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THE USE OF TORSION TEST METHOD TO EVALUATE THE SHEAR PROPERTIES OF TIMBER JOISTS

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ABSTRACT: This paper presents details of the experimental method and test results from a series of torsion tests undertaken to evaluate the shear modulus and shear strength of solid timber joist. The variation of shear modulus within and between test samples, failure modes and the correlation of shear strength and shear modulus were studied. Test results obtained indicate that there was considerable (approximately 33%) variation in shear modulus between pieces of timber tested. It was also found that the shear strength of tested joists was higher than the published values in EN 338. The test joists fractured mostly at the middle with cracks propagated towards either supports or edges. A good correlation was found between shear strength and the shear modulus. The recent revision of the testing standard EN408 includes the torsion testing approach to obtain the shear modulus of timber. It is proposed that a torsion test also be adopted as a method for evaluating the shear strength of timber.

KEYWORDS: Torsion test, Shear strength, Shear modulus, Design values, Failure mechanism

1 INTRODUCTION

The shear modulus and shear strength are fundamental mechanical properties of wood that is used in general timber design. Compared with other engineering materials, timber has a relatively low shear stiffness and strength in comparison to its modulus of elasticity, and so shear deformation contributes a more significant portion of flexural deflection. In design, the shear properties are important factors for lateral-torsional stability of joists, particularly those with a long span and no lateral supports [e.g., 1]. The shear modulus is also needed when designing serviceability of wood-joist floors [e.g., 2], and is an input into analytical [e.g., 3] and finite element [e.g. 4] models to predict the vibrational serviceability.

The shear modulus and shear strength can be typically obtained from shear block [e.g., 5] or bending tests [e.g., 6, 7]. However, there are no known studies that have evaluated whether shear block and bending tests are suitable for determining shear properties in structural sized timber. Previous studies [e.g. 8, 9] have shown that the shear block test is inappropriate for estimating the actual shear strength of structural-sized timber because it includes stress concentrations and does not account for the influence of defects and orthotropy. Likewise, the combination of flexural and shear stresses encountered in a bending test leads to difficulties in obtaining the true value of shear strength [e,g 10, 11].

In contrast, testing a structural member in torsion creates a state of pure shear. Therefore, this approach could be better suited to obtaining the shear modulus and shear strength of wood. In this regard, Gupta et. al. [12, 13] used both experimental and finite element approaches to examine the torsion test method and concluded that it is a better approach to obtain the shear strength than other methods. Considering the limitations of shear block and bending tests for determining shear properties, it is not unreasonable to assume that they might not be appropriate for obtaining information on the shear modulus of structural timber. This was shown by Hindman et al. [14] who found that the torsional rigidity (GJ) of solid sawn timber and structural composite timber joists tested in torsion was 15 to 40% lower than values based on current methods [15]. Studies also show that torsional vibration provides a better measure of shear modulus than static bending [e.g. 16].

In this paper, an experimental study is described which was conducted to determine the shear modulus and shear strength of structural timber using torsion tests. The main objective was to investigate the variation of shear modulus within the length of the joists and to compare the shear strength test values with the published values from EN338 [17] and in the Wood Handbook [18]. The secondary objectives were to examine the failure mechanism of wood under torsion, the correlation of torsional shear strength with shear modulus.

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2 MATERIAL AND METHODS

Sitka spruce (*Picea sitchensis*) and Norway spruce (*Picea abies*) joists of nominal cross section of 45 × 100 mm were tested. Sitka spruce timber of C16 strength class was cut into four different lengths of 1.0 m, 2.0 m, 2.8 m and 3.6 m with 15, 10, 12 and 25 samples, respectively selected for each length (denoted here SP). Norway spruce (NS) wood of strength class C16 and C24 was cut into 2.4 m lengths with 14 and 12 specimens respectively. Before testing, all samples were conditioned in a controlled-environment room (21°C and 65% relative humidity) until they attained constant mass (approximately 12% moisture content).

A 1 kN-m torsion testing machine (Tinius Olsen, Pennsylvania USA) was used to test the timber joists under torsion. To measure the twisting displacement of the timber, inclinometers with a range of ± 30° were attached to the upper edge (45 mm dimension) of each sample. Multiple inclinometers were attached to each sample to allow the longitudinal variation in shear modulus to be investigated. The mounting positions for the inclinometers depended on the length of sample being tested, but in all cases inclinometers were mounted at least 200 mm from the clamps to avoid possible end effects. For 1.0 m long samples, two inclinometers, each located 200 mm from the end clamps allowed displacement to be measured on a 600 mm central segment. The 2.0 m and 2.8 m samples were partitioned into four segments of 400 mm and 600 mm, respectively (Figure 1), while the 3.6 m samples were divided into five segments of 600 mm with the end inclinometers mounted 300 mm from the clamps.

