Determination of Shear Strength of Timber Joists by Torsion Testing

Aamir KHOKHAR[1], Hexin ZHANG[2], Daniel RIDLEY-ELLIS[3]

[1]PhD Student, School of Engineering and the Built Environment, Edinburgh Napier University, UK,
a.khokhar@napier.ac.uk

[2]Lecturer, School of Engineering and the Built Environment, Edinburgh Napier University, UK,
j.zhang@napier.ac.uk

[3]Principal Research Fellow, Centre for Timber Engineering, Edinburgh Napier University, UK,
d.ridley-ellis@napier.ac.uk

ABSTRACT

This paper presents an experimental investigation in which the torsion testing approach was employed to evaluate the shear strength of Sitka spruce and Norway spruce joists. Rectangular structural size specimens of lengths ranging from 1.0 m to 3.6 m were tested using a 1 kN-m torsion testing machine. In order to determine the shear strength, specimens were tested until they either fractured, or exhibited pseudo-plastic behaviour under applied torque. The failure modes and the correlation of shear strength and torsional shear modulus were also studied.

In current testing standards, the measurement of shear strength for wood is mainly based on testing small clear samples and on bending tests of full-size structural lumber. Tests on shear blocks do not account the influences of wood defects and therefore the test procedure underestimates the heterogeneous nature of wood. In the bending test practice, the interaction of axial bending stresses and loading embedment with shear stress means it is impossible to obtain a state of pure shear.

By overcoming these problems using torsional loading, it was found that the characteristic shear strength of the wood in the tested joists was 166% to 200% higher than the published design values in EN 338 and the mean strength was 8% to 13% higher then the shear block based published values in the USDA Wood Handbook.

The test joists fractured mostly at the middle with cracks propagating towards either the supports or to the top or bottom surfaces. However, combined tension shear and crushing failure modes were sometimes observed at supports. A correlation ($R^2 = 0.40$) was found between the shear strength and the shear modulus obtained from torsion tests. However, it appeared from this study that knots do not have substantial influence on the shear strength.

INTRODUCTION

The shear strength parallel to grain (referred here as a shear strength) is a fundamental mechanical property of wood and is used in general timber structural design. Testing standards such as EN408 (CEN 2003) and ASTM D 143-94 (ASTM 2007) recommend that the shear strength can be

determined by testing small clear wood blocks, known as "shear blocks". The shear block test method allows the shear strength values to be obtained free from influence of wood defects and, therefore, the test procedure underestimates the heterogeneous nature of wood. To account the possible influence of wood defects and heterogeneity of wood, full size structural lumber can be tested under bending (three or four point) or torsion (ASTM 1996) to obtain the shear strength. The published shear strength values in EN338 (CEN 2003) are calculated on the basis of bending strength of timber. The bending strength can is measured by testing full size structural timber in four point bending and the shear strength is estimated by using the following equation:

$$f_{v,k} \quad = \quad 0.2\bigl(f_{m,k}\bigr)^{0.8} \tag{1}$$

Where $f_{v,k}$ is the characteristic shear strength and $f_{m,k}$ is the characteristic bending strength. The term characteristic denotes the 5th percentile test value obtained on the basis of all the test values ranked in ascending order.

The bending test is close to the real-life loading condition but may not provide the state of shear assumed in the test procedure due to the interaction of tensile, perpendicular compressive and shear stresses that take place. Although the torsion test does not represent the actual real-life loading condition it does produce a purer and more uniform system of shear stresses in specimen allowing measurement of the pure shear strength. However, until recently very little attention has been paid to use the torsion test method. Riyanto and Gupta (1998) conducted research to compare shear block, bending and torsion test approaches for attaining the shear strength and concluded that the torsion test is a better approach than the other methods. The recent draft of EN408 (CEN 2009) recommended the torsion test method to obtain the shear modulus of wood and there is evidence to support rejection of the old bending method unless shear strain can be measured directly (*e.g.* Ridley-Ellis *et al.* 2009).

