Paper 260

A Low Cost Non-Contact and Non-Destructive Method for Evaluating the Variation of the Shear Modulus for Glued Laminated Timber Beams using a Photogrammetric Approach

A. Mohamed[1,3], H. Zhang[1], I. Smith[1] and Z. Xiao[2]
[1]School of Engineering and the Built Environment
 Edinburgh Napier University, United Kingdom
[2]Faculty of Architecture and Civil Engineering
 Henan University of Technology, Zhengzhou, China
[3]Department of Civil Engineering
 University of Omar Al-Mukhtar, El-Beida, Libya

Abstract

This paper presents the experimental studies performed to investigate the feasibility of the proposed photogrammetric system for torsion tests. In this study, two binocular stereo systems were used to measure the surface rotation of timber glulam beams under torsional loading. The first stereo system was employed to monitor the photogrammetric pattern painted on the left sides of the timber samples whereas the second system was employed to monitor the pattern painted on the right sides of the timber samples. This test result has revealed how to provide more details on the surface deformation of timber samples as this may assist in understanding their torsional behaviour during loading. Several test series were conducted with twelve timber samples under torsional loading. The proposed approach was validated by comparing its angular measurements with those measured by inclinometers placed above the photogrammetric patterns. The results showed that the optical systems not only allowed assessing performance and reliability of inclinometers but also allowed monitoring the shear modulus of the samples at various locations by providing more information which would not be possible to obtain using the traditional techniques.

Keywords: torsion test, inclinometers, photogrammetric approach, stereovision, timber.

1 Introduction

Many different test methods have been developed and adopted by different researchers to evaluate the mechanical properties of timber materials. Torsion test is among those methods which can be used to evaluate the shear modulus of timber and glulam materials. This method is recommended by the European standards EN 408 (2010) [1] as a standard test method to characterize properties of structural-size

timber-composite materials. It is the only method which imposes a state of pure shear stress on specimen [2] and it has been proved that there are many advantages for measuring the shear modulus value of timber and glulam beams using the torsional test method [5]. Recently, torsion test has been adopted by more and more researchers including Zhang et al. [13], Khokhar et al. [8,7], Gupta et al. [4,3], and Hindman et al. [5] to evaluate the shear modulus of structural-size timber and glulam beams.

The exact measurements of the relative angle of twist over a gauge length are essential to determine the shear strain and hence enable the calculation of of the value and variation of shear modulus. Although the torsion testing machine can be used to measure the rotations of the torsion specimens, these measurements will not be accurate enough since slipping the ends of the specimens gripped to the testing machine is difficult to avoid during testing and this slippage may influence the angle of twist data measured by the torsion machine. Hence, traditional devices, such as troptometres and inclinometers, are commonly used for measuring the relative angle of twist of timber specimens. Even though troptometre can be used to read and determine the rotation of the torsion specimens, there are some limitations when using this device. For example, it is hard to keep troptometre aligned while mounting on the specimen. In addition to that, this instrument is designed with a limited range of rotation and it is difficult to read the angle from the protractor scale. Another device which is most commonly used for measuring the rotations of the samples is the inclinometer. Inclinometers are proven to be accurate and reliable for measuring accurately the angle of twist. However, because of their size and their contact with the torsion specimens, these sensors cannot be used to measure more details of the shear deformation of glulam beams, which is essential to evaluate the shear modulus at various locations on the samples. A non-destructive methodology is needed to overcome the limitations of the traditional sensors. Therefore, the development of non-contact, non-destructive and cost-effective approach is fundamental for the torsion test.

To overcome the limitations of the traditional devices and to minimize the contact effects, the stereo photogrammetric approach, comprising of two binocular stereo systems with photogrammetric targets was proposed for measuring the surface rotations of timber glulam beams under torsional loading. The proposed approach is a non-contact and non-destructive measurement technique that can be used to evaluate the variation of the shear modulus for glued laminated timber beams utilizing stereo images. Compared to the traditional techniques, the photogrammetric technique offers the possibility of measuring three-dimensional (3D) location of any point located on the object surface as well as measuring the rotations of the object at various locations without the need to touch the object. This measurement technique has a great potential to improve understanding the behaviour of timber beams under torsional loading.

