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Influence of lamination aspect ratios and test methods on rolling shear strength evaluation of cross laminated timber

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Influence of lamination aspect ratios and test methods on rolling shear strength evaluation of cross laminated timber

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ABSTRACT

Rolling shear (RS) strength may govern load carrying capacity of cross laminated timber (CLT) subjected to high out-of-plane loading because high RS stresses may be induced in cross layers and wood typically has low RS strength. This study investigates RS strength properties of none-edge-glued CLT via experimental testing (short-span bending tests and modified planar shear tests) and numerical modelling. CLT specimens with different manufacturing parameters including two timber species (New Zealand grown Douglas-fir and Radiata pine), three lamination thickness (20 mm, 35 mm, and 45 mm) and various lamination aspect ratios (4.1~9.8) were studied. The lamination aspect ratio was found to have a substantial impact on RS strength of CLT. Higher aspect ratios led to a significant increase of RS strength and an approximately linear relationship could be established. With similar lamination aspect ratios, the Radiata pine CLT had higher RS strength than the Douglas-fir CLT. The two different test methods, however, yielded comparable RS strength assessments. Numerical models were further developed to study the influence of the test configurations and gaps in the cross layers on stress distributions in the cross layers. It was also found the compressive stresses perpendicular to grain in cross layers had negligible influence on the RS strength evaluations.

KEYWORDS:
Cross laminated timber, rolling shear strength, lamination aspect ratio, short-span bending, planar shear, numerical modelling, Douglas-fir, Radiata pine

1. Introduction

Wood is a cylindrical anisotropic material composed of longitudinally aligned fibers which yield significantly different mechanical properties in longitudinal, tangential and radial directions. This natural characteristic contributes to both in- and out-of-plane mechanical properties of cross laminated timber (CLT) which is composed of multiple layers of timber laminations assembled orthogonally using mostly structural adhesive systems. Specifically, considering that flat-sawn boards are used in CLT manufacturing, perpendicular-to-grain shear properties along cross-sectional (i.e. tangential- and radial-longitudinal) planes affect the composite system's flexural strength and stiffness. Under out-of-plane loads, shear stresses induced along the cross-sectional planes will cause the wood fibers to roll over others. This phenomenon is called rolling shear (RS) mechanism. The RS properties may govern the design of CLT panels as per the ultimate limit state (strength) design. In literature, RS properties were

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found to be affected by test methods (Aicher et al., 2016), manufacturing processes (Fink, et al. 2018), and lamination characteristics such as species, sawing patterns, and aspect ratio $\gamma = w_\ell/t_\ell$, defined as the ratio between lamination width w_ℓ and thickness t_ℓ (Ehrhart & Brandner, 2018).

According to Wood Handbook (2010), RS strength of typical softwood species varies typically between 18% and 28% of its parallel-to-grain (i.e., longitudinal) shear strength. In Eurocode 5 (2008), the characteristic RS strength value $\tau_{rs,k}$ is 1.0 MPa regardless of the timber strength class. According to European Standard EN 16351 (2015), for edge-glued CLT manufactured by common softwood including Norway spruce (Picea abies), $\tau_{rs,k}$ is 1.1 MPa; for non-edge-glued CLT with $\gamma \geq 4$, $\tau_{rs,k}$ is also 1.1 MPa; and for other cases, $\tau_{rs,k}$ of 0.7 MPa should be used. Similarly, in North America, the minimum lamination aspect ratio γ of 3.5 is recommended for non-edge-glued CLT and $\tau_{rs,k}$ =1.0 MPa is specified for CLT made out of the Spruce-Pine-Fir species group (ANSI/APA PRG 320, 2018). These internationally acknowledged standards specify the $\tau_{rs,k}$ for the timber laminations exceeding the minimum γ in non-edge-glued CLT but do not explicitly address the influence of γ on RS strength when γ exceeds the minimum ratio.

It was reported that lamination geometry has a strong influence on RS strength properties of CLT, especially for non-edge-glued ones. Ehrhart et al. (2015) stated that there was a positive relationship between RS strength and γ, based on two-plate shear test results from 30 mm-thick Norway spruce laminations with γ = 2, 4, and 6; and characteristic RS strength $\tau_{rs,k}$ of 1.4 MPa was proposed for $\gamma \geq 4$. The influence of γ on the RS properties was also confirmed by finite element (FE) analyses in the paper, which showed that the corners of each cross lamination experienced normal stress concentration due to the shear stress release on free edges. The stress concentration becomes more severe as γ decreases. Christovasilis et al. (2016) also reported a similar positive relationship between γ and RS strength based on four-point bending tests on three-layer CLT using Norway spruce laminations with γ = 7.9 and 2.7. Li (2017) found that RS strength was increased by more than 17% as the aspect ratio increases from 4.7 to 9.8 based on short-span bending tests and modified planar shear test results of New Zealand Radiata pine CLT. Sikora et al. (2016) evaluated the effect of lamination thickness on RS strength of Irish Sitka spruce CLT under bending loads and observed that RS strength was adversely influenced by increasing CLT thickness. The test results also confirmed the CLT specimens with 20 mm thick laminations (with γ=4.8) had significantly higher RS strength than the specimens with 40 mm thick laminations (with γ=3.7). Jakobs (2005) also confirmed the effect of γ on RS properties by simulating the out-of-plane behaviour of three-layer CLT panels using FE models.

Similar to the test methods to evaluate RS properties of plywood, short-span bending tests and two-plate shear tests (sometimes also called planar shear tests) in ASTM D2718-18 (2018) can be used for CLT. In the short-span bending tests, specimens are loaded with a small span-to-depth ratio, for example, 5~6, to encourage RS failure mechanism in cross layers. In the two-plate shear tests, shear loads are applied by two metal plates face-glued onto face layers of CLT. Mestek et al. (2008) studied the influence of shear deformation of cross layers on load carrying capacity of CLT beams by conducting three-point bending tests. Zhou et al. (2014) used short-span bending tests and two-plate shear tests to study RS strength and stiffness properties of CLT made out of Canadian black spruce. Li (2017) used short-span bending tests and modified planar shear tests (based on NZS 2269.1:2012 test standard for plywood) to evaluate RS strength properties of CLT made out of New Zealand Radiata pine laminations. Other than the two commonly used methods, Li et al. (2014) and Lam et al. (2016) used torsional shear testing to evaluate RS strength of CLT in which cross layers were machined to have an annular cross-section to facilitate RS failure mechanism. However, the torsional shear specimens required a significant amount of machining effort to cut the cross layers.

The objective of this study is to develop a comprehensive test database of RS strength properties of CLT manufactured by Radiata pine (RP) and Douglas-fir (DF) timber laminations and to study the influence of lamination aspect ratio γ on the RS strength of non-edge-glued CLT when γ exceeds 4. The study also examines the influence of two commonly used test methods (short-span bending and planar shear) on RS strength evaluation. Numerical models are also used to understand non-uniform stress distributions and the effect of compressive stresses perpendicular to grain in the CLT specimens tested under two different test configurations.

2. Materials & Test Methods

Short-span bending test specimens and modified planar shear test specimens were sampled from full-size CLT panels pressed using a vacuum press on a commercial production line. One-component polyurethane adhesive was used to apply face gluing between laminations. The CLT panels consisted of three layers with equal thickness and had a size of 2×3 m or larger. Since they were non-edge-glued, small widthwise gaps of 0.2~2mm existed between the laminations. The laminations had three thicknesses (20 mm, 35 mm, and 45 mm) and the aspect ratio γ varied between 4.1 and 9.8. Sawing patterns of the laminations were not considered in this study considering mixed sawing patterns are typically used in commercial CLT production. SG8 grade timber (average Modulus of Elasticity or MOE = 8 GPa) was used for the laminations except that SG6 grade timber (average MOE = 6 GPa) was used for the cross layers of the RP specimens. SG8 is the most commonly used timber grade in New Zealand timber construction (NZS3603, 1993).

Table 1 lists the test matrix and lamination properties. Combining two wood species (DF and RP) and three lamination thicknesses, a total of six CLT configurations were studied. For each configuration, the supplier provided some 0.5×2.0 m CLT strips from big CLT panels and we sampled our specimens from those strips randomly. Both short-span bending and modified planar shear test method were used. Thirty replicates were tested for each CLT configuration and each test method. For simplicity, in the following context, DF20 refers to the DF CLT with 20 mm thick laminations, and similarly RP45 refers to the RP CLT with 45 mm thick laminations. Table 2 lists the measured densities and moisture contents of the specimens in terms of mean values and coefficients of variation.

Table 1 Test matrix and lamination properties

CLT config.	Test method	No. of specimens	Specimen dimensions	Lamination		
				cross section (mm × mm)	Aspect ratio γ	Timber grade
DF20	Bending	30	420×50×60	140×20	7.0	SG8/SG8/SG8
	Shear	30	140×50×60			
DF35	Bending	30	735×50×105	195×35	5.6	
	Shear	30	195×50×105			
DF45	Bending	30	945×50×135	195×45	4.3	
	Shear	30	195×50×135			
RP20	Bending	30	420×50×60	195×20	9.8	SG8/SG6/SG8
	Shear	30	195×50×60			
RP35	Bending	30	735×50×105	165×35	4.7	
	Shear	30	165×50×105			
RP45	Bending	30	945×50×135	185×45	4.1	
	Shear	30	185×50×135			

Table 2 Summary of density and moisture content

Measurement		DF specimens (n=180)	RP specimens (n=180)
Density (kg/m3)	mean	489	453
	COV	6.3%	6.7%
Moisture content	mean	9.4%	10.4%
	COV	13%	11%

Short-span bending tests

The bending specimens (B) were prepared, so that gap locations in the cross layers were random. A span-to-depth ratio of 6 was used in these tests to induce high RS stresses in cross layers. The loading rates were 1, 2, and 2.5 mm/min for the specimens with 20, 35, and 45 mm-thick laminations, respectively. Thus, the failure time was controlled within 4 to 6 min. As shown in Figure 1, central point loading was applied. For simplicity, the specimens were named by combining timber species (DF/RP), lamination thickness (20 mm/35 mm/ 45mm) and test methods (B for short-span bending; S for modified planar shear). For example, DF20-B now refers to DF specimens with 20 mm thick laminations tested under short-span bending tests.

Modified planar shear tests

For planar shear specimens (S), the test setup was modified based on the test standard NZS 2269.1 (2012) which is used to evaluate shear-through-thickness properties of plywood. As shown in Figure 2a, traditional planar shear test jigs consist of four steel plates in two pairs fastened with plywood via small bolts. In this study, the jigs were shown in Figure 2b, which were modified to accommodate for thicker CLT and higher load level. Compared to the test jigs in Figure 2a, the length of the steel plates in Figure 2b was increased, and screwed connections were used instead of small bolts to hold the steel plates and the test specimen in position. Two additional steel blocks were also installed on the top and bottom of the test jigs to apply the shear force by pressing the ends of the face layers in the opposite direction. The steel blocks will reduce the chance of having wood splitting in the face layers of the specimen caused by the screwed connections under high shear loads. One reinforcing solution to eliminate wood splitting along the screw line is to add short screws in the face layers along the perpendicular-to-grain direction. All the planar shear specimens were 50 mm wide. The length of the specimens was equal to the lamination width, while their thicknesses were the same as the corresponding CLT panel thicknesses. The specimens were prepared so that the face layers and the cross layers did not contain any gaps. The loading rate was 1 mm/min so that the failure time was controlled in 4~8 min. Figure 3 shows the test photos of the DF specimens. Similarly, DF20-S now refers to the DF20 specimens tested under modified planar shear tests.