This study also proposes that the torsion test method to be included in the test standards to attain the shear strength of wood. The main objective of presenting this paper is to describe the experimental torsion test approach to obtain the shear strength values and to compare with the published design values from EN338 and in Wood Handbook (USDA 1999). The secondary objective was to examine the failure mechanism of wood under torsion and the correlation of shear strength and shear modulus obtained from torsion testing.

MATERIALS AND METHODS

Tests were undertaken on Sitka spruce (*Picea sitchensis*) and Norway spruce (*Picea abies*) joists of nominal cross section of 45×100 mm. 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. 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). 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 (45 mm dimension) of each sample, as shown in Fig. 1.
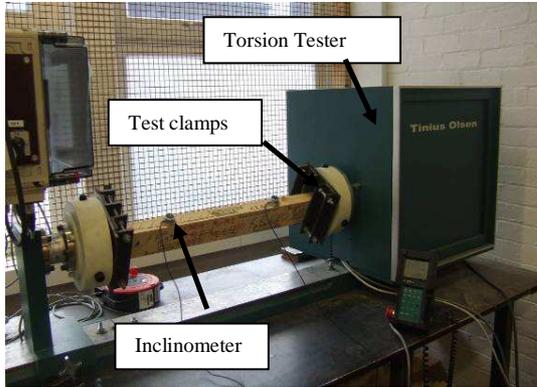

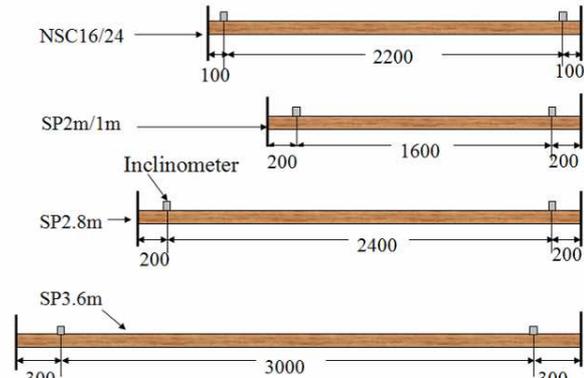*Figure 1: Torsion testing apparatus 1.0m sample*

Figure 2: Shear strength test arrangements for SP and NS joists (length in mm)

The mounting positions for the inclinometers depended on the length of sample being tested, but in all cases inclinometers were mounted at least 100 mm (from the clamps to avoid end effects. For 1.0 m long samples, two inclinometers, each located 200 mm from the end clamps allowing displacement to be measured on a 600 mm central span. Fig. 2 gives the positions of inclinometers for each length. The main purpose of mounting inclinometers was to obtain the relative twist of the span free from machine and clamp distortion to calculate shear modulus G. The shear strength was calculated on the basis of the maximum torque. All test specimens were tested at 4°/min (ASTM 1996) until each test specimen was fractured under applied torque. The shear strength and *G* of each test specimen was calculated on the basis of Saint-Venant torsion theory for rectangular sections as follows:

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

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

In Eqs. 2 and 3, *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 constant values depend on the depth thickness ratio (see e.g. Bickford 1998) The maximum applied torque is defined as the ultimate applied torque at which test joists were either fractured or reached at their maximum strain hardness point, as shown in Fig. 3. The stiffness was obtained by conducting linear regression analysis of
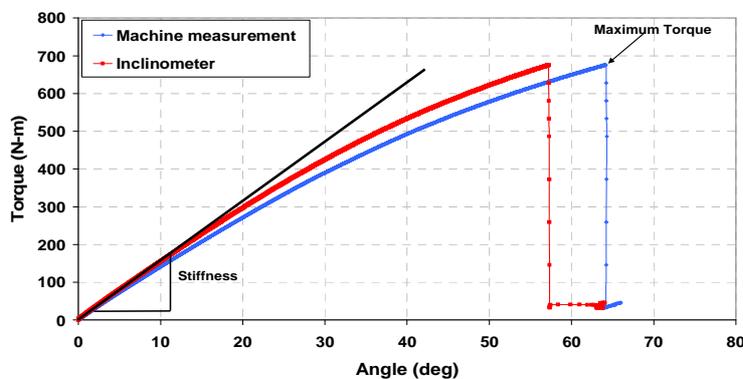

Figure 3: A typical applied torque and relative twist of 2.8m test sample

the applied torque and the relative twist per length within the elastic region as shown in Fig. 3. For most of the tested specimens the elastic region was between 3% and 30% of maximum applied torque, and therefore, linear regression analysis was conducted between 5% and 25% of maximum applied torque to obtain the stiffness.