The main objective of the work presented has been to use the developed non-contact binocular stereo system for determining the value and the variation of the

shear modulus of glulam beams during non-destructive torsion tests. Experimental studies were conducted on the torsion samples to investigate the feasibility of the proposed technique to determine the rotational surface deformation during the torsional loading. In these studies, two binocular stereo systems were employed to measure the surface rotations of timber glulam beams at two regions of interest under torsional loading. The binocular stereo systems were validated by comparing its angular measurements with those measured by inclinometers placed above the photogrammetric patterns. The results showed that the contact-free technique is found promising as a method monitoring the shear modulus of the samples at various locations by providing more information which would not be possible to obtain using the traditional techniques. The methodology and measurement process performed in this study can be summarized in the following workflow diagram shown in Figure 1.
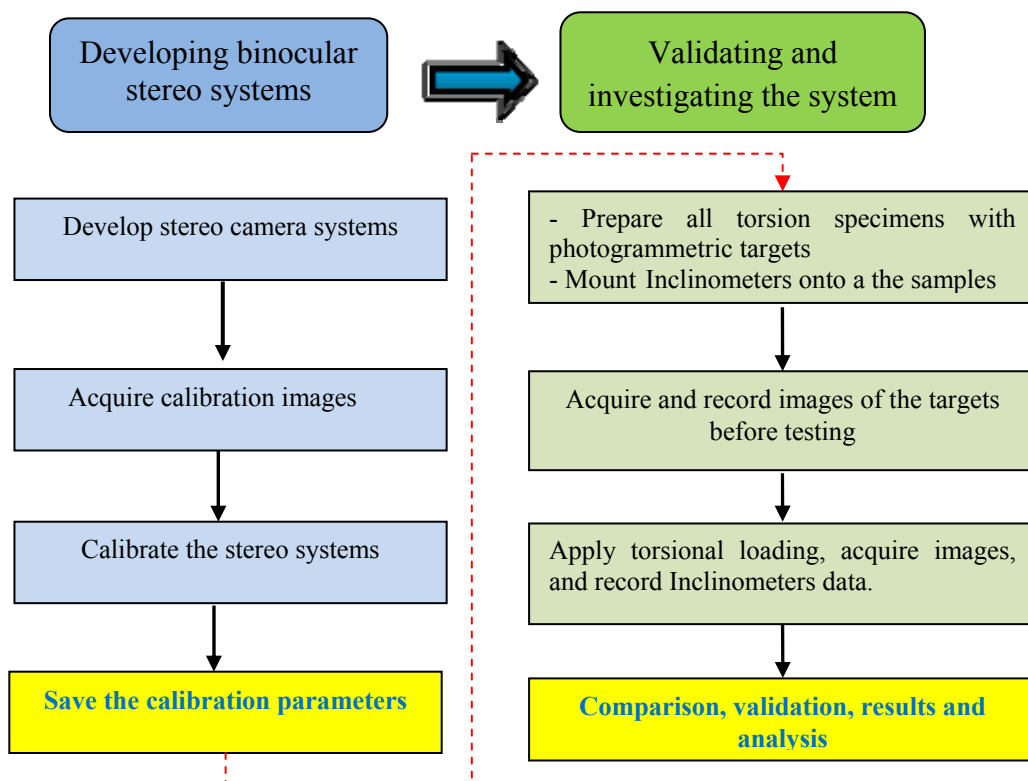

Figure 1: Workflow diagram of the experimental work.

2 The Binocular Stereo System

Binocular stereo system is based on the comparison between two stereo images of the same object taken from different locations and orientations by two cameras [11]. In order to map 2D image coordinates into 3D world coordinates and to correct lens distortions, the two-camera system must be calibrated before acquiring the stereo

images of the targets. The stereo camera calibration is an important step to determine the internal and external camera parameters. The internal parameters describe the mapping of the 3D world into pixels and the external camera parameters describe the relative pose of the left camera in relation to the right one [10].

After performing the stereo camera calibration and recording the stereo images during testing, an image processing algorithm can used to track and evaluate the position of the measurement targets on the object based on the principals of photogrammetry and stereo vision. The 3D locations of the target points on the object can be identified based on triangulation technique and the calibration parameters providing that the corresponding points in the two images captured by the binocular stereo system have to be determined [10]. These 3D measurement data can then be used to calculate the angular deformation of the timber surface. Generally, the steps for the derivation of 3D information mainly include: acquiring calibration images, calibrating the stereo camera system, rectifying images, using region of interest, 3D reconstruction, transforming the results into world coordinates, and visualizing the results. These steps are summarized in Figure 2 and detail discussion of each step can be found in [10].
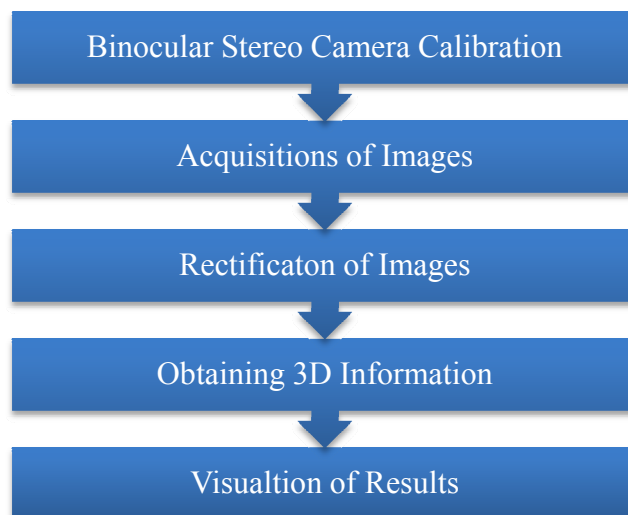
Binocular Stereo Camera Calibration

↓

Acquisitions of Images

↓

Rectificaton of Images

↓

Obtaining 3D Information

↓

Visualtion of Results

Figure 2: Flowchart of 3D reconstruction process[10].