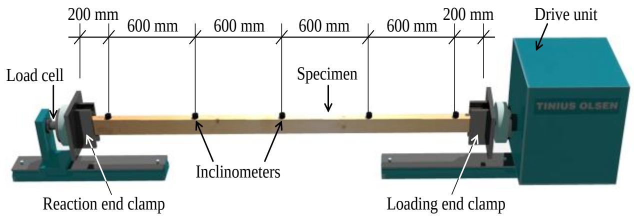

Figure 1: *Diagram for test setup of 2.8m specimen*

All test specimens were tested at 4°/min [6] until they fractured. The shear strength and shear modulus (*G)* of each test specimen was calculated on the basis of Saint-Venant torsion theory for rectangular sections as follows:

$$Shear\ Strength = \frac{Maximum\ Torque}{\left(d\ t^2\ k_2\right)} \qquad (1)$$

$$G = \frac{Stiffness}{\left(d\ t^3\ k_1\right)} \qquad (2)$$

In Equations (1) and (2), d is the depth (major cross-section dimension) and t is the thickness (minor cross-section dimension) of the test specimen and k_1 and k_2 are constants that depend on the depth thickness ratio (see *e.g.* [19]). Shear strengths were calculated on the basis of the maximum applied torque, as shown in Figure 2. The stiffness was obtained by conducting linear regression analysis of the applied torque and the relative twist per length within the elastic region as shown in Figure 2. For most of the tested specimens the elastic region was found between 3% and 30% of maximum applied torque, and therefore, linear regression analysis was conducted between 5% and 25% of the maximum applied torque to obtain the stiffness.

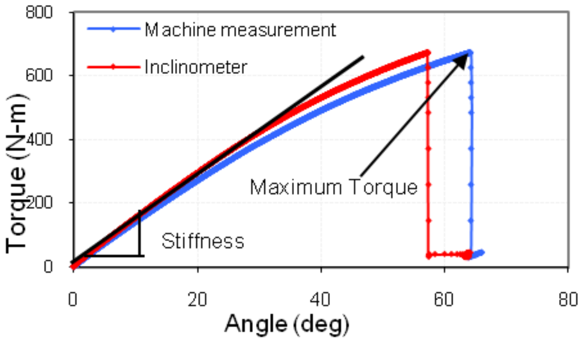

Figure 2: *A typical applied torque and relative twist of 2.8m test sample*

3 RESULTS AND DISCUSSIONS

3.1 VARIATION IN SHEAR MODULUS WITHIN AND BETWEEN SAMPLES

The variation of shear modulus was conducted for Sitka spurce joists. It was seen that shear modulus varied substantially for Sitka spruce (SP) joists. Across all the segments from each of the specimens tested, shear modulus ranged from 298 MPa to 762 MPa (Figure 3). From the relatively limited number of samples tested to date, G does not appear to be normally distributed, but is positively skewed (Shapiro-Wilk test p-value = 0.013). It should be noted that segments are not all independent of each other, with each test specimen containing between 1 and 5 segments.

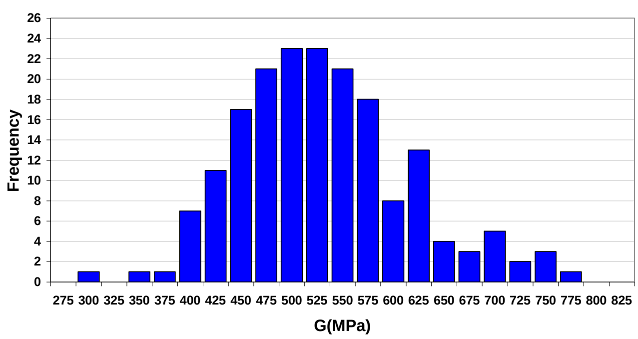

Figure 3: *Variation of shear modulus of the segments of tested samples*

The mean value of shear modulus for the different lengths tested varied between 470 to 540 MPa, being higher for the longer specimens (Table 1). A variance components analysis was undertaken in order to determine the relative magnitude of between-specimen and within-specimen variation. This analysis revealed that 66 percent of the variation in G was due to differences between specimens, while the remaining 33 percent was due to differences between the segments within a specimen. It is hypothesised that the source of the variation between segments of a specimen, and the apparent trend of increasing shear modulus with length, may be due presence of knots and other defects. Longer specimens have a greater probability of having large knots than shorter specimens but each large knot takes up a smaller proportion of the total length. The trend of increasing G with specimen length should be interpreted with some caution as different length samples were obtained from different sources and no attempt was made to randomly select material for the different lengths.