Table 1. The means shear strength values of tested joists

Group	Strength Grade	Length (m)	No. of Specimens	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 average		490	7.2
NS	C16	2.4	14	390	8.5
	C24	2.4	12	410	9.3

RESULTS AND DISCUSSION

Design Standard and Torsional Shear Strength Values

Table 1 provides the mean shear strength values of both Sitka Spruce and Norway spruce beams. It was clearly observed that the 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 the same species the shear strength was about 9% lower. For C16 Sitka spruce, the mean shear strength of 7.2 MPa attained, was about 15% lower than Norway spruce of the same grade, and 22% less then the C24 Norway Spruce. This is perhaps because the different species have different ratios of shear and bending properties.

In EN408, it is recommended that the shear strength values of timber be obtained by testing a 32×52×300 mm wood block. In EN338, the characteristics design shear strength values for C16 and C24 of 1.8MPa and 2.5MPa respectively, are given. 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. 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. Based on shear block tests, the Wood Handbook (USDA 1999) provided the mean shear strength values for SP and NS 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). Similarly, Riyanto and Gupta (1998) 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 Wood Handbook (USDA 1999).

The comparison shows that relatively higher shear strength values were achieved when the torsion test approach was used. Although it should be noted that only two species were tested in this research, an even higher difference in shear strength was found when they were compared with values given in EN338. This suggests that shear strength values obtained from bending tests underestimates the actual shear strength of timber and that interaction of axial, bending stresses and loading embedment may prevent full shear strength being achieved in such tests. Therefore, shear strength values obtained on basis of bending tests may be over-conservative for design purposes. It may be appropriate that the torsion test procedure be adopted to obtain the shear strength values.

Failure Mechanism under Torsional Loading

It was observed that all test samples fractured when tested under torsion. Samples of shorter length (1 to 2.4m) were ruptured within the range of 30° per meter twist, as well as, the longer samples (2.8m and 3.6m) long beams were fractured within the range of 20 to 30° per meter. During tests, most of specimens fractured with large bang sound and a puff of wood dust in air around the location of failure. It was found out that failure cracks were initiated within the clear wood even though a number of large knots were present in test joists. Four different types of failure modes crushing, shear, combined tension shear failure modes and horizontal shear failure modes were observed as described follows:

Crushing Failure

The crushing failure is defined here as a failure that occurs at the supports due mainly to clamps crushing the wood material. It was noticed that about 50% of SP and NS specimens were crushed at either the loading or reaction supports. 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 earlywood zone in RT plane (Fig. 4) and propagated along LR plane (long side), as shown in Fig 5. In some cases cracks were started in the latewood zone and travelled towards first the LT plane (short side) and then propagated towards the LR plane ended into crushing the material. It was observed that presence of knots, inner bark or pith was causing the discontinuation of the cracks and the battens failed immediately within elastic zone as a brittle failure.
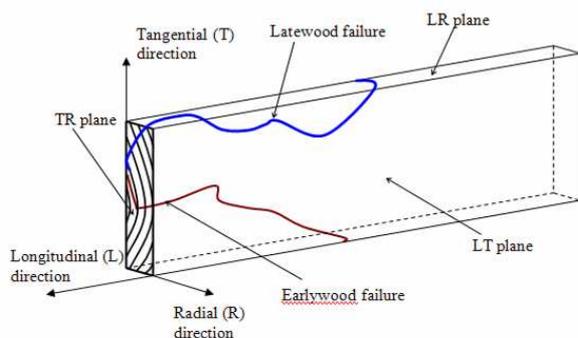