3 Materials and methods

3.1 Materials and angle of twist measurement sensors

Twelve rectangular cross section glulam timber beams were used in this study as samples for the torsion tests. Prior to testing, as described in EN 408 (2010) standards, the glulam specimens were conditioned in a room with a constant temperature of 20°C and relative humidity of 65%. These conditions will ensure uniform and constant moisture content (MC) of about 12%. Figure 3 shows glulam beams used during the torsion tests.

In order to employ the stereo camera systems for proper measurement of the angle of twist during the torsion test, the glulam beams were prepared by applying circular photogrammetric targets to their surfaces. These black targets were painted on a white background to be easily distinguished during image processing. Figure 4 shows the glulam samples after being prepared with the photogrammetric targets.

Figure 3 : Image of glulam timber beams used in the study.

Figure 4: The glulam samples after being painted with the photogrammetric patterns.

Angle of twist measurement sensors

In this study, two different measurement methods, inclinometers and non-contact deformation measurement systems were used to monitor the rotational deformation of the samples during testing. Inclinometers [6] (Model IS-2-30, Level Developments, UK) were used to measure the angles of twist at the attached points.

A data log interface system, implemented in Visual Basic programming language, was developed to record and transfer data received from inclinometers to a desktop computer (PC1), depending on the time interval specified by the user of the system. Figure 5 shows an image shot of the graphical user interface of this package.

In addition to inclinometers, two binocular stereo camera systems were used in this investigation for image acquisition to monitor the torsion angles of the specimens. Each of the binocular systems, which are shown in Figure 6, consists of two DMK 23GP031 cameras (from The Imaging Source Company) with a total resolution of 2592 x 1944 pixels and high speed CMOS area scan sensor. The two stereo cameras were fitted with an Azure- 3514M5M lens having a constant focal length of 35mm and pixel size of 2.2 microns. The stereo cameras, mounted on adjustable tripods, were focused onto the region of interest. The DMK 23GP031 cameras were connected via Gigabit Netgear switch to a desktop computer (PC2) where the image processing software was installed. Additionally two LED light sources were employed to assist in providing a homogenous illumination of the calibration plate during the calibration process.

In order to acquire and process the stereo images of the proposed photogrammetric approach, a software package, as shown in Figure 6, was developed based on visual C++ 2010 and the graphical user interface (GUI) of the package was implemented in the Microsoft Foundation Classes (MFC), providing the functions necessary to calibrate the binocular system and to record the image data during testing. The developed software makes use of libraries included in the image processing software, HALCON version 11[9], including functions not only for calibrating the binocular stereo system easily and accurately but also for 3 dimensional image photogrammetry [10].
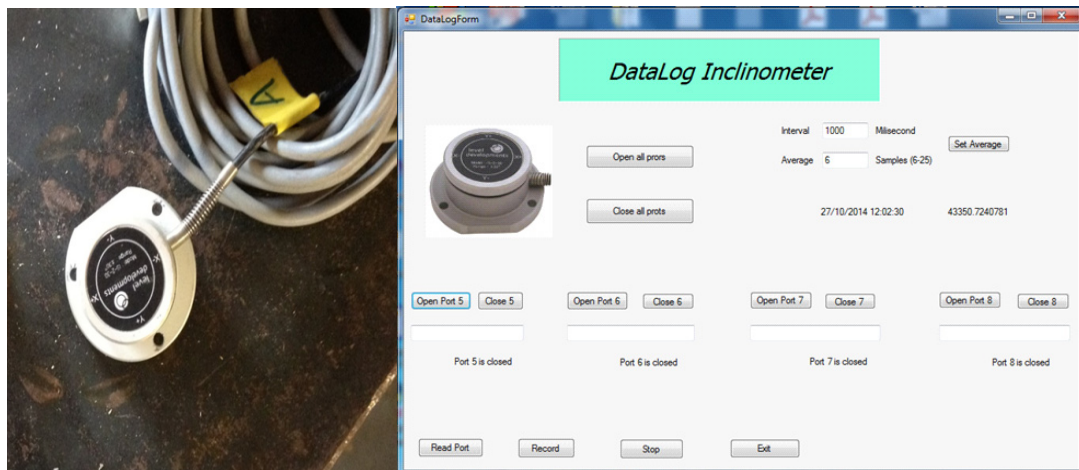