3. Results & Discussions

Failure modes

During the short-span bending tests, bending failure occurred in 8 specimens before RS failure was observed. These specimens were not accounted in the statistics and extra specimens were tested to reach the sample size 30. The brittle RS failure was shown in Figure 4. Shear cracks were initiated in the cross layers with inclined angles about 30˚ ~ 60˚ with respect to the beam span direction. In some specimens, cracks further propagated to the glue lines between the layers. Because the laminations have various sawing patterns, shear cracks could propagate along the annual growth rings or cross the annual growth rings. A small number of specimens also experienced secondary tensile failures at the bottom edges at the ultimate loading stage.

As shown in Figure 5, the planar shear specimens had very similar RS failure modes to the bending specimens. One or multiple shear cracks with inclined angles with respect to the loading direction developed in the cross layers and propagated to the glue lines, which also caused a very brittle failure mode.

Calculation of RS strength

A number of composite beam theories can be used to derive the RS strength properties from the short-span bending test results. In ASTM D2718 standard, the classic beam theory with the assumption of parabolic shear stress distribution along beam depth is used. This assumption is however not suitable for CLT because cross layers of CLT have much lower MOE and shear modulus (G) values than longitudinal layers. Therefore, in this study, the RS strength calculation of the bending specimens followed the shear analogy method (Kreuzinger, 1999) which considers the influence of low RS modulus of the cross layers. Table 3 lists the input lamination stiffness properties for the shear analogy method. Based on the characteristic MOE of SG8 and SG6 timbers (NZS3603, 1993), the stiffness relationships $E_{\perp} \approx E_{\parallel}/30$, $G \approx E_{\parallel}/15$, and $G_{RS} \approx G/10$ were assumed according to the CLT Handbook (2011), where $E_{\parallel}$ is MOE parallel to grain, $E_{\perp}$ is MOE perpendicular to grain and G_{RS} is rolling shear modulus. The material was assumed to be transverse isotropic with the same properties along the radial and tangential directions.

Table 3 Input stiffness properties of laminations for shear analogy calculation

Lamination grade	$E_{\parallel}$(MPa)	$E_{\perp}$(MPa)	G_0(MPa)	G_{RS}(MPa)
SG8	8000	267	533	53
SG6	6000	200	400	40

In the modified planar shear test method, the rolling shear strength was simply calculated by

$$\tau_{rs} = \frac{F_{max} \cdot \cos\theta}{w_l \cdot d_l} \quad \text{Eq. (1)}$$

where F_{max} is the peak load corresponding to the RS failure, θ is the angle between the loading direction and the orientation of the planar shear specimen, as shown in Figure 2b. θ of each group of specimens was calculated based on its length and thickness of layers. For RP20-S, RP35-S, RP45-S, DF20-S, DF35-S and DF45-S, θ was 4˚, 7˚, 9˚ , 4˚, 8˚ and 14˚, respectively. w_l and d_l are width and depth of the specimen, respectively. In this study, w_l was equal to the lamination width, and d_l was equal to 50 mm.

Figure 6 shows the cumulative distributions of the RS strengths of six CLT configurations evaluated with two test methods. Table 4 summarises the statistics of the RS strengths of different test groups. The average RS strength value $\tau_{rs,m}$, coefficient of variation (COV) and characteristic RS strength value $\tau_{rs,k}$ are listed. $\tau_{rs,k}$ was derived following Method 3 (non-parametric) in NZS 4063.2 (2010), as shown in Eq. (2).

$$\tau_{rs,k} = \left(1 - \frac{1.8 \times COV}{\sqrt{n}}\right) \times \tau_{0.05} \quad \text{Eq. (2)}$$

where COV = coefficient of variation; n = sample size; and $\tau_{0.05}$ is the non-parametric 5[th] percentile value from the cumulative distribution curve.

Table 4 Statistics of experimental results of different test groups

Specimen Type	No. of Specimens	Aspect ratio γ	$\tau_{rs,m}$ (MPa)	COV	$\tau_{rs,k}$ (MPa)
DF20-B	30	7.0	2.51	11%	1.92
DF35-B	30	5.6	1.60	16%	1.12
DF45-B	30	4.3	1.35	17%	0.94
DF20-S	30	7.0	2.45 (2%)	26%	1.46 (24%)
DF35-S	30	5.6	1.69 (6%)	21%	1.08 (4%)
DF45-S	30	4.3	1.43 (6%)	22%	0.95 (1%)
RP20-B	30	9.8	2.45	14%	1.77
RP35-B	30	4.7	1.97	13%	1.45
RP45-B	30	4.1	1.67	15%	1.06
RP20-S	30	9.8	2.33 (5%)	13%	1.84 (4%)
RP35-S	30	4.7	1.99 (1%)	12%	1.49 (3%)
RP45-S	30	4.1	1.65 (1%)	13%	1.20 (13%)

Note: numbers in parentheses represent the difference of RS strengths evaluated by the modified planar shear tests relative to the strengths evaluated by the short-span bending tests

Douglas-fir vs. Radiata pine

Figure 7 shows the cumulative distributions of all DF and all RP specimens regardless of the test methods and the CLT layup. Table 5 presents a summary of mean and characteristic RS strengths of all the DF-B, DF-S, RP-B, RP-S specimens as well as all the DF and RP specimens. As shown in Table 5, combining the results from both test methods, the average RS strength of all DF specimens was 1.83 MPa, 9% lower than that of all RP specimens although the average density of the DF specimens was 8% higher than that of the RP specimens. Because of relatively higher variability among the DF specimens, the characteristic RS strength of all the DF specimens was 1.02 MPa, 24% lower than that of the RP specimens. In NZS3603 (1993), regardless of timber grade, the specified characteristic longitudinal shear (LS) strength for DF timber is 3.0 MPa, 21% lower than that of RP timber (3.8 MPa). The difference of RS strength between the DF specimens and the RP specimens were consistent with the LS strength difference in NZS3603.

Table 5 Statistics of experimental results of all DF specimens and all RP specimens

Specimen Type	No. of Specimens	$\tau_{rs,m}$ (MPa)	COV	$\tau_{rs,k}$ (MPa)
All DF-B	90	1.82	31%	1.03
All DF-S	90	1.86 (2%)	32%	0.99 (4%)
All RP-B	90	2.03	21%	1.42
All RP-S	90	1.99 (2%)	19%	1.39 (2%)
ALL DF	180	1.83	31%	1.02
ALL RP	180	2.01	20%	1.35

Note: numbers in parentheses represent the difference of RS strengths evaluated by modified planar shear tests relative to the strengths evaluated by the short-span bending tests

It is well recognized that the shear strength of wood is sensitive to defects such as splits and cracks that may be caused by growth stresses or moisture change. When drying from green to moisture content of 12%, DF has shrinkage rates of 4.9% and 2.8% along the tangential and radial directions, respectively; and for RP, they are 3.9% and 2.1%, respectively (Buchanan, 2007). The differences of the shrinkage rates indicate that more drying checks are likely to be formed in DF and these drying cracks can reduce shear strength. Another factor that may affect the RS strength is the density difference between earlywood and latewood in timber. According to New Zealand Pine User Guide (WMPA, 1996), the average densities of earlywood and latewood in RP are 350 kg/m^3 and 550 kg/m^3, while those of DF are 300 kg/m^3 and 690 kg/m^3, respectively. Despite the higher overall density, the lower density earlywood and higher inhomogeneity between the earlywood and latewood in DF may explain the lower shear strength of the DF specimens compared with the RP specimens.

Influence of lamination aspect ratio γ

For CLT manufactured with Norway spruce, Ehrhart (2014) proposed Eq. (3) to establish a linear relationship between the γ ratio and characteristic RS strength $\tau_{rs,k}$. But it also sets the strength limit of 1.4 MPa for $\gamma \geq 4$. Thus, the equation does not acknowledge the benefit of using timber laminations with high aspect ratios.

$$\tau_{rs,k} = \min\begin{cases} 0.2 + 0.3\gamma \\ 1.4 \end{cases} \qquad \text{Eq. (3)}$$

As shown in Figure 8, $\tau_{rs,k}$ of the DF and RP specimens evaluated by both test methods, however, showed a significant impact of the γ factor on the RS strength when γ exceeded 4 within in a range of 4.1-9.8. Laminations with large γ ratios led to higher RS strength. Based on the two lower bound characteristic strength values, linear equations Eq. (4) and Eq. (5) can be conservatively established for the RP specimens and the DF specimens, respectively, as plotted in Figure 8 as well. However, Eq.(4) and Eq.(5) are based on short-term experimental tests. For long-term RS strength, long-term factor should be used to reduce the strength due to the crack's development and moisture change. Further research is needed for the suitable value of long-term factor.

$$\tau_{rs,k,RP} = 0.6 + 0.12\gamma \text{ (MPa)} \quad \text{for } 4 \leq \gamma \leq 10 \qquad \text{Eq. (4)}$$

$$\tau_{rs,k,DF} = 0.3 + 0.15\gamma \text{ (MPa)} \quad \text{for } 4 \leq \gamma \leq 10 \qquad \text{Eq. (5)}$$

Short-span bending test vs. modified planar shear test

As shown in Table 4, the difference of $\tau_{rs,m}$ evaluated by two methods ranged between 1% and 6% . The two-sample t-test was used to check the results between two test methods. The null hypothesis H_0 was that no difference between the mean values of two test methods and the alternative hypothesis H_1 was that there was difference between the mean value of two test methods. The significant level α was set as 0.05. The p values for DF20, DF35 and DF45 were 0.62, 0.51 and 0.46, respectively. Because all p values were higher than 0.05, H_0 was accepted, which means that two different test methods yielded comparable mean RS strengths in this study. The difference of characteristic RS strength $\tau_{rs,k}$ ranged between 1% and 24%. The high difference of $\tau_{rs,k}$ for the DF20 specimens was mainly caused by high variability among the group of DF20-S specimens (COV=0.26) although the average strength $\tau_{rs,m}$ of the DF20-S specimens was only 2% lower than that of the DF20-B specimens.

Finite element models

To further investigate the influence of different test configurations and boundary conditions, linear elastic finite element (FE) models were developed using a commercial software package ABAQUS 6.14 (2014). Six DF specimens DF20-B, DF20-S, DF35-B, DF35-S, DF45-B, and DF45-S were selected and modelled following the specimen geometries listed in Table 1. Solid 3-D elements (C3D8R) were used for the specimens. The meshing size was 5 mm for DF35-B and DF45-B specimens and 4 mm for the rest of specimens. Due to the mixed sawing patterns in the laminations, transverse isotropic material properties were assumed, and the average properties between the tangential and radial directions of the DF timber were used. Rigid bonding between CLT layers was also assumed by defining face layers and cross layers' connections as tie constraints. Gaps between the laminations in the cross layers were considered as no contacts in models.

