncertainties by improving the setup.

3.2 ROLLING SHEAR MODULUS

The rolling shear modulus was determined from three different deformation measurement methods: the relative shear displacement of the tracking points directly on the rolling shear specimen, $G^{\mathrm{S}}_{\mathrm{v,r}}$; the relative shear displacement of the tracking points on the loading plates, $G^{\mathrm{P}}_{\mathrm{v,r}}$; and the relative shear displacement of a single LVDT attached to the loading plates, $G^{\mathrm{L}}_{\mathrm{v,r}}$.

Five rows of tracking points were applied on the specimens (Fig. 1), however, only the three central rows were identified as useful for the determination of the rolling shear modulus. Neglecting the outside points is done because there is no shear stress at the free face of the rolling shear specimen and that at the outer (corner) points the stress state is complex due to the presence of compression and tension stresses in the transverse direction, see [5]. From the three central rows, shear deformation for each row is determined and a correlation between force and deformation is calculated. To avoid errors due to noise in the point tracking measurements of individual rows, a correlation requirement of $R \geq 0.99$ was applied and any measurement that did not meet the criteria was rejected from the analysis. The rolling shear modulus was determined only for specimens with at least two rows of suitable deformation data, whereby the average deformation was considered. In addition, ten specimens did not have point tracking points because they were selected for digital image correlation analysis and will later be investigated in terms of a full-field strain analysis.

Fig. 4a provides a scatter plot of the rolling shear modulus determined from the point tracking points on the specimens and the loading plates. The resulting mean values are $E[G^{\mathrm{s}}_{\mathrm{v,r}}] = 200$ MPa and $E[G^{\mathrm{p}}_{\mathrm{v,r}}] = 183$ MPa. The coefficient of variation is $CV[G^{\mathrm{s}}_{\mathrm{v,r}}] = 0.23$ and $CV[G^{p}_{\mathrm{v,r}}] = 0.25$, respectively. Although the moduli are generally similar, measurements made directly on the specimen frequently result in a larger modulus compared to the measurements made on the loading plates. An explanation for this is the influence of the bond-surface quality. With a low bond-surface quality, displacement between the loading plate and the specimen may occur if the bond-surface exhibits poor adhesion or low stiffness. The result is overall larger deformations, as deformations in the bond-surface are added to the deformations of the rolling shear specimen. Slipping between the plate and the specimen was observed in the videos, particularly in specimens that exhibited $G^{\mathrm{s}}_{\mathrm{v,r}} \gg G^{\mathrm{P}}_{\mathrm{v,r}}$. As such, measurements made directly on the rolling shear specimen suggest a more reliable result, compared to measurements made on the loading plates.

It is observed that during loading, rotations of the setup occur. Fig. 5a illustrates the deformation of a test specimens near the maximum load ($F = 50$ kN). The deformed specimen is overlaid with the initial position of the unloaded setup, shown in yellow dashed lines. Minor rotations are observed, e.g., by comparing the deformed position of the loading plates with the initial position, whereby clockwise rotations are evident. The rotation at each image step in the video is quantified using the tracking points on the loading plates. To isolate shear displacements from rotations, the rotations are removed from the overall point displacement by means of an inverse rotation transformation at each image step.

Fig. 4b compares the results of $G^{\mathrm{s}}_{\mathrm{v,r}}$ and $G^{\mathrm{L}}_{\mathrm{v,r}}$. As evident from the scatter plot, the LVDT measurements frequently result in larger moduli compared to the values obtained directly on the rolling shear specimen. However, the opposite can also be observed in rare cases. The difference between $G^{\mathrm{s}}_{\mathrm{v,r}}$ and $G^{\mathrm{L}}_{\mathrm{v,r}}$ may be explained by the slipping/shearing of the bond-surface, since the LVDTs are attached to the loading plates as well as the rotations in the setup during loading.

The rotations have significant implications for the LVDT setup, since rotations can decrease the measured transducer extension, as a result of the lever arm rotating on the right-sided loading plate where it is attached, see Fig. 5b. This rotation introduces error into the shear deformation measurement, making the $G^{\mathrm{L}}_{\mathrm{v,r}}$ larger than it should be. Erro-