Figure 5: Dual-axis inclinometer (left) and the developed data log interface for recording the readings of inclinometers.
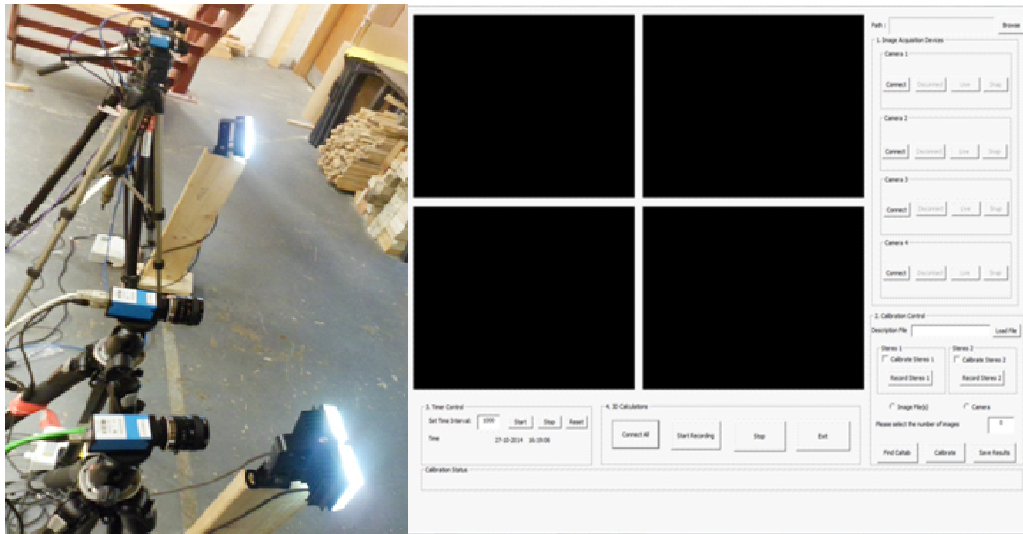
Figure 6: The binocular stereo camera systems (left) and the implemented photogrammetric software for image acquisition and camera calibration (right).

3.2   Experimental Setup and Procedure

A Tinius Olsen Universal Testing Machine [12] with instrumentation monitoring the applied torque was used to conduct the torsion test. Figure 7 depicts schematically the components of the torsion test setup and an image of this experimental setup is shown in Figure 8. The torsion test specimen was mounted onto the torsion testing machine by attaching its right end to a clamp mounted on the weighing chuck and its left end with a clamp attached to the loading chuck.

For a correct evaluation of the shear modulus and to increase the accuracy of angle of twist measurements, two methods, inclinometers and stereo camera systems, were employed to measure the rotational deformations of the timber surface during the test. As illustrated in Figure 7, a total of four inclinometers were attached to the upper surface of each sample. The two end inclinometers (A and D) were mounted at a distance of 130 mm from the clamps to avoid possible end effects arising from the attaching clamps. The other two inclinometers (B and C) were placed at the middle of torsion specimen sufficiently away from the grips according to the standard EN 408 [1]. The inclinometers were connected to a data acquisition system which transforms all data received from the inclinometers directly to a desktop computer, PC2. In addition to inclinometers, two stereo camera systems (left and right) were used to monitor the angle of twist between the photogrammetric targets utilizing their computed 3D coordinates at each time interval. For validation purposes, inclinometers B and C were placed exactly above the photogrammetric patterns.

Prior to all torsion tests, the two camera systems were calibrated using a calibration plate and based on the stereo camera calibration of HALCON [9]. In the

7

calibration process, a100mm x100mm fabricated calibration plate was placed in front of the two cameras near the location of the proposed photogrammetric pattern as can be seen in Figure 9. The cameras and lens were locked to prevent them from moving during testing. The calibration plate was acquired from the left and right cameras in different positions and orientations relative to the stereo camera system. The outputs of the calibration were saved to the desktop computer, PC1.