Average peak loads of each test group were applied to the models. For the bending specimens, the load was applied at the mid-span with a loading area of 30×50 mm for the DF20-B model and 60×50 mm for the DF35-B and DF45-B models to consider different loading head sizes used in the testing. To simulate the loading mechanism of the steel blocks in the modified planar shear test setup, the compressive load and restraints were applied on the upper end and the lower end of the face layers, respectively. Table 6 lists the input properties of the DF laminations with SG8 grade according to NZS3603 (1993) and Wood Handbook (2010).

Table 6 Input elastic properties of DF laminations

DF grade		Modulus (MPa)					Poisson's ratios		
	E_L	E_T	E_R	G_{LR}	G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}
SG8	8000	267	267	533	533	53	0.29	0.29	0.39

Figure 9 through Figure 11 show the results of non-uniform distributions of RS stresses (S23) and normal stresses perpendicular to grain (S33) in the cross layers of the DF20-B, DF35-B, and DF45-B specimens subjected to the average peak loads obtained from the tests. It should be noted that S33 stress distributions are illustrated by the middle layer of elements (4~5 mm thick) in the cross layers. The RS stresses in the vicinity of the gaps were very small due to the shear stress release around the free edges. Also, the RS stress level under the central loading point was low compared with the other parts of the cross layers. Such stress distribution agreed well with the test observation that the RS failures typically occurred at a certain distance from the gaps and away from the central loading point, as has been shown in Figure 4. The vast majority of the cross layers was also loaded in compression perpendicular to grain, and compressive stresses had a range of 1.2 ~ 2.5 MPa, mainly near the central point loading area. In NZS3603, regardless of timber grade, the characteristic perpendicular-to-grain compressive strength of DF and RP timber is 8.9 MPa. Therefore, such a low compressive stress level will unlikely cause any damage. Although tensile stress perpendicular to grain up to 1.1 MPa was observed in the cross layers, this stress level was well below the average strength of 2.3 MPa for DF according to Wood Handbook (2010). Also, the tensile stresses might also be caused by the sharp change of the lamination geometry due to the gaps in the FE models in term of that no tensile damage perpendicular to grain was observed around these gaps during tests.

Figure 12 shows the distributions of RS stresses (S23) and normal stresses perpendicular to grain (S33) in the cross layers of the DF20-S, DF35-S and DF45-S models, respectively. Similarly, S33 stress distributions are illustrated by the middle layer of elements (4~5 mm thick) in the cross layers. The vast majority of the cross layers experienced high RS stresses except for the free edges where the shear stress release occurred. The maximum compressive stresses perpendicular to grain were observed in a range of 1.5~3.3 MPa, and the maximum tensile stress perpendicular to grain was about 0.3 MPa. These stress levels were well below the characteristic strengths of DF timber. The RS stress distributions agreed well with the test observation that the inclined shear cracks were initialized with a certain distance from the free edges, as shown in Figure 5.

Table 7 provides a comparison of average RS strength of the DF specimens evaluated by the FE models and the calculation methods. Since the FE models were able to capture the non-uniform RS stress distributions caused by the stress release around the gaps / free edges while the calculation methods had the assumption of homogeneous material properties and uniform stress distributions, the FE results were found to be 3~17% higher than the calculation results with an average of 8%. The overall normal stresses perpendicular to the grain were found to be at a very low level in both test methods although there were local stress concentrations near free edge/gaps in both test configurations. However, in term of that no significant failure was initiated at those locations during tests, the high normal stresses were mainly from the limitation of the FE models such as sharp change of the lamination geometry and hard contact interface. Therefore, it was believed that the normal stresses perpendicular to grain in the cross layers have a negligible impact on the RS evaluations by these two test methods. The comparable RS strength results were observed in this study.

Table 7 Comparison of average RS strengths evaluated by calculation methods and FE modelling

CLT type	$\tau_{RS,m}$ (MPa) calculation method	$\tau_{RS,m}$ (MPa) ABAQUS	Difference
DF20-B	2.51	2.59	3%
DF35-B	1.60	1.71	7%
DF45-B	1.35	1.44	7%
DF20-S	2.45	2.87	17%
DF35-S	1.69	1.82	8%
DF45-S	1.43	1.57	9%

4. Conclusions

In this study, RS strength properties of Douglas-fir and Radiata pine CLT specimens were evaluated by short-span bending tests and modified planar shear tests. Numerical models were also developed to study the influence of the two different test methods on RS strength evaluations. The main findings are listed as follows:

- The RP specimens had higher rolling shear strength than the DF specimens although their average density was lower than that of the DF specimens. It may be attributed to the higher inhomogeneity between earlywood and latewood in DF, and the presence of drying cracks in the DF specimens.
- Both test methods showed a positive relationship between the lamination aspect ratio γ and the RS strength when γ exceeded 4. Based on the lower bound strengths, two linear equations were established to approximately correlate the lamination aspect ratio and the characteristic RS strength for the DF specimens and the RP specimens, respectively. Based on this, higher RS strength for CLT manufactured with lamination aspect ratios exceeding 4 can be specified.
- Short-span bending tests and modified planar shear tests generally yielded comparable RS strength properties although these two test methods have different test configurations and boundary conditions. The FE modelling results of the DF specimens indicated both test methods were able to introduce high RS stresses in the specimens and the influence of normal stresses perpendicular to grain in the cross layers was not significant. Therefore, both methods are suitable for evaluating RS strength of CLT.

5. Acknowledgement

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Table 1 Test matrix and lamination properties

CLT config.	Test method	No. of specimens	Specimen dimensions	Lamination		
				cross section (mm × mm)	Aspect ratio γ	Timber grade
DF20	Bending	30	420×50×60	140×20	7.0	SG8/SG8/SG8
	Shear	30	140×50×60			
DF35	Bending	30	735×50×105	195×35	5.6	
	Shear	30	195×50×105			
DF45	Bending	30	945×50×135	195×45	4.3	
	Shear	30	195×50×135			
RP20	Bending	30	420×50×60	195×20	9.8	SG8/SG6/SG8
	Shear	30	195×50×60			
RP35	Bending	30	735×50×105	165×35	4.7	
	Shear	30	165×50×105			
RP45	Bending	30	945×50×135	185×45	4.1	
	Shear	30	185×50×135			

Table 2 Summary of density and moisture content

Measurement		DF specimens (n=180)	RP specimens (n=180)
Density (kg/m^3)	mean	489	453
	COV	6.3%	6.7%
Moisture content	mean	9.4%	10.4%
	COV	13%	11%

Table 3 Input stiffness properties of laminations for shear analogy calculation

Lamination grade	$E_{\parallel}$(MPa)	$E_{\perp}$(MPa)	G_0(MPa)	G_{RS}(MPa)
SG8	8000	267	533	53
SG6	6000	200	400	40

Table 4 Statistics of experimental results of different test groups

Specimen Type	No. of Specimens	Aspect ratio γ	$\tau_{rs,m}$ (MPa)	COV	$\tau_{rs,k}$ (MPa)
DF20-B	30	7.0	2.51	11%	1.92
DF35-B	30	5.6	1.60	16%	1.12
DF45-B	30	4.3	1.35	17%	0.94
DF20-S	30	7.0	2.45 (2%)	26%	1.46 (24%)
DF35-S	30	5.6	1.69 (6%)	21%	1.08 (4%)
DF45-S	30	4.3	1.43 (6%)	22%	0.95 (1%)
RP20-B	30	9.8	2.45	14%	1.77
RP35-B	30	4.7	1.97	13%	1.45
RP45-B	30	4.1	1.67	15%	1.06
RP20-S	30	9.8	2.33 (5%)	13%	1.84 (4%)

RP35-S	30	4.7	1.99 (1%)	12%	1.49 (3%)
RP45-S	30	4.1	1.65 (1%)	13%	1.20 (13%)

Note: numbers in parentheses represent the difference of RS strengths evaluated by the modified planar shear tests relative to the strengths evaluated by the short-span bending tests

Table 5 Statistics of experimental results of all DF specimens and all RP specimens

Specimen Type	No. of Specimens	$\tau_{rs,m}$ (MPa)	COV	$\tau_{rs,k}$ (MPa)
All DF-B	90	1.82	31%	1.03
All DF-S	90	1.86 (2%)	32%	0.99 (4%)
All RP-B	90	2.03	21%	1.42
All RP-S	90	1.99 (2%)	19%	1.39 (2%)
ALL DF	180	1.83	31%	1.02
ALL RP	180	2.01	20%	1.35

Note: numbers in parentheses represent the difference of RS strengths evaluated by modified planar shear tests relative to the strengths evaluated by the short-span bending tests

Table 6 Input elastic properties of DF laminations

DF grade		Modulus (MPa)					Poisson's ratios		
	E_L	E_T	E_R	G_{LR}	G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}
SG8	8000	267	267	533	533	53	0.29	0.29	0.39

Table 7 Comparison of average RS strengths evaluated by calculation methods and FE modelling

CLT type	$\tau_{RS,m}$ (MPa) calculation method	$\tau_{RS,m}$ (MPa) ABAQUS	Difference
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DF20-S	2.45	2.87	17%
DF35-S	1.69	1.82	8%
DF45-S	1.43	1.57	9%

Figure 1

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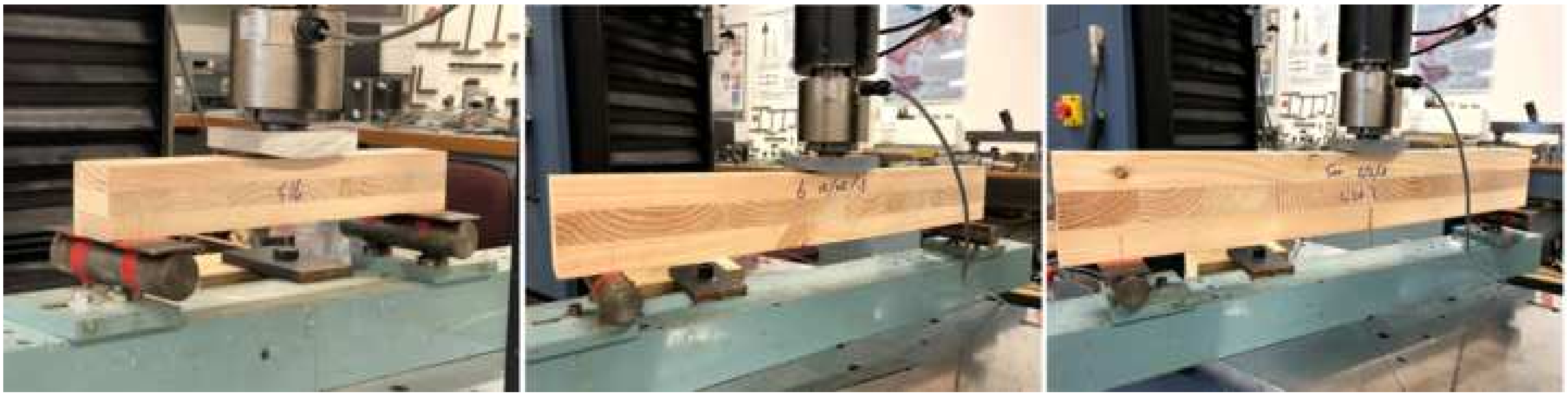

