Determining the Shear Modulus of Sitka Spruce from Torsion Tests

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Summary

This paper presents details of the experimental method, and preliminary results from, a series of torsion tests undertaken to evaluate the shear modulus of Sitka spruce (*Picea sitchensis*) timber. Direct torsion tests were used to determine the variation of shear modulus within and between pieces of timber with rectangular cross-sections and with lengths ranging from 1 m up to 3.6 m. Preliminary results obtained indicate that there was considerable variation in shear modulus between pieces of timber tested, but that there was no relationship with the modulus of elasticity in bending, or knot area. Approximately 33 percent of the variation in shear modulus was due to variation along the length of a piece of timber sample. More detailed investigation of the shear transfer mechanism within a timber beam is required, particularly to identify those physical and anatomical characteristics which influence the shear properties.

1. Introduction

The shear modulus (G) is a fundamental mechanical property of wood that is used in general timber design. Compared with other engineering materials, timber has a relatively low shear stiffness in comparison to its modulus of elasticity, and so shear deformation contributes a more significant portion of flexural deflection. In design, G is an important factor for lateral-torsional stability of joists, particularly those with a long span and no lateral supports [e.g., 1]. G 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. Information on the shear modulus is 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 G 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 strength, 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 G than static bending [e.g. 16].

When measured values of shear modulus are not available, G is often assumed to be in proportion to the modulus of elasticity in bending. On face value this seems to be a reasonable supposition as both properties depend, primarily, upon wood microstructure, i.e., density, the angle of cellulose microfibrils within the cell walls, and lignin content [17]. In structural timber, slope of grain and defects such as knots and checks may also have a substantial influence on G. Any influence of knots in particular is likely to be a function of their size, location and frequency within a piece of timber. The associated grain deviation around a knot could result in variation of shear flow which in turn may affect the shear rigidity. Therefore, the presence of knots may lead to a variation in shear modulus along the length of a piece of sawn timber.

In this paper, an experimental study is described which was conducted to determine the shear modulus of Sitka spruce (*Picea sitchensis*) structural timber using torsion tests. The main objective was to investigate the variation of G within the length of the batten in relation to the knots along it. Because design usually involves values of G inferred from information about modulus of elasticity (E), a secondary objective was to assess the relationship between these two properties.

2. Methods and Materials

Tests were undertaken on Sitka spruce timber with nominal cross sectional dimensions of 100×47 mm. The timber had been kiln dried and graded to the C16 strength class. Timber was cut into four different lengths (1.0 m, 2.0 m, 2.8 m and 3.6 m) with 15, 10, 12 and 16 samples, respectively selected for each length. Prior to 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). The modulus of elasticity in bending of each 1.0 and 2.0 m sample was obtained from four point bending tests [7] undertaken before the timber was cut to length. For the 2.8 m and 3.6 m samples, the dynamic modulus of elasticity was obtained from measurements of longitudinal stress wave velocity and density [18]. Knot Area Ratio (KAR) was measured for each segment in accordance with EN 4978 [20]

Each sample was mounted in a 1 kN-m torsion testing machine (Tinius Olsen, Pennsylvania USA). To measure the displacement of the timber under a torsional load, inclinometers with a range of ± 30° were attached to the upper edge (47 mm dimension) of each sample. Multiple inclinometers were attached to each sample to allow the longitudinal variation in G and the influence of knots 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.

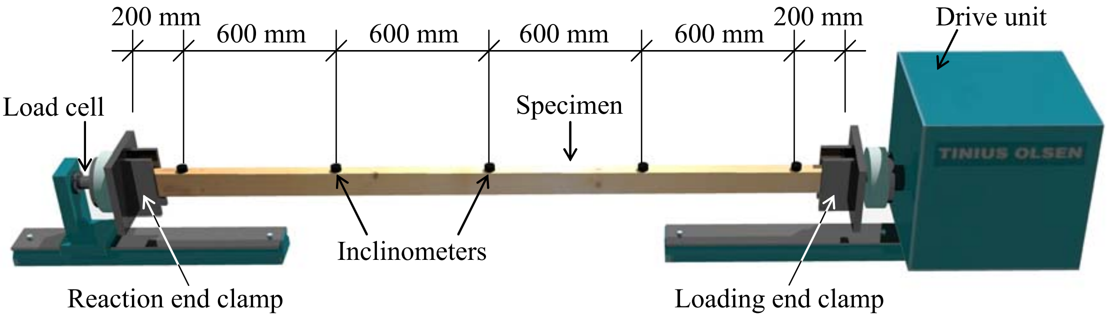

Fig. 1 Diagram for test setup of 2.8m specimen.