Once the binocular stereo systems have been calibrated, the torsion tests were carried out four times for each torsion specimen according to CEN (EN, 2010) procedure of the standard torsion tests. Twelve glulam timber beams were used in this study. Preliminary torsion tests were carried out on the first sample (HT-001) to determine the rate of loading and to estimate the elastic range of the sample in order to ensure that no permanent deformation occur during testing under torsional loading. A torque was applied continuously within the elastic range to the specimen at a constant rate of twist equal to five degrees per minute in both the clockwise and anticlockwise direction until the torsion angle of tester reached 15°. During testing, the implemented GUI was used to automate capturing and recording stereo images of the two regions of interest with a time interval of about 5 seconds. The implemented GUI developed for inclinometers was also employed to record their reading every one second during the period of the test.
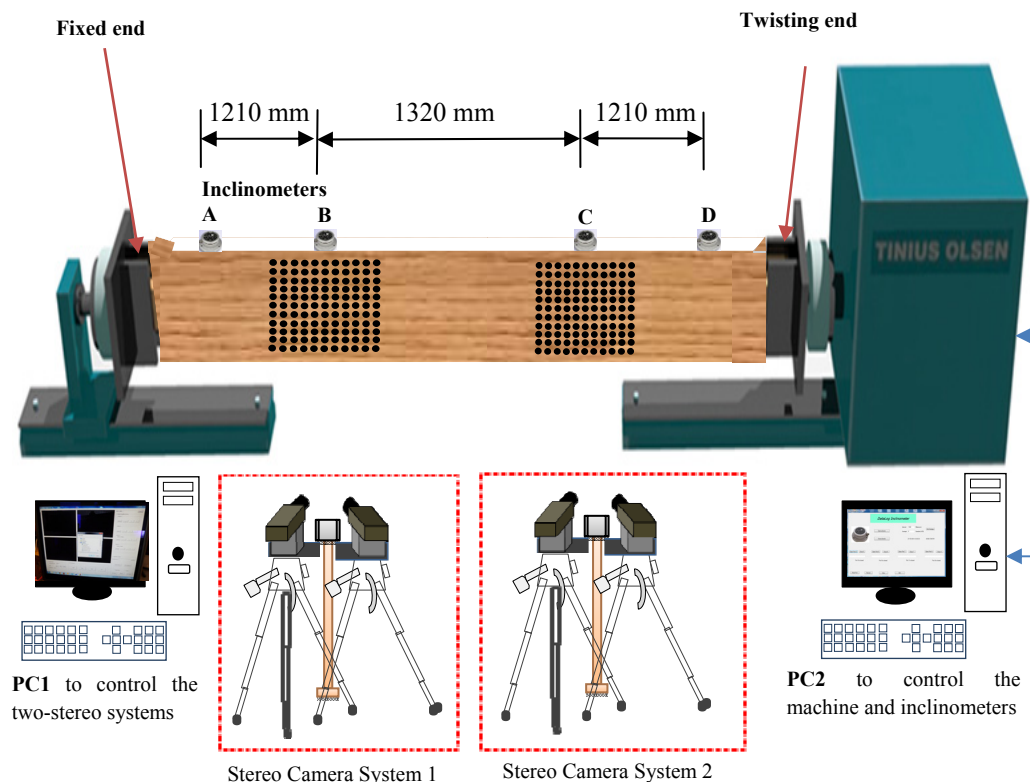

Figure 7: Torsion test arrangement and equipment.

Figure 8: Image of experimental setup of the torsion test (left) and a detail of the photogrammetric pattern (right).
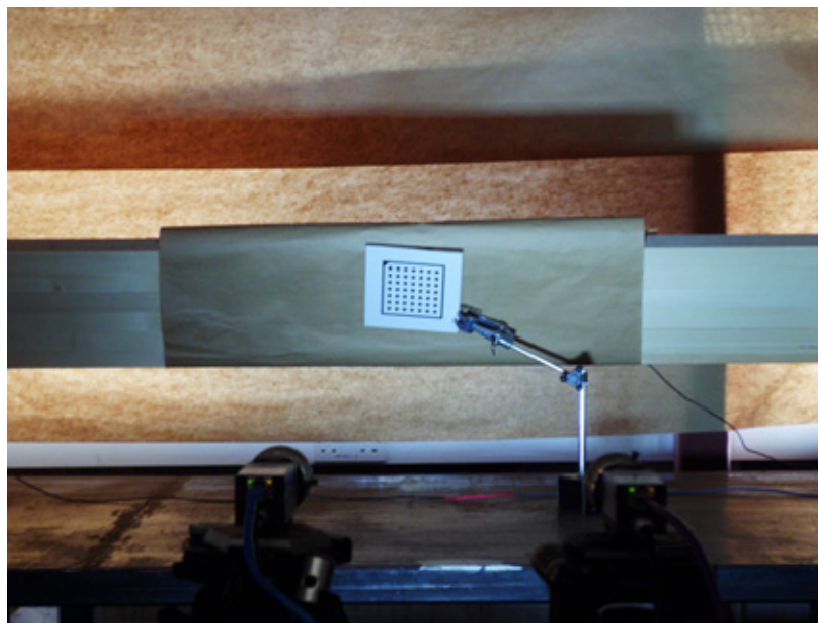

Figure 9: Image of the stereo camera system 1 during the calibration process.

4   Experimental results and discussions

4.1   Calibration results

In order to reconstruct the 3D coordinates and hence their rotational deformations of the photogrammetric targets captured by the stereo cameras, the internal as well as the external parameters of the stereo camera systems were determined by performing the binocular stereo camera calibration of each system using the image processing software. This was achieved via a least square solution with suitable chosen parameters of the cameras that can be determined from the specification of the camera sensor and lens **[10].** Table 1 and 2 show selected examples of the internal as well as the external parameters including the rotation angles and the translation vector determined from the first stereo system (camera 1 and 2).