Figure 2

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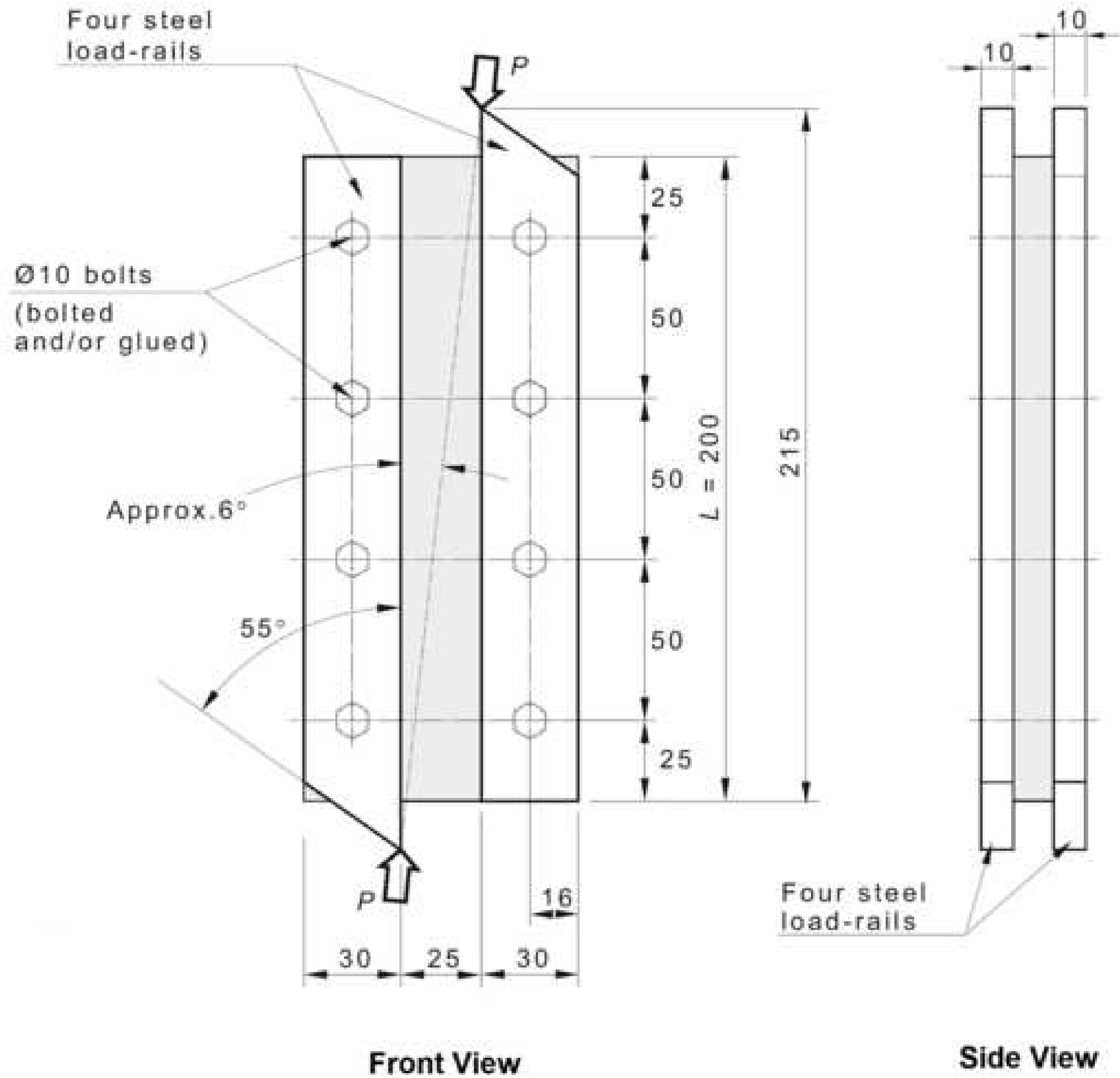

Figure 2b

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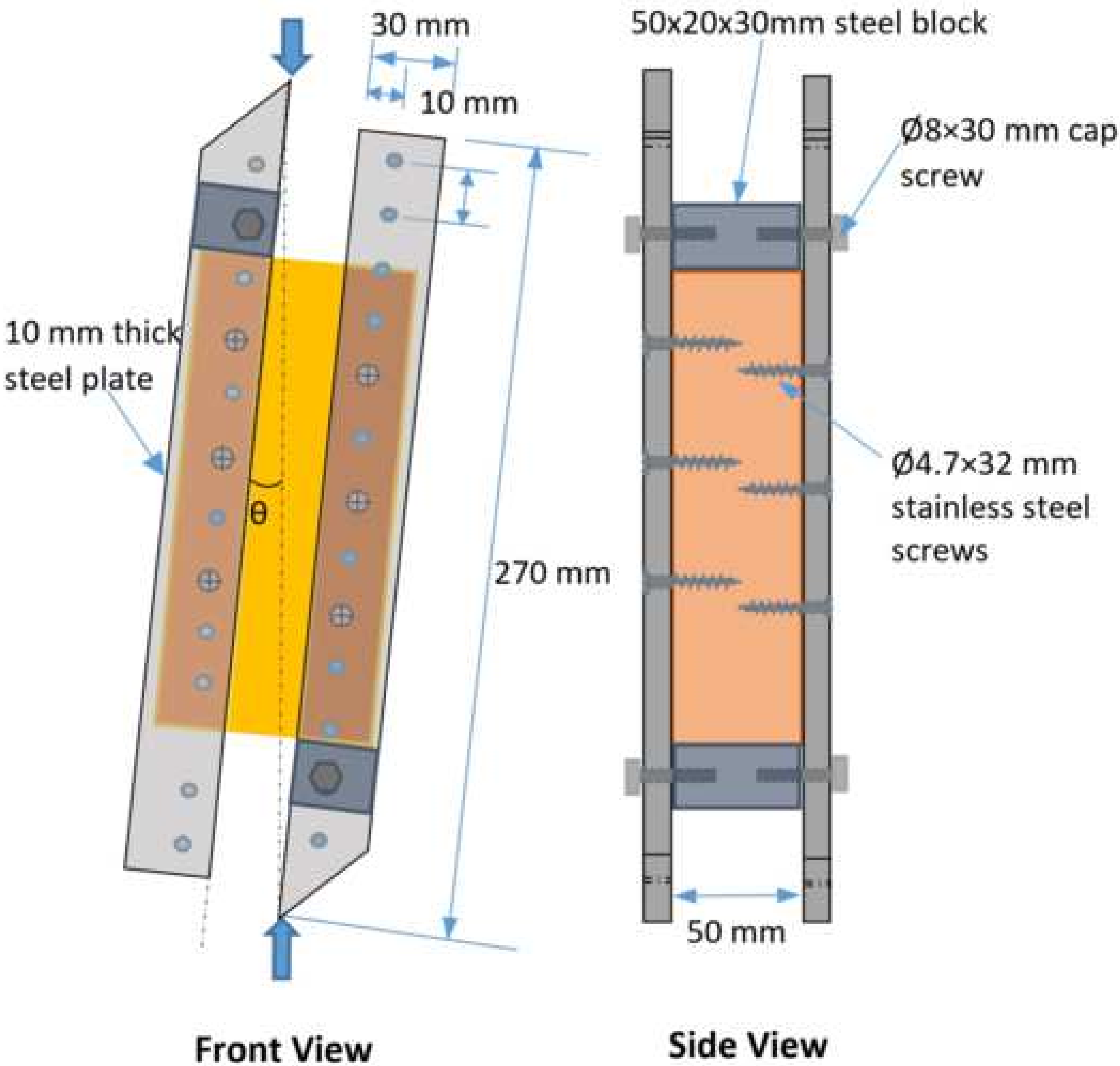

Figure 3 Click here to access/download;Figure;Fig 3 Modified planar shear tests.tif

Figure 4

Click here to access/download;Figure;Fig 4 Typical RS failure modes in shear test specimens.tif

Figure 5

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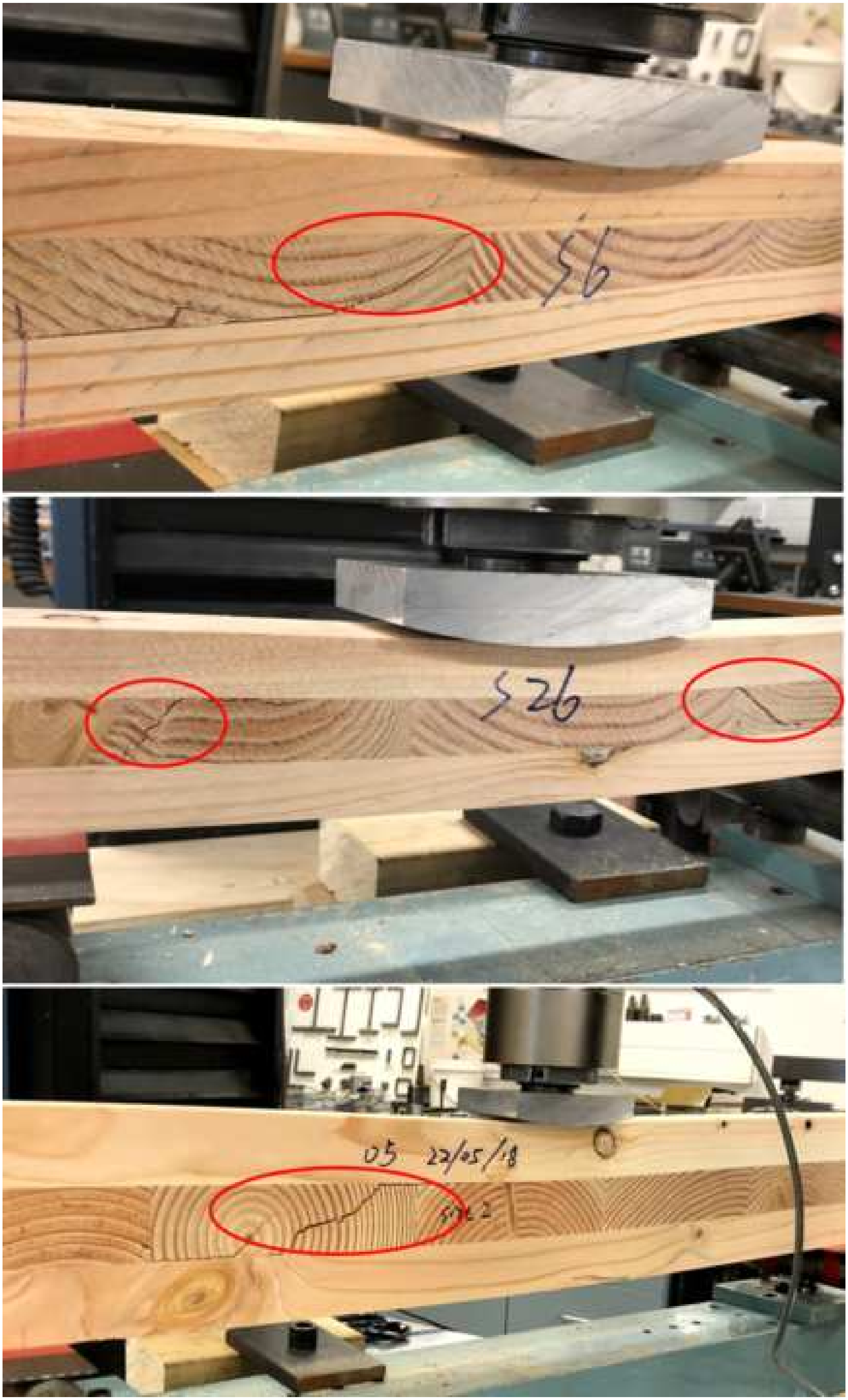