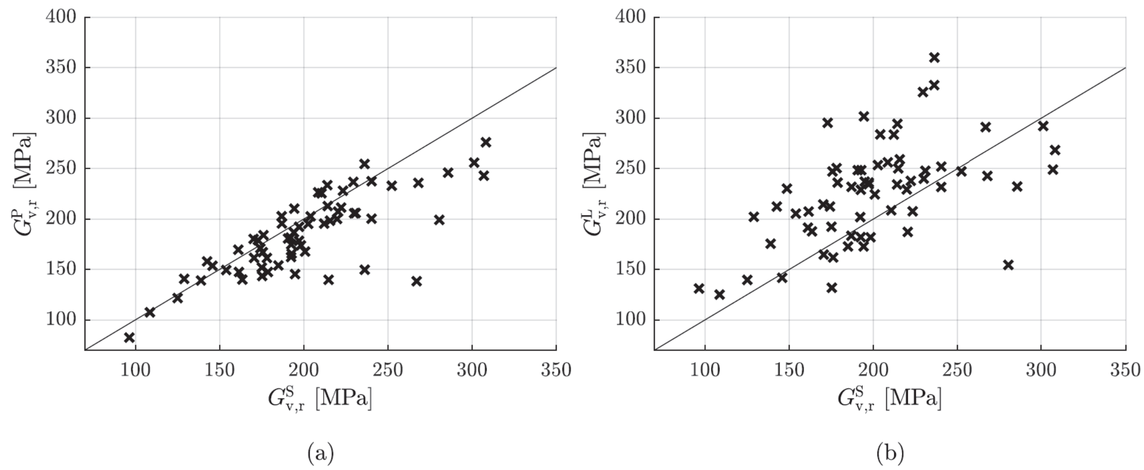

Figure 4: Comparison of the shear modulus determined based on (a) point tracking points on the rolling shear specimen $G^{S}_{v,r}$ versus point tracking points on the loading plates $G^{P}_{v,r}$, and (b) point tracking points on the rolling shear specimen versus LVDT measurements $G^{L}_{v,r}$.

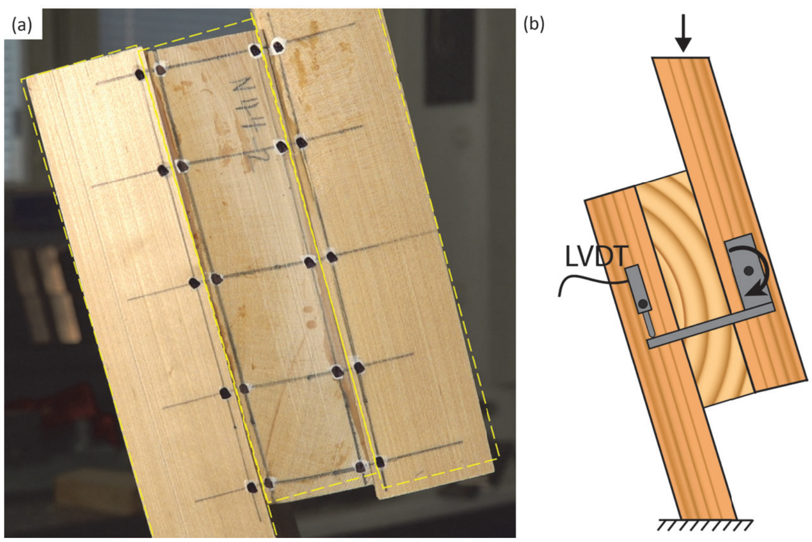

Figure 5: (a) A specimen loaded to $F = 50$ kN showing the deformed shape along with the initial unloaded shape outlined in yellow dashed lines and (b) The influence of clockwise rotations on the LVDT measurement setup.

neous measurements due to rotations of the loading plates were also described in a prior study [14], whereby laser sensor extensometers (comparably similar to the LVDT setup of the present study) were vulnerable to minor rotations. Therefore, the use of non-contact image analysis methods are preferred to avoid this issue.

4 – CONCLUSION

In the present study, shear tests were conducted on rolling shear test specimens sandwiched between two longitudinally oriented wooden loading plates. The specimen and loading plate material was silver birch. A total of 98 specimens were tested and the advantages and challenges of the test setup and methodology were investigated.

In the vast majority of tests, the failure modes were rolling shear type failures, indicating the suitability of the setup. However, in some cases, failures occurred at the bond-surface between the plate and the specimen. In such cases, the result is considered to be censored, such that the strength of the specimen is treated as greater than or equal to the maximum shear stress obtained from the test. A statistical representation of the strength properties is determined by linking the failure modes with censoring criteria.

The shear modulus was determined from three different deformation measurement methods: shear deformations of the tracking points directly on the rolling shear specimen; shear deformations of the tracking points on the loading plates; and deformations from a single LVDT. The most reliable results were identified with the tracking point methods directly measured on the test specimen. The shear modulus determined from deformations on the loading plates is frequently lower, resulting from deformations in the bond-surface. In contrast, the LVDT measurement resulted in larger shear moduli, which was considered to be erroneous because rotations in the setup improperly influence the measurements.

The rolling shear specimens of this study were obtained

https://doi.org/10.52202/080513-0265

from timber boards previously tested in tension. Comparison of the rolling shear properties of the prior tested material to a batch of raw untested material indicated that there was no obvious influence from prior testing. This supports a cascading test regime in which different mechanical tests may be performed on the same material.

5 – ACKNOWLEDGMENTS

The authors acknowledge the foundational contribution of Isak Jungerstam's master's thesis, which served as the basis for this article. The authors also thank Joonas Jaaranen for permitting the use of his digital image point-tracking algorithm.

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