Table 1: *Comparison of shear modulus (G) between different sample lengths*

Group	Number of specimens	Number of segments	Mean G (MPa)	Max. G (MPa)	Min G (MPa)
SP 1.0m	15	15	465±94	715	298
SP 2.0m	10	40	497±58	604	339
SP 2.8m	12	48	513±79	695	375
SP 3.6m	16	80	542±91	762	382
Overall	53	183	565±87	775	421

3.2 DESIGN STANDARDS AND TORSIONAL SHEAR STRENGTH VALUES

Table 2 provides the mean shear strength values of both Sitka Spruce and Norway spruce beams. For C16 Sitka spruce, the mean shear strength of 7.2 MPa was attained and that was about 15% lower than Norway spruce of the same grade, and 22% less than the C24 Norway Spruce. C24 class timber has the highest shear strength (9.3 MPa), which agreed with expectations that the higher strength class would have higher shear strength values. For the C16 of Norway spruce the shear strength was about 9% lower than C24 of the same species. It was found that different species has different shear strength values. This is perhaps because the different species have different ratios of shear and bending properties.

In the current EN338 [20], the characteristic shear strength values for C16 and C24 are 1.8 MPa and 2.5 MPa respectively. These values are calculated on the basis of bending strength of full size structural timber beams tested under four point bending test in accordance with EN408 [21]. Much higher characteristic shear strength values of 4.8 MPa (166% higher) of C16 (combined SP and NS) and 7.5 MPa (200% higher) of C24 were achieved when joists were tested under torque. The revision of EN338 [20] has raised values of characteristic shear strength for these grades (3.2 MPa and 4.0 MPa) but these are still substantially less than those observed experimentally in this study.

Table 2: *The mean shear strength values of tested joists*

Group	Strength Grade	Length (m)	Number of specimen	Max. Applied Torque (N-m)	Mean Shear Strength (MPa)
SP	C16	1.0	15	485	7.8
	C16	2.0	10	460	6.7
	C16	2.8	12	550	7.7
	C16	3.6	25	475	6.7
	C16	Overall		490	7.2
NS	C16	2.4	14	390	8.5
	C24	2.4	12	410	9.3

Based on shear block tests of clear samples, the Wood Handbook [18] provides the mean shear strength values for Sitka spruce and Norway spruce of 6.7 MPa and 7.4 MPa respectively. From this research, mean shear strength of SP was 7.2 MPa (8% higher) and for NS was 8.5 MPa (13% higher), even though the material tested was of structural size and not clear wood. Similarly, Riyanto and Gupta [11] have shown that in comparison to the shear block tests, the torsional shear strength values of Douglas-fir were about 18% higher than the shear strength values of tested shear blocks and about 20% higher than the published values in the Wood Handbook [18].

This comparison shows that relatively higher shear strength values were achieved when the torsion test approach was used, even in comparison to tests on clear timber. Although it should be noted that only two species were tested in this research, a marked difference in shear strength was found compared with values given in EN338 [20].

This suggests that the assignment of shear strength values according to the results of bending tests may be over-conservative, at least for lower grades where knots affect bending strength, but not so much the shear strength (which may even be improved by knots). It may be appropriate that the torsion test procedure be adopted as a standard method to obtain the shear strength values, especially in light of its inclusion as a method to obtain shear modulus.

3.3 MECHANISM UNDER TORSIONAL LOADING

All test specimens were fractured when tested under torsion. Samples of shorter length (1 to 2.4 m) fractured within the range of 30° per meter twist, while longer samples (2.8 m and 3.6 m) fractured within the range of 20 to 30° per meter. This amounts to a high value of total twist for long specimens. Throughout the tests, small cracking noises were heard and it was noticed that small horizontal hair-type cracks appeared in the test samples while torque was still applied on specimens. During tests, most of the joists fractured with large bang sound and a puff of wood dust in air around the location of failure was seen. It was found that failure cracks, in many cases, were initiated within the clear wood even though a number of large knots were present in test joists.