Figure 6

Click here to access/download;Figure;Fig 6 Distributions of RS in various test groups.tif

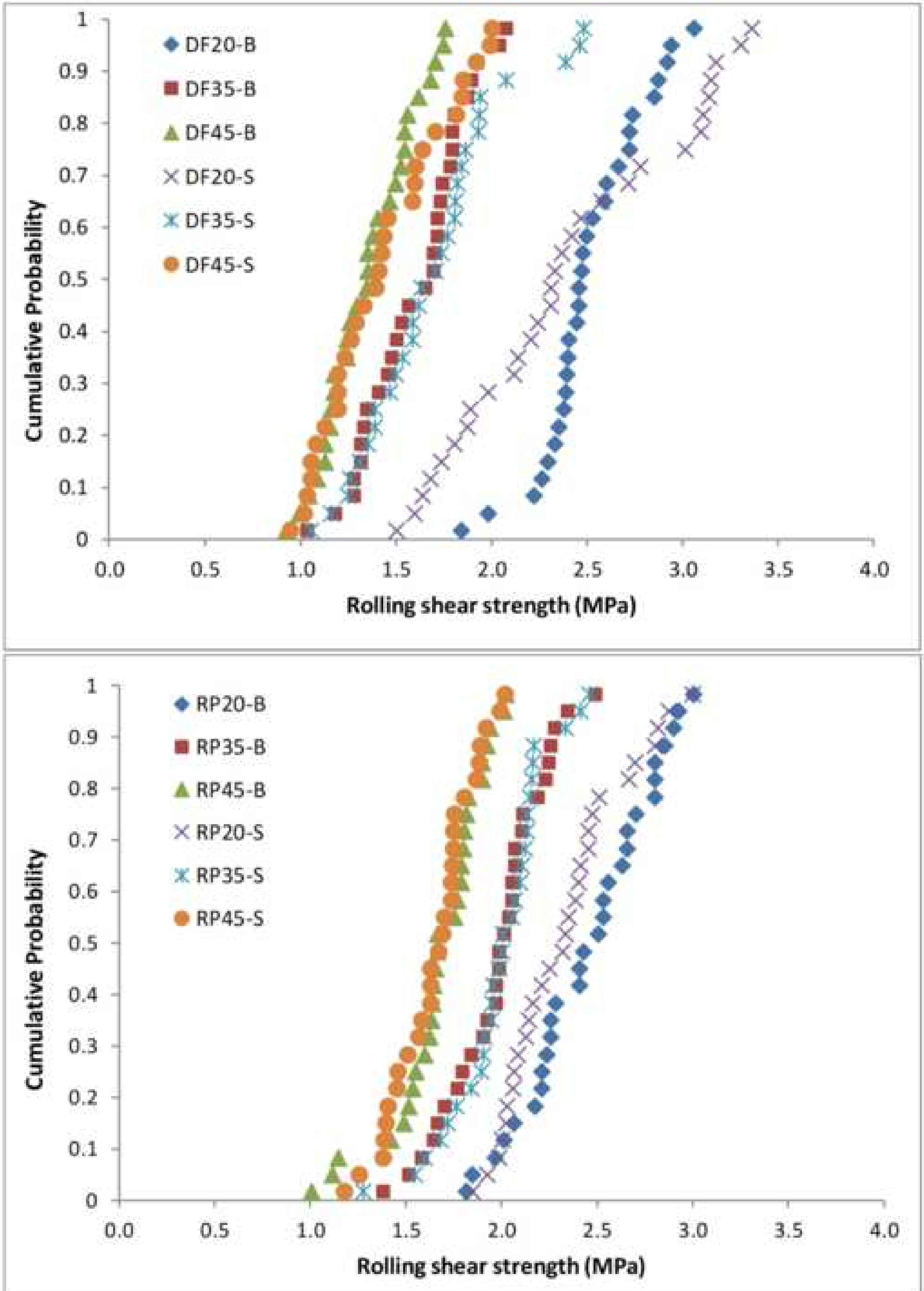

Figure 7

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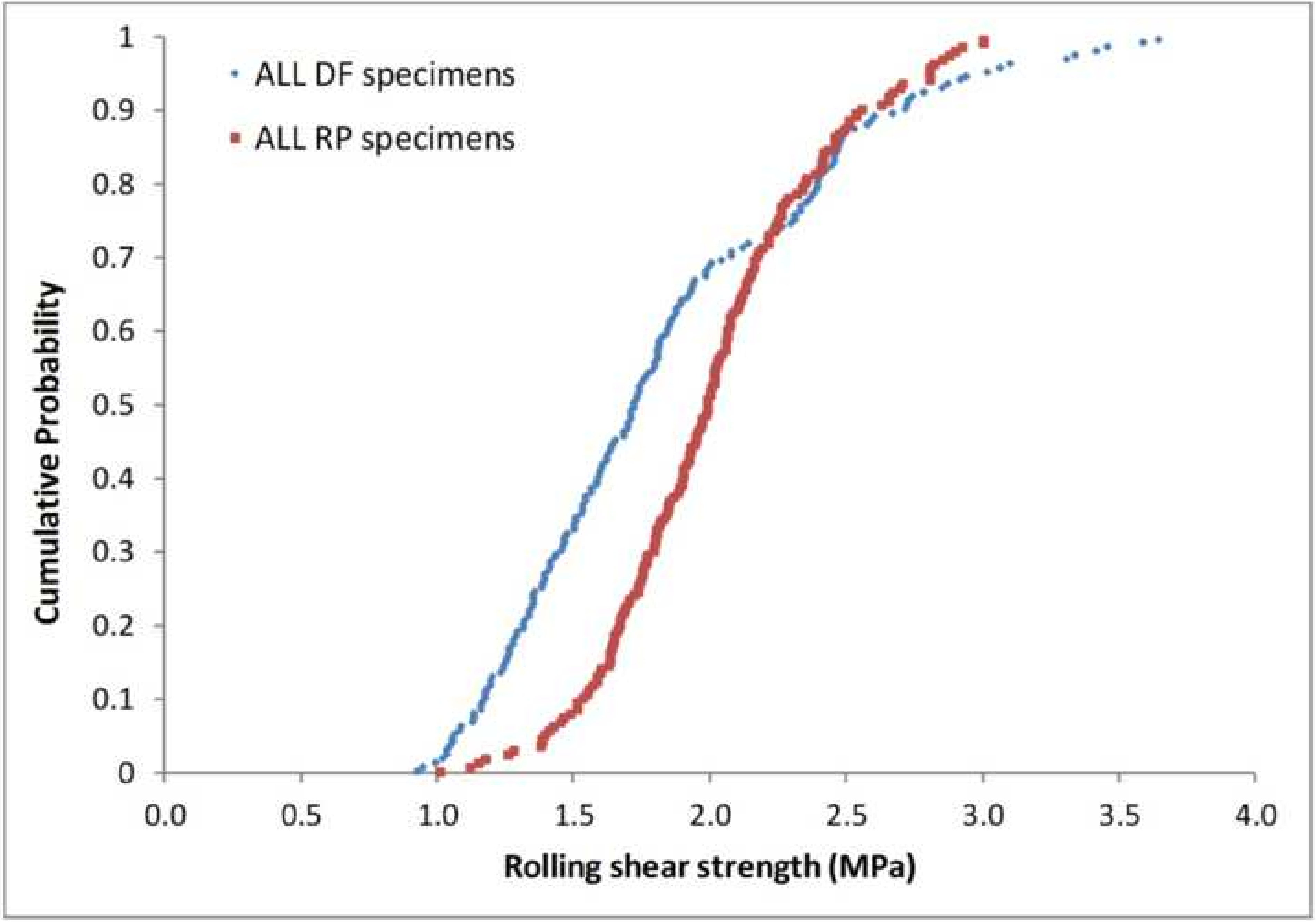


Figure 8

Click here to access/download;Figure;Fig 8 Characteristic RS strength vs lamination aspect ratio.tif