Torque was measured to an accuracy of ± 0.5%, while the inclinometers measured the angle of rotation to an accuracy of ± 0.05°. Measurements of twist from the torsion tester were used to control the application of the torque, but were not used in the data analysis as they included other components of twist in addition to the twist of the specimen itself. The clamps were designed to allow easy installation of the specimens and yet grip the specimens in such a way as to avoid excessive embedment. Since only two to four inclinometers were available during the testing, repeat tests were made, where necessary, to collect data for all the positions. Trials to determine the level of repeatability confirmed that this could be done without any compromise to the experiment.

For each test specimen, the applied torque (T) in N-m and the relative twist per length (θ) in degrees per metre were obtained and the shear modulus (G) was then calculated by using Saint-Venant torsion theory for rectangular cross section [19]:

$$G = \frac{T}{\theta \left(d\, t^3 k \right)} \qquad (1)$$

where *d* is depth (m), *t* is thickness (m) of the batten and *k* depends on the depth-to-thickness ratio.

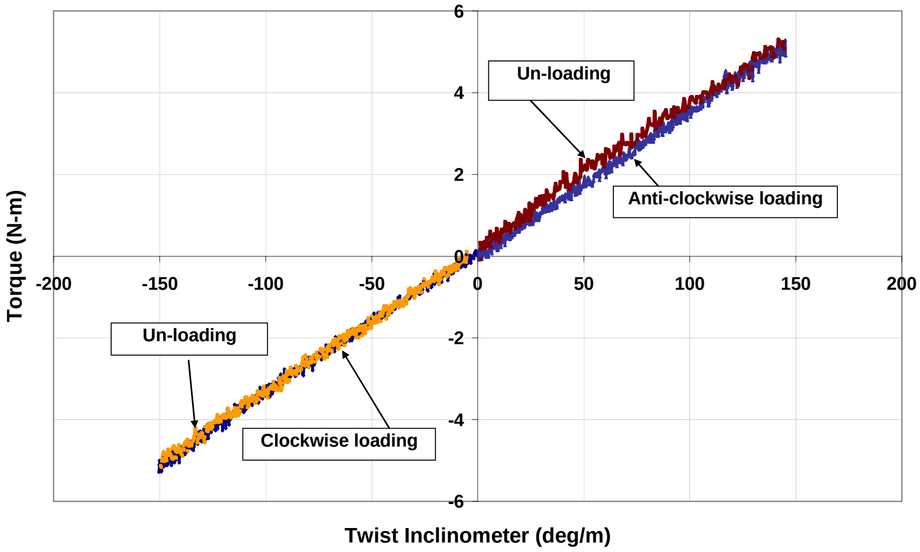

Fig. 2 Torque-rotation diagram for a 2m

During each test, the torque was applied at a constant rate of 4°/min [6]. The sample was loaded within its elastic range by applying a clockwise torque, then unloaded at the same strain rate before being loaded again in the anti-clockwise direction (Figure 2). Preliminary testing was performed to locate the upper limit of the region of elastic behaviour for each sample length. This was achieved by testing five samples of each length until they failed or began to exhibit non-linear behaviour. Based on these tests, it was determined that 1-m-long samples could be twisted by up to 10°/m before they began to yield. Therefore a maximum displacement of 6°/m was used in all subsequent tests on 1 m samples. The corresponding maximum displacements were 6°/m, 5°/m and 4°/m for 2.0 m, 2.8 m and 3.6 m samples, respectively.

3. Result and Discussion

3.1 Influence of cyclic loading

Test samples of 1m and 2m were tested under two cycles of clockwise and anti-clockwise torque to observe if there is difference in G in either direction. However, it was found that G was not influenced by twisting the samples in either direction, as shown in Figure 3.