Four different types of failure modes (*viz* crushing (40% of tested specimens), shear (25%), combined tension shear failure (12%) and horizontal shear failure (23%)) were observed as described below.

3.3.1 Crushing Failure

The crushing failure is defined here as a failure that occurs at the supports triggered mainly by clamps crushing the wood material. It was noticed that 40% of SP and NS specimens were fractured either at loading or reaction clamps with crushing failure mode. The main reason behind crushing of wood was because, in addition of shear stresses, the test clamps induced compressive stresses on the cross sectional area and the combined shear and compressive stresses caused small cracks in growth rings which, in turn, caused crushing failure. The cracks began in the earlywood zone in radial tangential (RT) plane and and propagated along longitudinal radial (LR) plane (Figure 4).

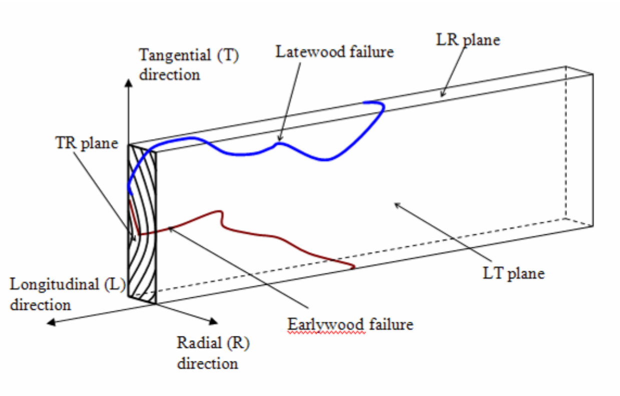

Figure 4: *Schematic diagram of timber joists showing grain direction*

3.3.2 Combined Shear Tension Failure

Another type of failure mode observed was the combined shear-tension failure and this occurred mostly in Sitka spruce joists. Nine out of 46 SP joists fractured with combined shear tension failure mode. The applied torque produces shear stresses and these stresses were dominant in causing this type of fracture. In the case of clear wood, the shear crack initiated from the middle of the LT plane and due to tension propagated towards, and was ended, in the LR plane. This may be because the grain angle might not be parallel to the longitudinal axis and, therefore, grains were fractured locally in tension and the failure travelled diagonally along the grain direction. It was also observed that when a crack approaches a knot it travelled around the knot rather than pass through it. Thus, this indicates that knots may provide some resistance to the shear failure. Figure 5 shows a combined shear tension failure

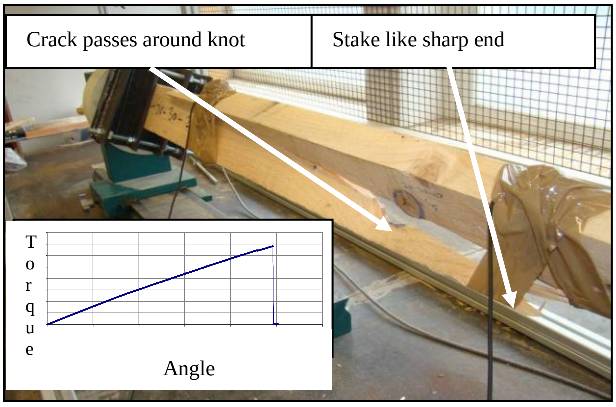

Figure 5: *A combined shear tension failure occurred in 2.8m joist and crack passed through knot and ends up with a sharp end*

3.3.3 Shear Failure

Another type of failure that occurred was the shear failure, which was also mainly seen in the Sitka spruce joists. About 18 out 46 SP joists fractured with shear failure mode. It was observed that shear stresses were the main cause of initiating the cracks for this failure mode, and that these cracks were usually started at either the top or bottom side, due to a knot, and then propagated as a diagonal crack along the long side to rupture the specimen in shear due to the knot at the other edge. This failure takes place because edge knots are usually surrounded by cross grain and this cross grain breaks locally in shear to initiate the failure (Figure 6).