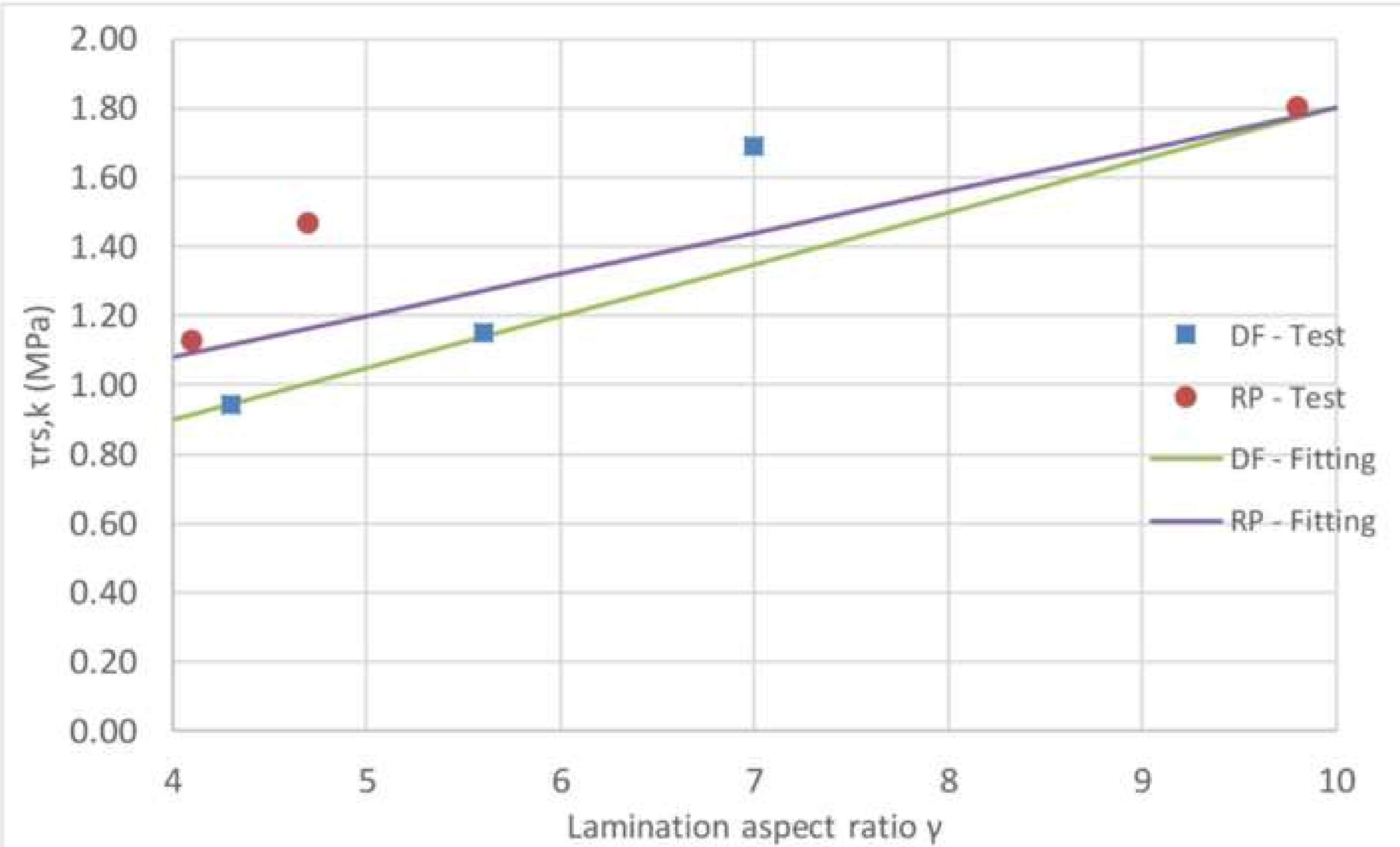
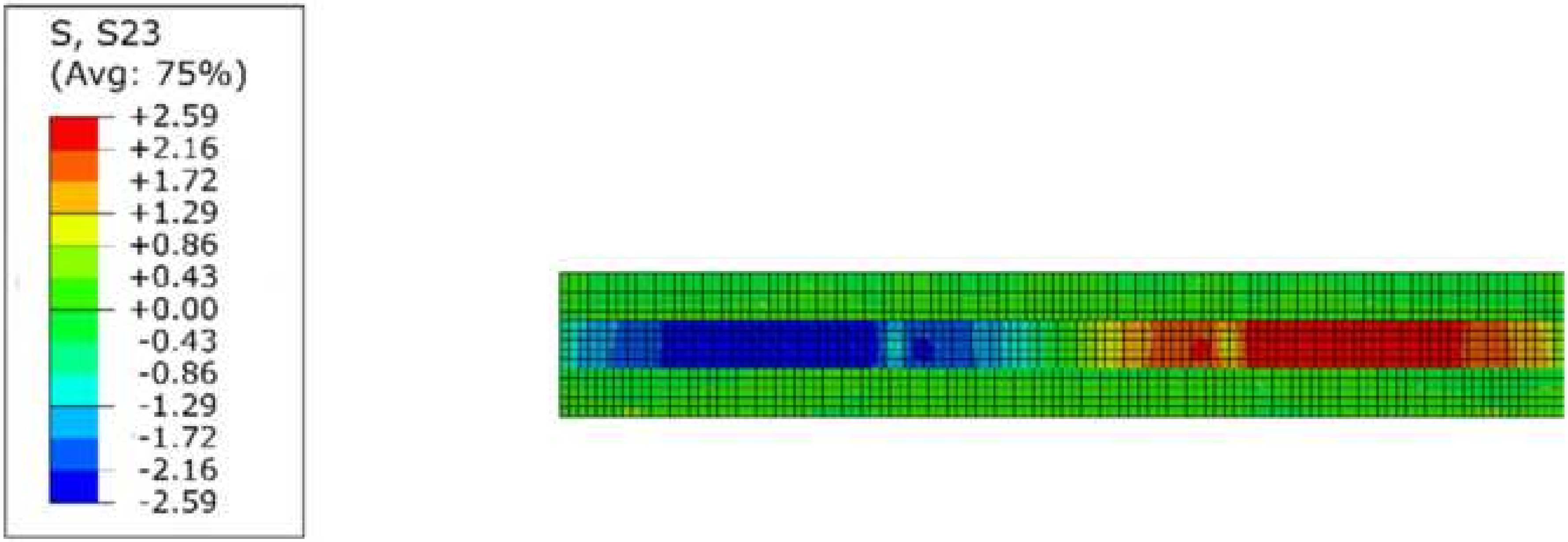


Figure 9

Click here to access/download;Figure;Fig 9 Distribution of RS & perp-to-grain stresses DF20-B.tif



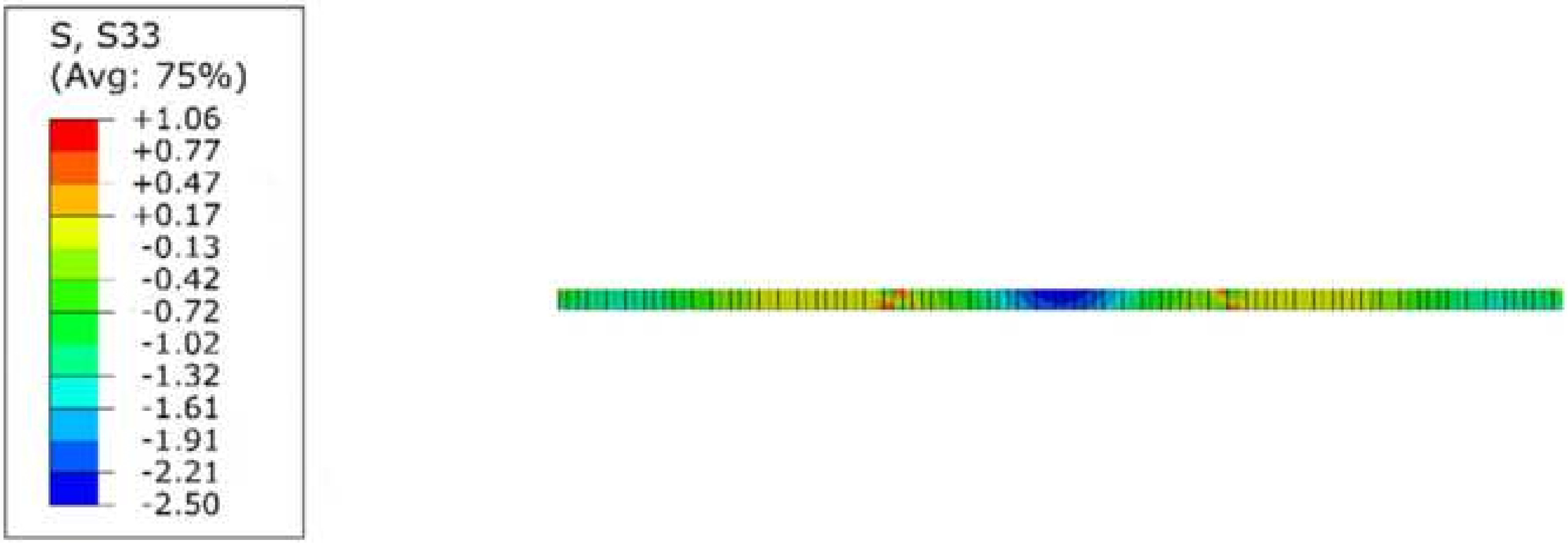


Figure 10

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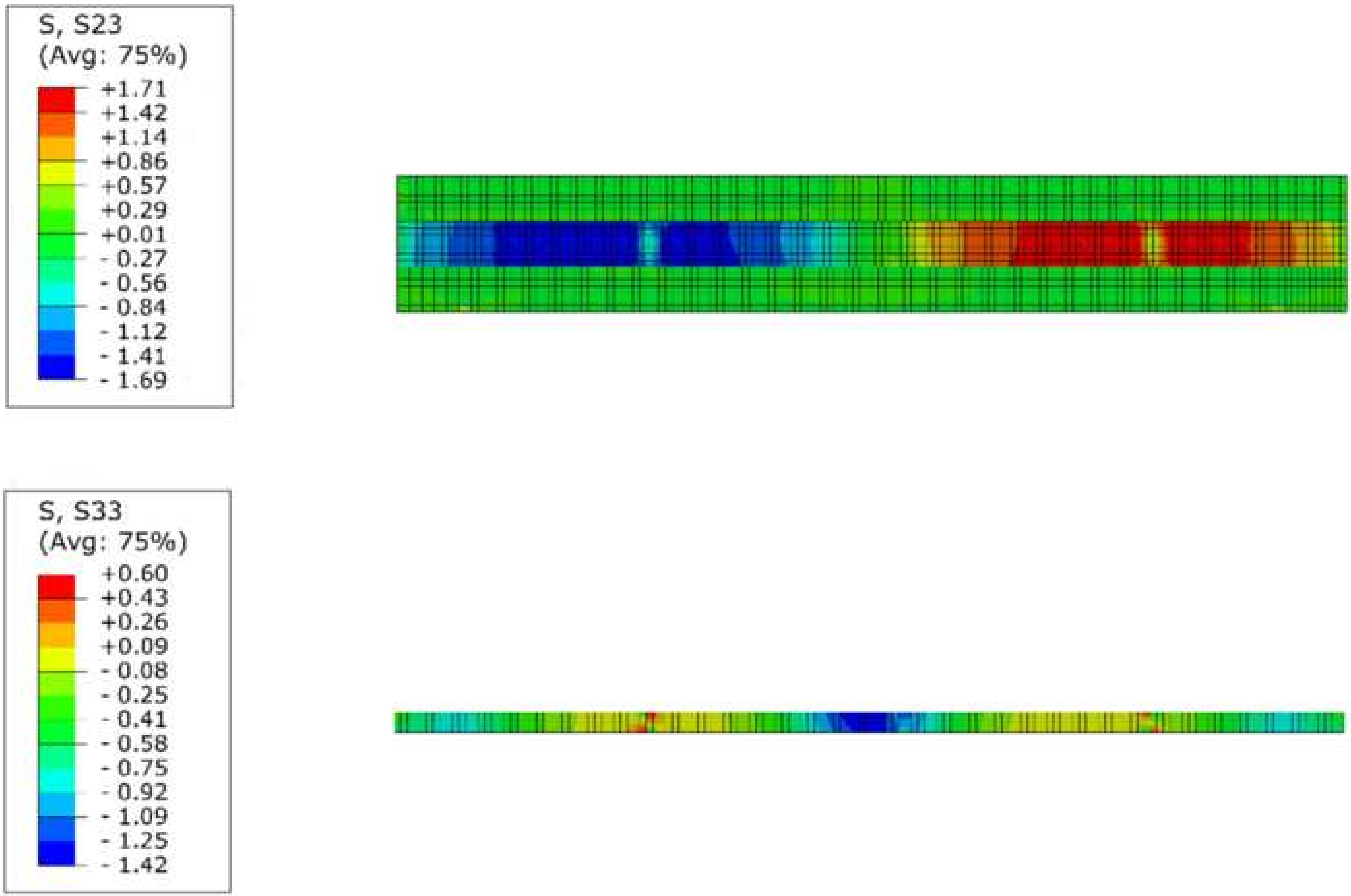