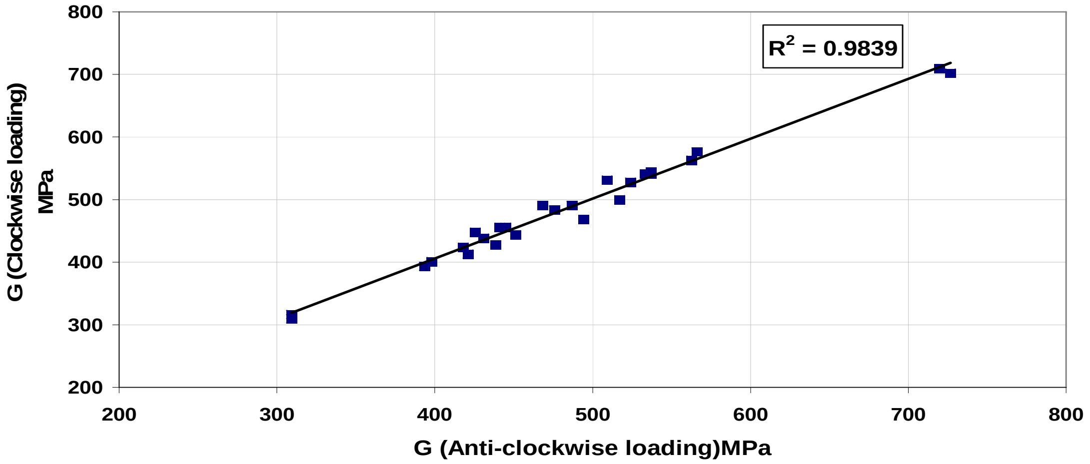

Fig. 3 Comparison of G of 1m samples in both clockwise and anti-clockwise direction.

3.2 Variation of shear modulus within and between samples

Across all the segments from each of the specimens tested, G ranged from 298 MPa to 762 MPa (Figure 4). 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.

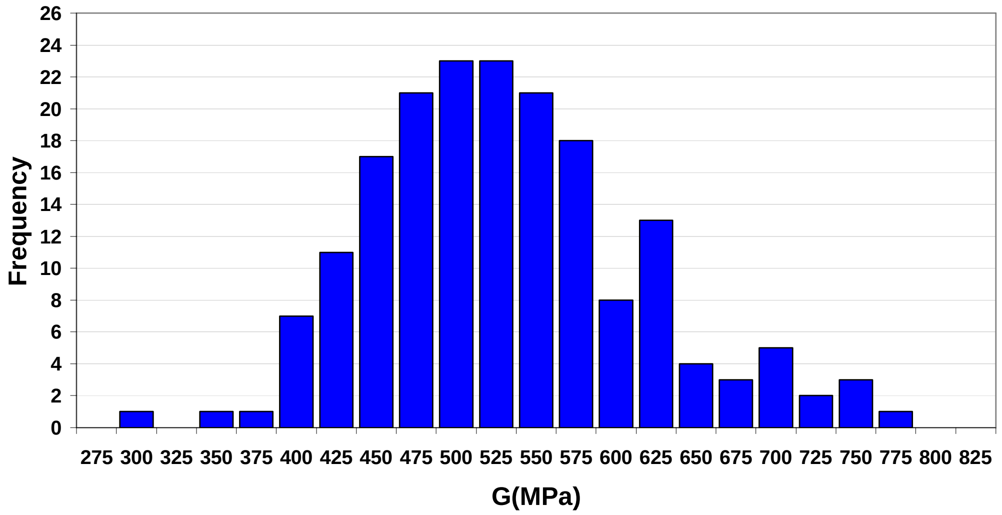

Fig. 4 Variation of shear modulus of the segments of tested samples

The mean value of G 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. An example of the relative within and between specimen variation for 3.6-m-long samples is shown in Figure 5. 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 between different sample lengths.