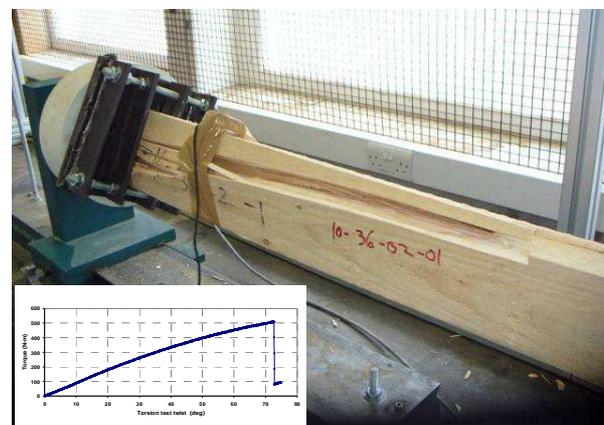*Figure 4: The Schematic diagram of timber joists showing grain direction.*

Figure 5: A crushing failure of 3.6m batten and its torque-twist relationship

Shear Failure

The other type of failure mode observed was the shear failure and occurred mostly in Sitka spruce joists. 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 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, the failure travelled diagonally along the grain direction. It was also observed that when crack approaches a knot then the crack travelled across the knot rather than pass through the knot. Thus, this indicates that knot may provide some resistance to the shear failure. Fig. 6 shows a shear failure, and it can be seen that the crack passed around the knot and produced a stake shaped end. In some samples it was observed that combined knot and grain deviation on the LR plane and knot fissures initiated the shear failure and that test joists were fractured within their elastic range as a brittle member.

Combined Tension Shear Failure

Another type of failure that occurred was the combined tension shear failure, which was also mainly observed in the Sitka spruce joists. In this failure mode, the cracks usually were started at either the top or bottom side in tension due to a knot and then propagated as a diagonal crack along the long side and ruptured in tension due to the knot at the other edge. This failure takes place because edge knots are usually surrounded by cross grain and these cross grain broke locally in tension rather than shear and initiated the failure, as shown in Fig. 7. It was found that in this type of the failure the cracks passed around the knots that were present in the long side of the battens. This shows that knots are not the weaker plane along the long side of the battens.
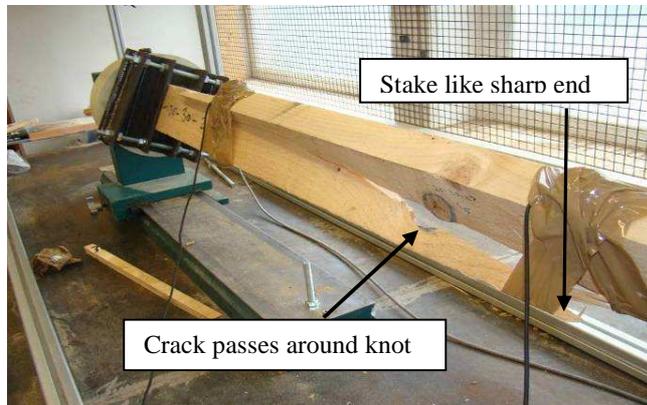

Figure 6: A shear failure occurred in 2.8m joist and crack passed through knot and ends up with sharp edges

Figure 7: A typical combined tension shear failure occurred in 2.8m specimen due to top and bottom edge knots

Horizontal Shear Failure

This type of failure was only appeared when Norway spruce specimens were tested. 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 Fig 9. The term horizontal shear failure is given here because the shear cracks ran horizontally along the length of the joists. It

is thought that this type of failure occurred because the NS specimens did not have a high slope of grain and that grain direction was completely parallel to the longitudinal axis along the joist span. Therefore, when failure occurred the cracks travelled through grain parallel to the length. Secondly, it was observed that knots diverted the crack path in Sitka spruce specimens but the NS test joists had no large knots (diameter > 25mm) that could have diverted the crack direction. Therefore, the cracks travelled parallel to the longitudinal axis towards the support ends

Relationship Between Shear Strength and Shear Modulus

In this regard, a linear correlation between the shear strength and G of Sitka spruce (SP) and Norwegian spruce (NS) joists was developed, as shown in Fig. 10. The R-squared values were calculated without including the higher shear strength values of NS test specimens. This is because only two higher shear strength values were obtained and this will unduly bias the correlation of shear strength and the G. It is thought that the slightly higher correlation for NS was obtained because most of NS specimens were free of wood defects and joists failed within clear wood. However it was also noted in this study that knots have very little influence on G and on shear strength overall. Rather, in some SP 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.