Figure 11

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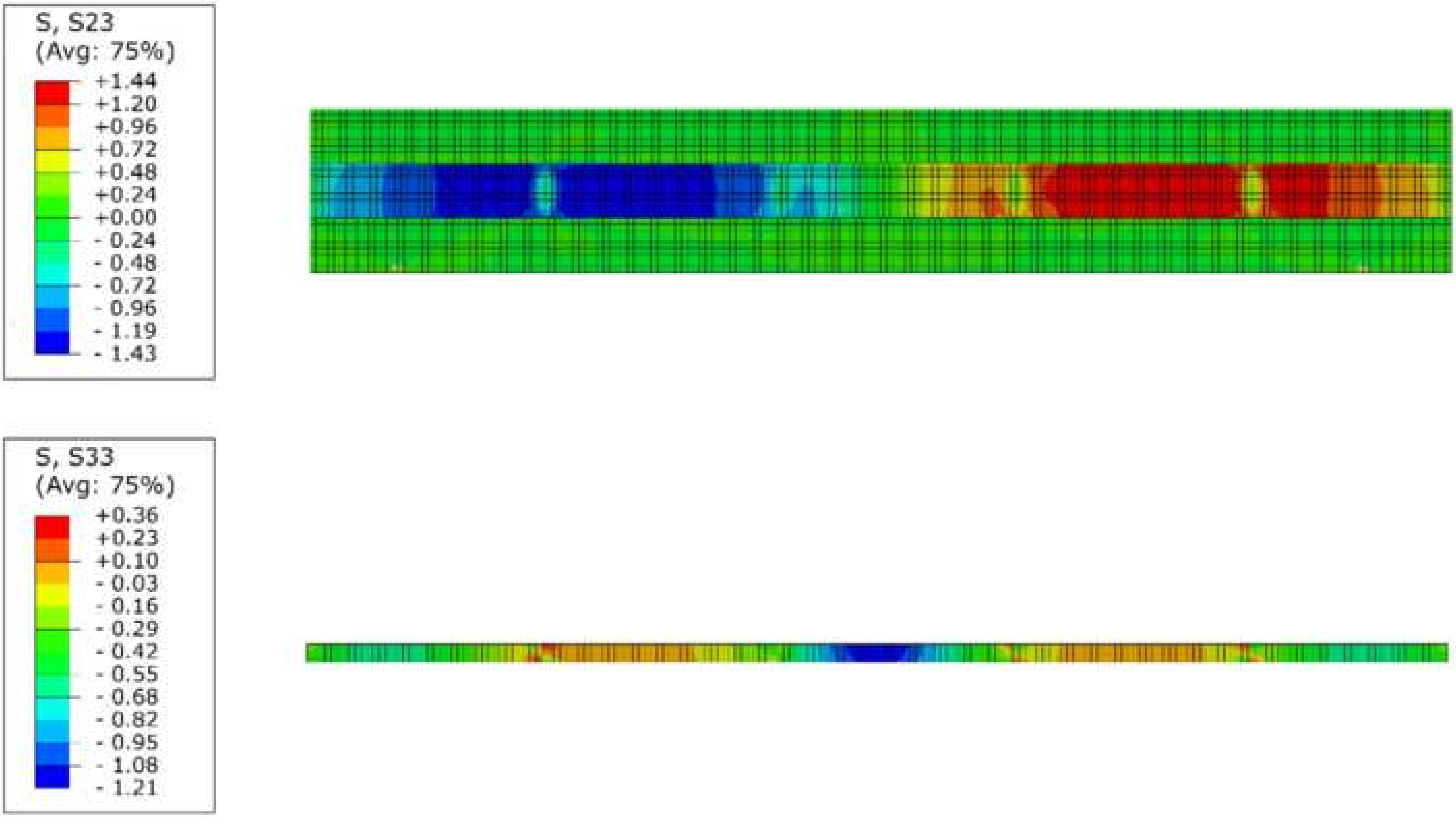
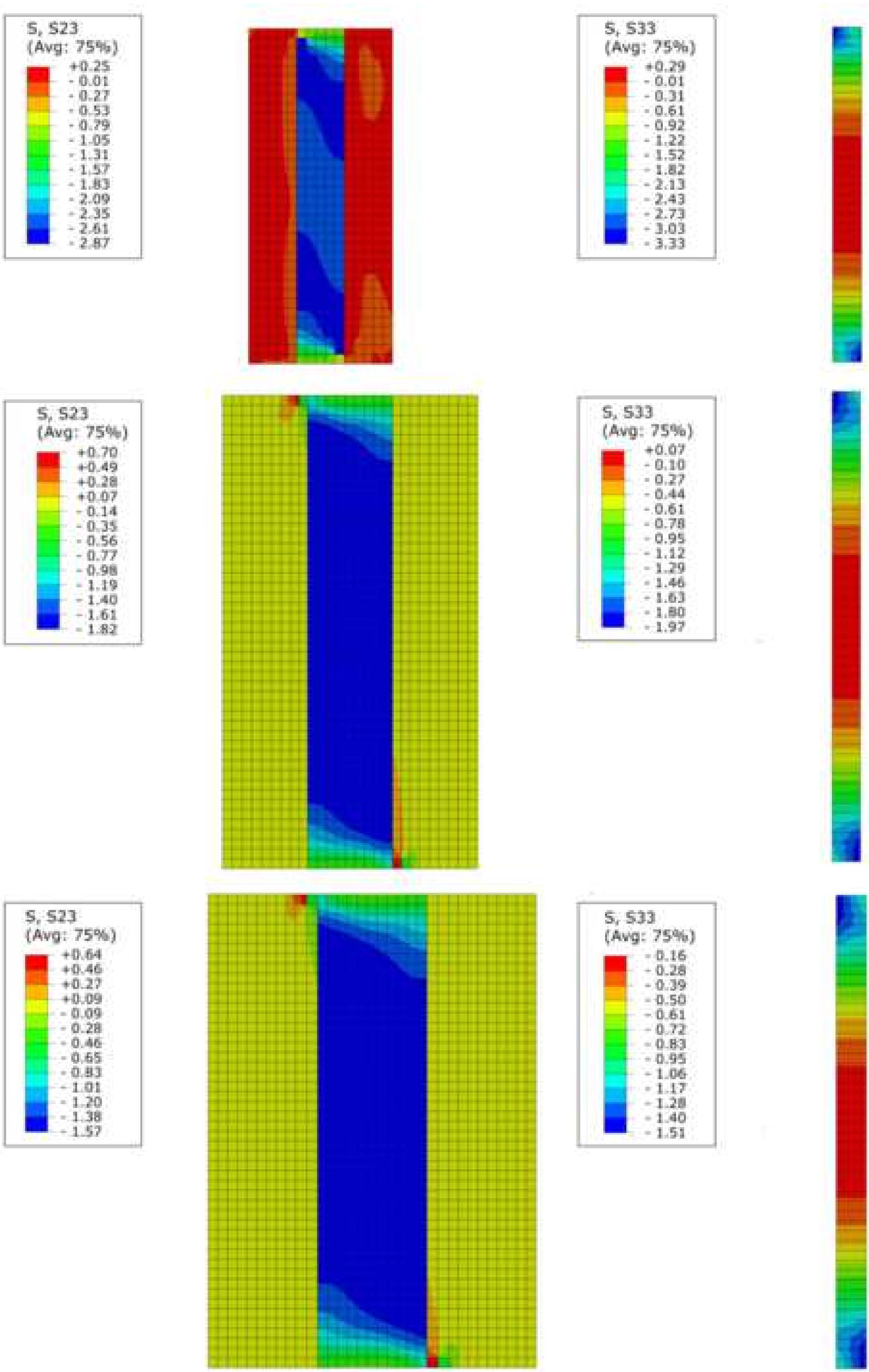


Figure 12

Click here to access/download;Figure;Fig 12 RS & perp-to-grain stresses in planar shear models.tif



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Response to reviewers' criticisms

Paper title: Influence of lamination aspect ratios and test methods on rolling shear strength evaluation of cross laminated timber

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Response for reviewer #1

1) **Comment 1.1:** [Line 51-52] "The influence. . . " who is this sentence attributed to?
Reply 1.1: Addressed.

2) **Comment 1.2:** [Line 65] Please update D 2718 reference. Standard was revised in 2018.
Reply 1.2: Addressed.

3) **Comment 1.3:** [Line 70] 'both test methods' Suggest you restate what the test methods are.
Reply 1.3: Addressed.

4) **Comment 1.4:** [Line 111] - Please explain numbering system fully with an example (all three classifications)
Reply 1.4: An explanation has been added.

5) **Comment 1.5:** Table 4 - What are % values in parentheses?
Reply 1.5: A note has been added under the table.

6) **Comment 1.6:** [Line 205-209] These are really good conclusions and I don't think anyone else has made these comments about drying and EW/LW layers. Can you expand on this?
Reply 1.6: We observed more checks in DF CLT specimens compared to RP CLT and also contacted timber processors for inquiry. They confirmed with our observations and mentioned the drying issues in DF timbers when DF and RP timbers follow the similar manufacturing processes. More detailed research is needed in future to understand how drying cracks and the difference of EW/LW affects the RS strength in CLT.

7) **Comment 1.7:** [Line 228-234] This paragraph would benefit from a t-test to illustrate statistical value of difference
Reply 1.7: The t-test content has been added to confirm the conclusion.

8) **Comment 1.8:** [Line 235] Suggest you make this a new section head here for the modelling part. I would like to see the modelling fleshed out - add a description of element types, sensitivity study, etc.
Reply 1.8: Addressed and more information about our model has been added.

9) **Comment 1.9:** Discussion of Figures 9-11 and 12 should be expanded.
Reply 1.9:. The main purpose of having FE modelling in this study was to investigate the influence of the test configuration/methods on the RS evaluations of the specimens. In order to model the rolling shear stress distribution considering more influencing factors, a more comprehensive and rigorous modelling process is needed for future. This is out of scope of this study.

Response for reviewer #2

1) **Comment 2.1:** I recommend introducing all symbols and parameters the first time you use it. For example, E and G [line 157] are not introduced.
Reply 2.1: Addressed.

2) **Comment 2.2:** I recommend being consistent with the wording. For example, you use both "cross-laminated timber vs. cross laminated timber", "non-edge-glued vs. non-edge glued", "three-ply vs. three-layer", "20mm vs. 20 mm", "modelling vs modeling" etc.
   Reply 2.2: Addressed.

3) **Comment 2.3:** You only mention in [line 117] that plywood is used between steel and the DF or RP board / specimen. Neither Figure 2 nor Figure 3 nor Figure 5 clearly show that the steel set is screwed to the plywood, but the specimen itself is loaded by gluing it to the plywood. The impression may arise that the screws are put directly into the end grain of the specimen, which could have a major influence on the strength determined. I recommend to clearly name the plywood and the RP or DF boards in figure 2 and to make them visible e.g. by different colors.
   Reply 2.3: we added a traditional planar shear test picture from NZS 2269.1(2012) to Figure 2 as Figure 2a and some extra sentences to explain it better.

4) **Comment 2.4:** In [line 117] you call the fastener "bolt", in figure 2 you call it "screws". Is there a reason for this? If not, I recommend to used consistent terms.
   Reply 2.4: Addressed with Comment 2.3 together.