Group	Number of specimens	Number of segments	Mean shear modulus (MPa)	Maximum shear modulus (MPa)	Minimum shear modulus (MPa)
1.0m	15	15	465±94	715	298
2.0m	10	40	497±58	604	339
2.8m	12	48	513±79	695	375
3.6m	16	80	542±91	762	382
Overall	53	183	518±84	762	298

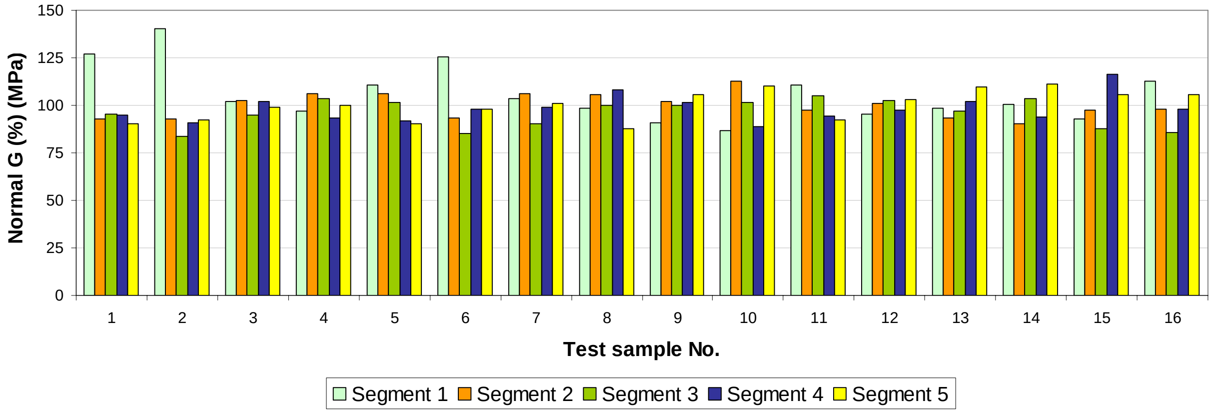

Fig. 5 Variation in shear modulus along the length of 3.6m test battens.

3.3 Influence of knots

There was no evidence of a relationship between KAR and the shear modulus (p=0.16; Figure 6). This indicates that knots do not appear to have a significant influence on G, much the same as they are generally not found to have a significant influence on the flexural modulus of elasticity [18].

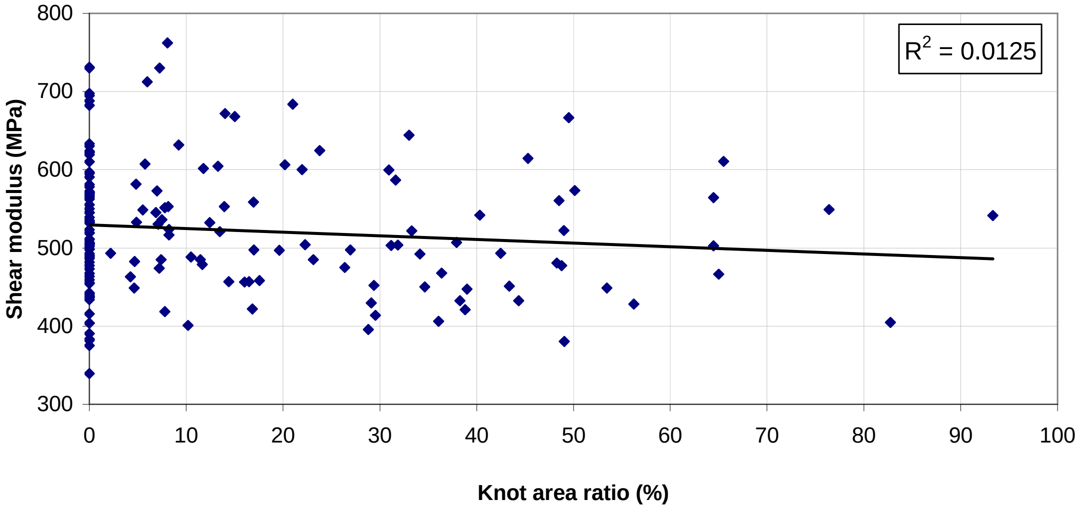

Fig. 6 Influence of knots on the shear modulus

3.4 Comparison between Shear Modulus and Modulus of Elasticity

The longitudinal modulus of elasticity (E) for the each of the groups of specimens tested in torsion ranged from 4727 MPa up to 11108 MPa (Table 2). The value of E for the 1m group is higher than the other three groups. This may be due to the timber coming from a different forest. Although the values of E for the 2.8 m and 3.6 m samples were obtained from measurements of longitudinal stress wave velocity and density, the correlation between static E and dynamic E is very good (R^2 approx 0.75) and allows reliable conversion to static E values [18].