An algorithm was implemented to process the images capture by the stereo cameras of the non-contact measurement systems. This algorithm fits the circular targets to ellipses, mark their centres with cross, and finds the image coordinates for the centre of each target. With the knowledge of the calibration parameters, the 3D positions of the photogrammetric targets were determined from its stereo projections by triangulation [11].

Camera : Parameter	Description	Unit	Left Camera	Right Camera
Focus	Focal length of the lens	m	0.035	0.035
Kappa	Radial distortion coefficient	m^{-2}	31.57	-14.16
Sx	Width of a cell on the CCD-chip	m	2.2e-006	2.2e-006
Sy	Height of a cell on the CCD-chip	m	2.2e-006	2.2e-006
Cx	X-coordinate of the image centre	Pixels	1503.89	1424.04
Cy	Y-coordinate of the image centre	Pixels	957.12	992.70
ImageWidth	Width of the images	Pixels	2592	2592
ImageHeight	Height of the images	Pixels	1944	1944

Table 1: Internal camera parameters of the first stereo camera system.

Translation vector (X Y Z [m])	X	0.175
	Y	-0.008
	Z	0.000
Rotation angles [degree]	Rot(X)	359.68
	Rot(Y)	355.53
	Rot(Z)	359.16

Table 2: 3D pose parameters (rotation and translation).

4.2 Effects of the direction of the applied torque and loading phases and on torsional behaviour
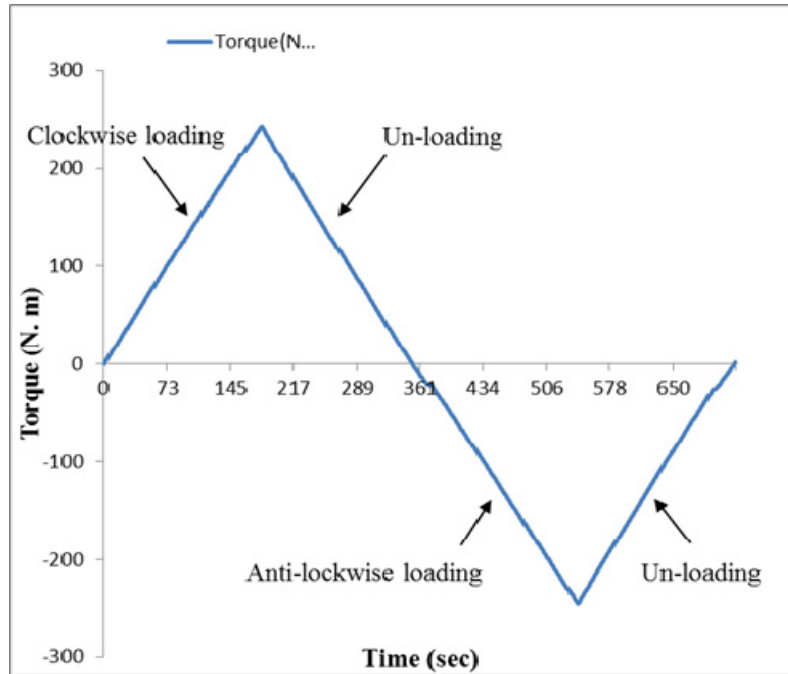

Figure 10: Responses of the sample HT002 to torques during the four phases of loading.

4.3 Comparison of angular deformations measured by inclinometers and the non-contact measurement systems

It is not feasible to employ the torsion testing machine for the direct measurement of the angular deformations. Therefore, as seen schematically in Figure 11, inclinometers as well as the binocular stereo camera systems were employed for this type of measurements. The performance of the proposed approach for measuring the actual angles of twist of the torsion specimens was evaluated by comparing the rotational deformations measured at sections 1 and 2 by the inclinometers B and C and those measured by the binocular stereo systems 1 and 2. In order to compare the results of inclinometers and photogrammetric systems, the averages rotations of the photogrammetric patterns were determined by finding the pixel coordinates of the targets of each pattern and averaging these values to define a point with the average pixel coordinates of the pattern.

To understand the differences between the rotations of the long and short sides of the cross section, the rotations of the photogrammetric patterns 1 and 2 and the rotations of the inclinometers B and C, were plotted in the same Figure. These data were measured in both clockwise and anticlockwise directions under torque loading