5) **Comment 2.5:** Figure 2: can you describe why you have chosen this configuration / have changed the "original" one we have experience with? Pros and possible cons / disadvantages? If I understand correct, you did a 2d FE analysis. However, the specimen is loaded via the screws "linearly" and not over the whole surface. Do you think, the outer areas of the specimen close to the steel plates are loaded more than the inner area, similar to a shear lag effect?
   Reply 2.5: We made three modifications compared to traditional planar shear test for plywood. 1) Increase the length of steel plates 2) Replace the small bolts with screws 3) Add steel blocks at the edge of specimens.
   The reasons and pros are 1) The CLT specimens are wider than traditional plywood specimen and the longer steel plates can reduce the inclined angle 2) CLT specimens are thicker than plywood specimens. Small bolts are not long enough to go through the whole thickness and clamp two steel plates together. The screws can be installed from both sides to hold the steel plates in positions. 3) The screws wouldn't transfer the load to CLT specimen evenly as the reviewer mentioned (similar to a shear lag). Besides that, with the increase of specimen thickness and length, higher load was required to break the specimen, which meant more screws were needed. However, too many screws can reduce the net cross sections and cause some splitting perpendicular to the grain. In order to avoid that, steel blocks were added to the end of the face layers in the opposite direction. In this way, most of load were transferred by steel block's bearing more evenly. The screws were mainly used to hold the steel plates and carried some loads perpendicular to the grain.
   By using the steel block, the load could be transferred mainly from the end of face layers, which was quite similar with the 2D FE model's loading condition so we don't need to consider the "shear lag effect".

6) **Comment 2.6:** In [line 136] you say that the bending specimens "mostly" failed in rolling shear. I recommend avoiding vague formulations like "mostly" or "very". Here, I would be interested in how many specimens actually failed in rolling shear and which other failures you experienced. Furthermore, if there is a failure mode different to rolling shear, I recommend to used censored data analysis to take account of it.
   Reply 2.6: The information about other failure modes has been added. We also mentioned how we processed them during our statistics.

7) **Comment 2.7:** In [line 139-140] you say that "shear cracks could propagate … or cross the annual growth rings". Did you check if these failures propagated along the wood rays as described in Wang et al. (Constr Build Mater 2017;151-172-7)?
Reply 2.7: We checked the test photos and the failed specimens in the lab again. For those specimens with shear cracks propagating across the annual growth rings, most of them didn't failure along the wood rays. Therefore, we think the shear cracks propagating cross the annual growth rings were mainly due to the principle tensile stress and some of them were due to initial defects such as existing cracks.

8) **Comment 2.8:** In [lines 146-149] you describe the failure modes of the planar shear tests. Did you observe cracks in the edges where you have tension stresses perpendicular to grain? Mestek (2011) and Ehrhart (2016) reported about such cracks. If you had any, please let us know. If not, you could say that your test configuration "works better" in this regard.
Reply 2.8: The steel blocks can reduce the chance of having wood splitting in the face layers of the specimen caused by the screwed connections under high shear loads. After we added the steel blocks, we didn't observe the cracks in the edges.

9) **Comment 2.9:** The "assumption" you mention in [line 155-156] is not questionable but wrong.
Reply 2.9: Addressed.

10) **Comment 2.10:** In [line 169] eq 1 you present the equation you have used to calculate the rolling shear strength. Do you give information about the actual angle omega anywhere in your paper? It also has an influence on the stresses perpendicular to grain and it would be interesting to know the angle for comparison to other studies.
Reply 2.10: We have added the angle in Figure 2b and the angle value in the paper.

11) **Comment 2.11**: In [line 214-218] you say that the eq 3 presented by Ehrhart (2014) "does not acknowledge the benefit of using laminations with high aspect ratios". Theoretically I agree with you that for the short-term strength of boards with e.g. gamma=10 can be higher compared to gamma=4. However, I think the main reason to limit this equation at a gamma of 4 with 1.4MPa was to consider long term effects, i.e. cracks within a board may have the same effects as gaps between boards. When you propose eq4 and eq5 and "conservatively" [line 222] characteristic rolling shear strengths of up to 1.8MPa, I think you should discuss that point or at least mention that this is only valid for crack-free cross layers (or argue against what I have just written).
Reply 2.11: Our test results were based on short-term loading. In NZ design standard NZS3603, we use a reduction factor of 0.6 to reduce the strength under the long-term effect. More research about long-term effect on RS strength reduction caused by crack development is needed.

12) **Comment 2.12:** In [line 223] I recommend to exchange DF and RP to have it in the correct sequence with regard to the equations.
Reply 2. 12: Addressed.

13) **Comment 2.13:** Figure 8: You present a linear curve to fit the experimental data. Don't you think that the effect of gamma may be stronger for lower w/t ratios (as also the RP data points suggest)?
Reply 2.13: We agree that the effect of γ could be stronger for lower γ. In this study, we only have three data points and a bi-linear model might not be accurate. In future research more configurations are needed to produce more data points and develop a more accurate equation.

14) **Comment 2.14:** Can you tell from the FE analysis if the proposed eq. 4 and 5 are "physically correct"?

Reply 2.14: The models we developed were linear elastic models with the main objective to investigate the influence of the test configuration/methods on RS evaluations and to get information about the stress distribution (shear stresses but also compression and tension stresses perpendicular to the grain) within the specimen when using certain test configurations and geometries. We extracted the ultimate forces from the experimental tests and then applied them on the elastic models to get the failure stresses. The models have limitations to predict failure loads of the CLT specimens with other configurations since we need to well understand the failure criteria of the wood we used and this needs more investigations.

15) **Comment 2.15:** [Line 235-242]: can you give more information about the element type, mesh size, and so on? Also, with regard to your statement in [line280] I think it is crucial to consider the element size when talking about local stresses like the "maximum tensile stress perp to grain" of 0.3MPa. Mestek (2011) and Ehrhart (2016) reported about cracks in this zone. In this respect, it would also be interesting to know which angle omega you have used.
Reply 1.15: Relative information has been added in the paper.

16) **Comment 2.16:** In [lines 275-283] you say that the S33 stresses are shown for a 4mm thick layer but you do not mention where this layer is (in the middle of the specimen or directly at the plywood)? Again, I wonder why you did not find any issues with tension perp to grain. (figures 9-12).
Reply 2.16: This has been clarified in the paper.

17) **Comment 2.17:** Figures 9-12: Is it possible to define the scale to get rid of the random decimal digits (e.g. 2.5 instead of 2.586)?
Reply 2.17: Addressed.

18) **Comment 2.18:** [Line 289] "listed" vs. "lists"
Reply 2.18: Addressed.

19) **Comment 2.19:** [Line 297-299] "Therefore, it was believed …" I recommend to rewrite this sentence to be more precise and clear.
Reply 2.19: Addressed.

20) **Comment 2.20:** In [lines 309-310] you say that you had "…more drying cracks…" Are these cracks not to be seen similar to gaps between boards when talking about the gamma value w/t? If you have cracks or expect them during the lifetime of a building, would you actually recommend to use very high (characteristic) rolling shear strengths (of up to 1.8) and take into account w/t ratios of more than e.g. 4 or 6?
Reply 2.20: We didn't consider the cracks as gaps in our calculations because these cracks were mostly surface cracks caused by drying and didn't penetrate through the whole section. We think treating them as gaps is not very appropriate. In NZ standard NZS3603, we use a long-term strength reduction factor of 0.6 to consider the long-term effect.

Response for reviewer #3

1) **Comment 3.1:** [Line-2] The reviewer suggested to modify "cross laminated" to cross-laminated in title and keywords for consistency.
Reply 3.1: Addressed.

2) **Comment 3.2:** [Line 27] "adhesive systems" to structural adhesive systems.
Reply 3.2: Addressed.

3) **Comment 3.3:** [Line 32] delete "serviceability limit state (stiffness) design and"

Reply 3.3: Addressed.

4) **Comment 3.4:** [Line 38] "$\tau_{rs,k}$" to "$\tau_{rs,k}$ value"
Reply 3.4: Addressed.

5) **Comment 3.5:** [Line 77] "This study is to" to "The objective of this study is to"
Reply 3.5: Addressed.

6) **Comment 3.6:** [Line 79] "It also examines" to "The study also examines"
Reply 3.6: Addressed.

7) **Comment 3.7:** [Line 92] "MOE" to "Modulus of Elasticity (MOE)"
Reply 3.7: Addressed.

8) **Comment 3.8:** [Line 95-101] How did you sample the test samples? Can you add more details?
Reply 3.8: We added the sample process in the paper.

9) **Comment 3.9:** [Line 104] The reviewer suggests to use % for COV.
Reply 3.9: Addressed.

10) **Comment 3.10:** [Line 157] "E" to "MOE" and "G" to "shear modulus (G)"
Reply 3.10: Addressed.

11) **Comment 3.11:** [Line 168] What angle was used? Was this variable or fixed for the various thicknesses? Please clarify!
Reply 3.11: Relative information has been added in the paper.

12) **Comment 3.12:** [Line 182-183] "Figure 6" to "Figure 6." and "Table 4" to "Table 4.". The reviewer also suggested to say that $\tau_{rs,m}$ was average and modified COV to %.
Reply 3.12: Addressed.

13) **Comment 3.13:** [Line 183] The reviewer mentioned that the difference of $\tau_{rs,k}$ from two different methods for DF20 was significant.
Reply 3.13: the characteristic value $\tau_{rs,k}$ can be calculated according to B2.4 in ASNZS 4063.2:2010. For DF20-B and DF20-S, the $\tau_{rs,m}$ was close but the COV and 5th percentile strength $\tau_{0.05}$ was quite different. Especially for DF20-S, $\tau_{0.05}$ was quite low, which caused a much lower $\tau_{rs,k}$ 1.46 Mpa. That's the reason that two test methods produced a 24% difference.

14) **Comment 3.14:** [Line 205-206] "The differences of the shrinkage rates indicate that more drying checks those can reduce shear strength are likely to be formed in DF" to "The differences of the shrinkage rates indicate that more drying checks are likely to be formed in DF which can reduce shear strength"
Reply 3.14: Addressed.

15) **Comment 3.15:** [Line 231-234] How could the DF-45-S group have a high variability in the COV (22%) but yet low variability in the $\tau_{rs,k}$ of 1% from Table 4?
Reply 3.15: The characteristic value $\tau_{rs,k}$ not only depends on COV but also 5th percentile strength $\tau_{0.05}$ and mean values $\tau_{rs,m}$. For DF45-B and DF45-S, three of them are similar, which produced very closed $\tau_{rs,k}$. Therefore, the difference of $\tau_{rs,k}$ between two test methods was only 1%.

16) **Comment 3.16:** [Line 275] “perp” to “perpendicular”
Reply 3.16: Addressed.

17) **Comment 3.17:** [Line 289] “listed the” to “provides a comparison”
Reply 3.17: Addressed.

18) **Comment 3.18:** [Line 300] “modelling” to “modeling”
Reply 3.18: Addressed.

19) **Comment 3.19:** [Line 309-310] “and more drying cracks existed in the DF specimens” to “and presence of drying cracks in the DF specimens”
Reply 3.19: Addressed.

20) **Comment 3.20:** [Line 314-315] “By doing so, it can specify higher RS strength for CLT manufactured with laminations with aspect ratios exceeding 4 ” to “Based on this, higher RS strength for CLT manufactured with laminations with aspect ratios exceeding 4 can be specified”
Reply 3.20: Addressed.

21) **Comment 3.21:** [Line 316] “Shear tests yielded comparable” to “Shear tests generally yielded comparable”
Reply 3.21: Addressed.