Table 2. The modulus of elasticity of different length groups.

Group	Mean modulus of elasticity (MPa)	Maximum modulus of elasticity (MPa)	Minimum modulus of elasticity (MPa)
*1.0m	7574±1559	9900	5100
2.0m	6058±1220	7960	4370
†2.8m	6743±843	7866	5084
†3.6m	6878±1791	11107	4727
Overall	6699	11107	4370

* taken from a different forest
† tested dynamically and then converted into static E

Overall, the average ratio of E to G is approximately 14:1 which is comparable to ratio of 16:1 presented in the codes. However, at an individual specimen level there was no relationship between G and E ($p = 0.16$; Figure 7). This suggests that G is independent of E.

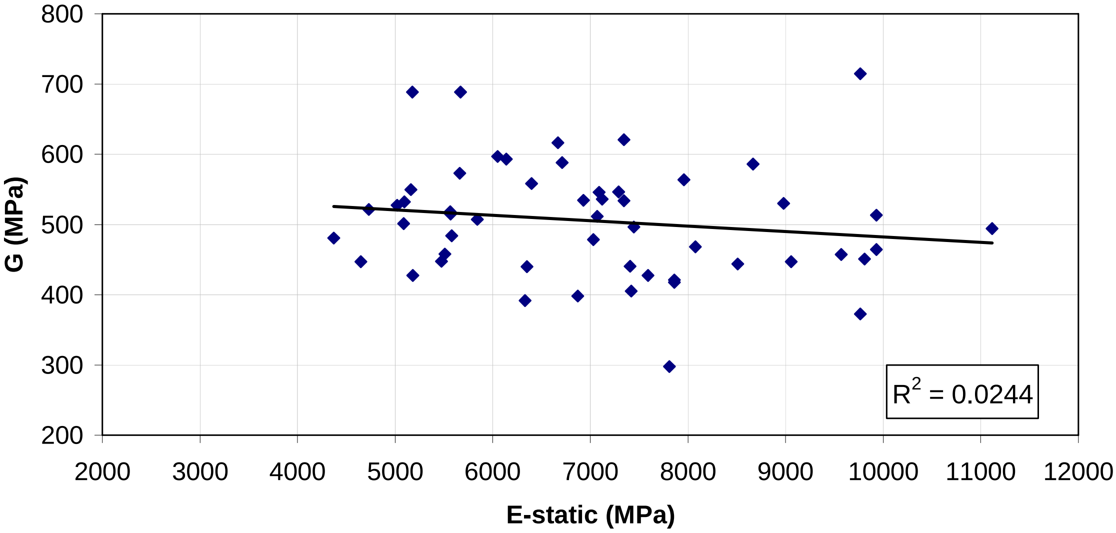

Fig. 7 The relationship of E and G of tested samples.

4. Conclusions and Future Work

Preliminary 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, but this did not appear to be influenced by the measure of knot size used in this study.

For Sitka spruce, the E:G ratio is often assumed to be 16:1, and shear modulus estimate from a known E value accordingly. While the average ratio found in this study was similar to 16:1, this investigation has found no evidence of any correlation between these two mechanical properties at an individual specimen level within the range of values tested.

This suggests that G values should be estimated with caution and that it may be potentially dangerous to assign timber to a grade on the basis of an E value obtained from a strength grading machine as it does not necessarily confirm that shear modulus values are adequate for the grade.

However, only one species was tested in this investigation and properties where limited to the C16 strength grade range. Further tests are planned to include stiffer C24 material from a different softwood species. In addition small clear test specimens will be tested under torsion and by acoustic methods to ascertain if a correlation between E and G can be found if the influence of wood macro structure is removed.

5. References

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