11

and unloading phases. Figure 12 and 13 show some selected examples of theses comparisons and indicates remarkable results. It is evident that a good agreement between the two methods has been observed and this indicates that the measurements of the rotations of the short side with inclinometers are acceptable. This is also supported in Figures 14 in which the rotations measured in the torsional direction by the inclinometer B and those measured by the first binocular stereo system were plotted against each other to investigate the correlation between the two measurements. As illustrated in this Figure, a good correlation was observed between the two sensors with a value of R square equal to 0.999.
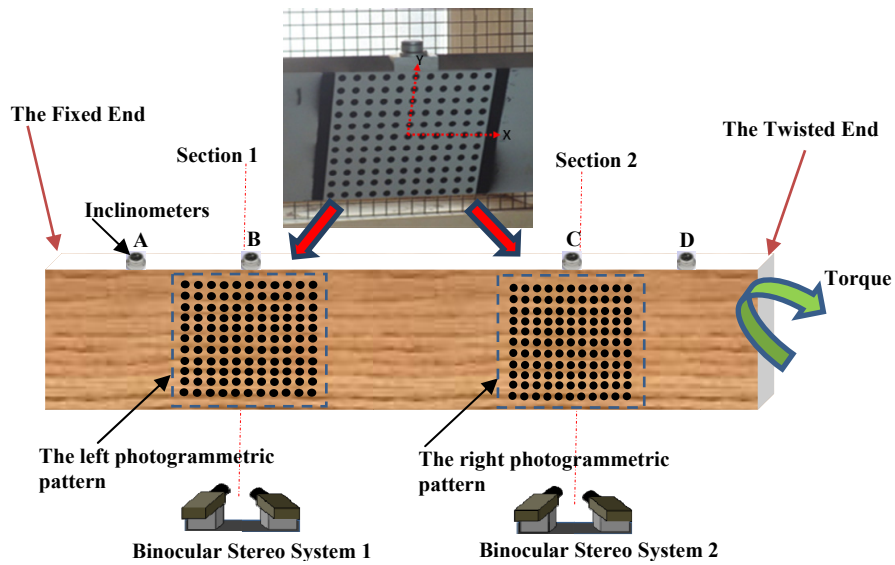
Figure 11: Schematic of the angular deformation sensors.
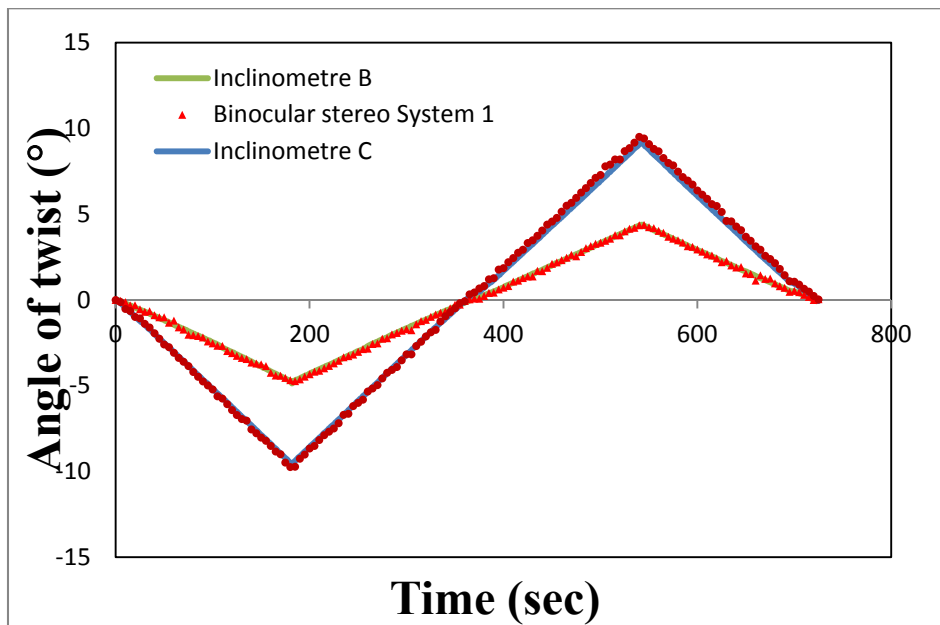

Figure 12: Comparison between inclinometers and optical measurements for sample 1 in the first trial torsion test.
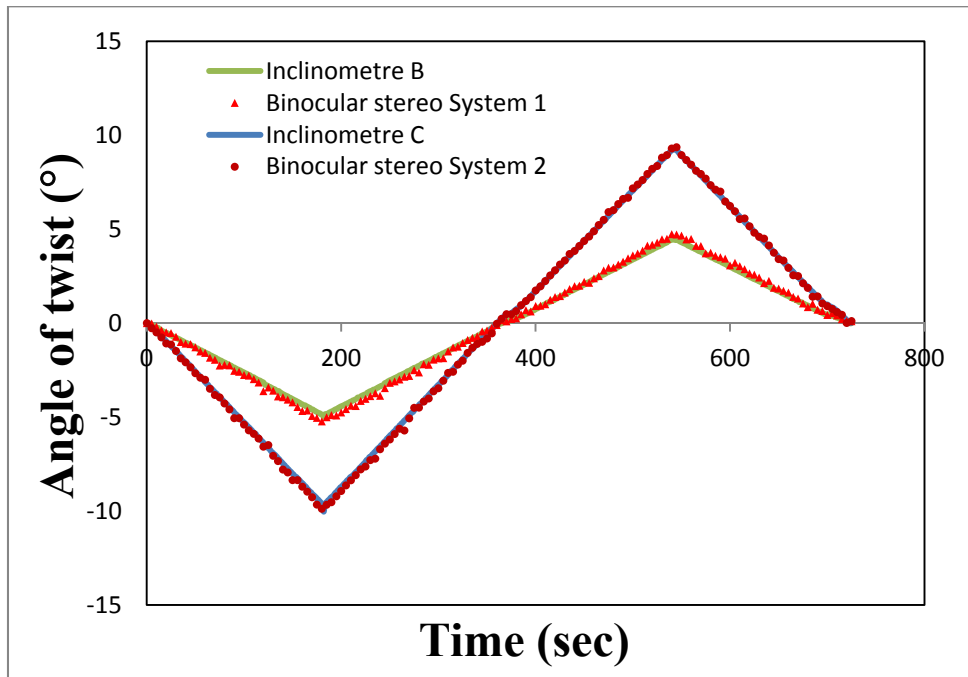
Figure 13: Comparison between inclinometers and optical measurements for sample 3 in the first trial torsion test.