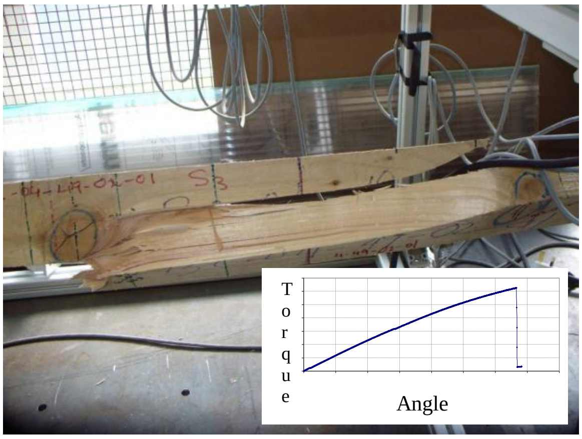

Figure 6: *A typical shear failure occurred in 2.8m specimen due to top and bottom edge knots*

3.3.4 Horizontal Shear Failure

This type of failure was only observed in Norway spruce specimens. In this type of failure, the shear cracks were usually initiated from clear wood within the LR plane and travelled parallel to the longitudinal direction towards end supports, as shown in Figure 10. 16 out of 26 Norway spruce battens fractured with horizontal shear failure mode. The term horizontal shear failure is given here because the shear cracks ran horizontally along the length of the joists.

3.4 RELATIONSHIP BETWEEN SHEAR STRENGTH AND SHEAR MODULUS

3.4.1 Shear Strength and Shear Modulus Correlation

A linear correlation between the shear strength and *G* of Sitka spruce and Norway spruce joists was developed, as shown in Figure 7. The R-squared values were calculated without including the outlying higher shear strength values of the Norway spruce test specimens. This is because only two higher shear strength values were obtained and this their inclusion would unduly bias the correlation of shear strength and *G*. It is thought that the slightly higher correlation for Norway spruce was obtained because most of these specimens were free of wood defects and joists failed within clear wood. The Sitka spruce specimens, on the other hand, contained more knots resulting in some specimens failing prematurely in a brittle manner. However, it was also noted in this study that knots have very little influence on *G* and on shear strength overall. Rather, in some Sitka spruce specimens it was found that knots initiated the failure and caused a low shear strength values but had no major affect on *G*, which may weaken the correlation.

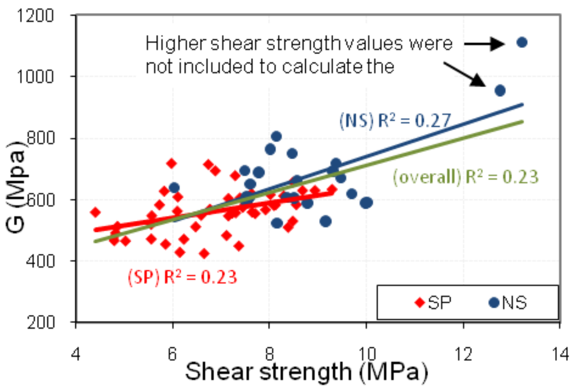

Figure 7: *Linear relationship between G and the shear strength of SP and NS joists*

4 CONCLUSION

This paper has presented the outline results of a series of torsion tests to determine the shear modulus and shear strength of Sitka spruce and Norway spruce joists. Results have been presented of an investigation into the variation of shear modulus in Sitka spruce timber. Torsion testing has been found to be a repeatable method of obtaining values of G at joist scale that also permits measurement of variation of G within a single joist. Approximately 33 percent of the variation in G was found to be attributed to differences between segments within a sample.

The torsion test procedure has been seen to produce higher strengths than values published based on bending and shear block tests.

In the test method, it was found that samples fractured within the long side where shear stresses are presumed to be maximum under applied torque (except in the cases where fracture was initiated by crushing at the support).

It was noticed that the cracks were commonly initiated within clear wood and caused shear failure, but that, in some specimens, cracks started due to shear and then propagated as a tensile failure. Support conditions were found to be important. It was noticed that testing clamps induced additional compressive stresses which lead to crushing of the wood at the supports and premature failure for some specimens. Therefore, this is important to design such testing clamps so that they minimise localised compressive stresses.

The recent draft revision of the testing standard EN408 [21] includes the torsion testing approach to obtain the shear modulus of timber. In this study it was found that both shear strength and shear modulus can be obtained from torsion tests and it is proposed that EN408 allow the torsion test to be used to determine shear strength as well. However it is also noted that the torsion testing approach requires careful application to avoid premature failure due to crushing at the specimen grips.

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