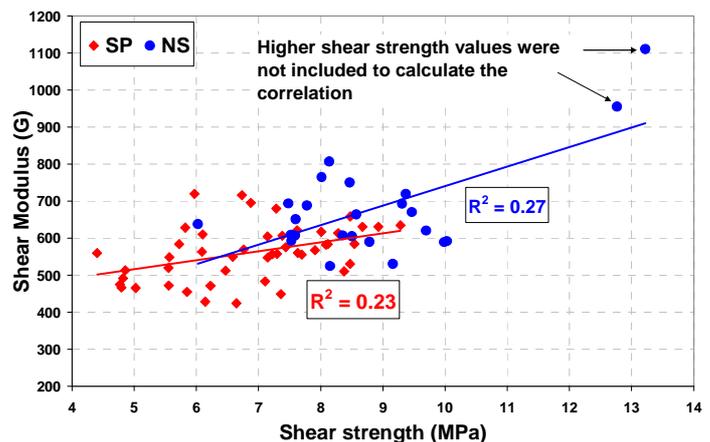*Figure 9: A typical NSC16 batten ruptured under torsion loading with horizontal shear crack*

Figure 10: Linear relationship between G and the shear strength of SP and NS battens

Conclusion

Test results have been presented for an investigation of the shear strength of Sitka spruce and Norway spruce obtained using the torsion testing approach. The torsion test procedure has been found to produce higher strengths than 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.

It was noticed that the cracks were commonly initiated within clear wood and caused shear failure, but that, in some specimens, edge knots initiated local tensile failure which then propagated as a shear 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(CEN 2009) recommended the torsion testing approach to obtain the shear modulus of timber. In this study it was found out that both shear strength and shear modulus can be obtained from torsion tests and have a reasonable correlation as well. Although in this research only two wood species were tested, it is concluded that torsion testing provides an effective way to obtain shear strength and it is proposed that this also be included in the next edition of the code.

REFERENCES

American Society for Testing and Materials (2007) Standards Methods of Testing Small Clear Specimens of Timber, *ASTM D 143-94*, Volume 04, Serial Designation, Conshohocken, PA. USA.

American Society for Testing and Materials (1996) Standard Methods of Static Test of Lumber in Structural Size, *ASTM D 198-94*. Volume 04.10 Wood, West Conshohocken, PA. USA.

Bickford W. B., (1998) Advanced Mechanics of Materials, Addison *Wesley Longman, Inc*. California, USA

CEN (2003) Timber structures-structural timber and glued laminated timber - determination of some physical and mechanical properties perpendicular to the grain, EN 408:2003, *European Committee for Standardization*, Brussels, Belgium, 2003.

CEN (2003) Timber Structures - Strength Classes, EN338:2003, *European Committee for Standardization, Brussels*, Belgium, 2003.

CEN (2009) Timber structures-structural timber and glued laminated timber- determination of some physical and mechanical properties perpendicular to the grain, prEN 408:2009 DPC: 09/30159969 DC, *European Committee for Standardization*, Brussels, Belgium, 2009.

Ridley-Ellis, D., Moore, J.and Khokhar, A (2009) Random acts of elasticity: MoE, G and EN408. *COST Action E53 "Quality Control for Wood and Wood Products" and Wood Drying Seminar*, Bled, Slovenia, 23rd April 2009.

Riyanto, D. S., and R. Gupta. (1998) A Comparison of Test Methods for Evaluating Shear Strength of Structural Lumber, *Forest Products Journal*, Vol. 48, No. 2, pp 83-90.

USDA (1999) Wood Handbook, Wood as Engineering Material, Forest Product Laboratory, USDA Product Society, Madison, Wisconsin, USA.