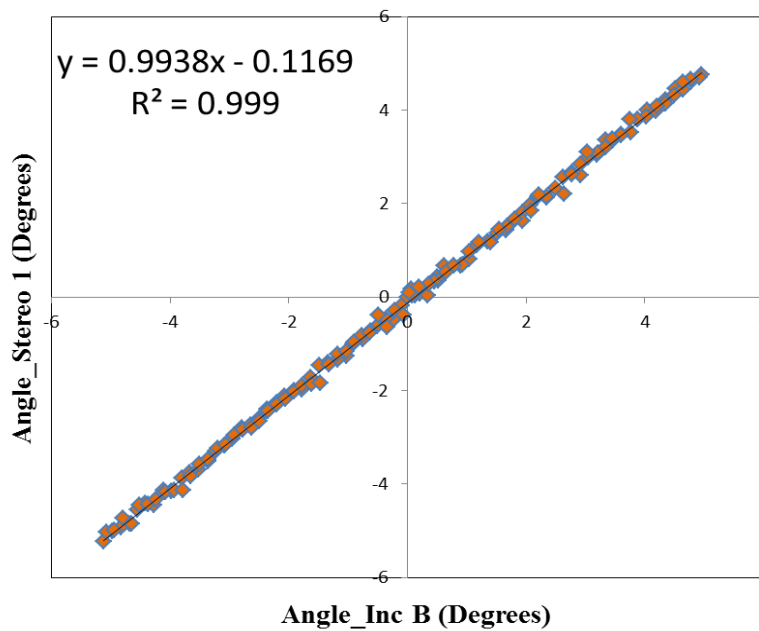$y = 0.9938x - 0.1169$
$R^2 = 0.999$

Figure 14: Comparison of the measurement results between inclinometer B and the first binocular system.

4.2 Relationship between Torque and Angle of Twist under different loading phases

Each sample was tested in torsion under torque loading and unloading applied in both clockwise and anticlockwise directions. The torque in addition to the relative rotational deformations was measured by of inclinometer B and C at two sections, 1 and 2 over a gauge length, l_2. Using these data, the relationship between torque and relative angle of twist per unit length is shown in Figure 15 and 16. The linear regression of the data was established in the linear part of curve in this graph to determine the magnitude of the torsional stiffness. The torque stiffness was determined using a linear regression equation and can be used together with St Venant torsion constant to calculate the value of shear modulus [1].

Figure 7 shows the torsional stiffness calculated at each loading phase. From these comparisons it is evident that the torsional stiffness calculated at each loading phase is very closely related to each other. It is clear that twisting timber specimens in either clockwise or anti-clockwise direction does not has substantial influence on the torque stiffness and hence the shear modulus. It was also observed that loading and unloading in either of the two directions does cause only a fundamental influence on the torque stiffness.

5   Conclusions

Compared to other experimental methods for determining the value of shear modulus, the torsion test has an advantage that it is the only method which induces a pure state of shear on the test specimen. The torsion test method may be a better approach to determine the shear properties of structural-size timber-composite materials. The difficulty in measuring reliable angular deformation using torsion testing machines, such as Tinius Olsen Machine, directed us to develop the photogrammetric approach for this type of measurements. The proposed method provides a cost effective and non-contact method for determining reliable torsional deformations at multi-locations of the torsion specimen, which may assist in understanding the behaviour of the torsion specimen under torsional loadings. This technique overcomes the limitations of the traditional contact devices which only measure the angular deformation on restricted number of points of the surface of the torsion specimens and can be destroyed during destructive tests.

This research describes the proposed photogrammetric approach and investigates its ability to determine possible deformation of the surface of the timber specimens under torsional loadings. To determine the rotational deformations of glulam beams in the regions of interest, this technique involves calibrating the stereo camera systems and then taking images of the torsion specimens before and after the rotational deformation has occurred. The use of image data and the calibration parameters of the stereo systems enable the determination of the shear modulus, G, of the samples.
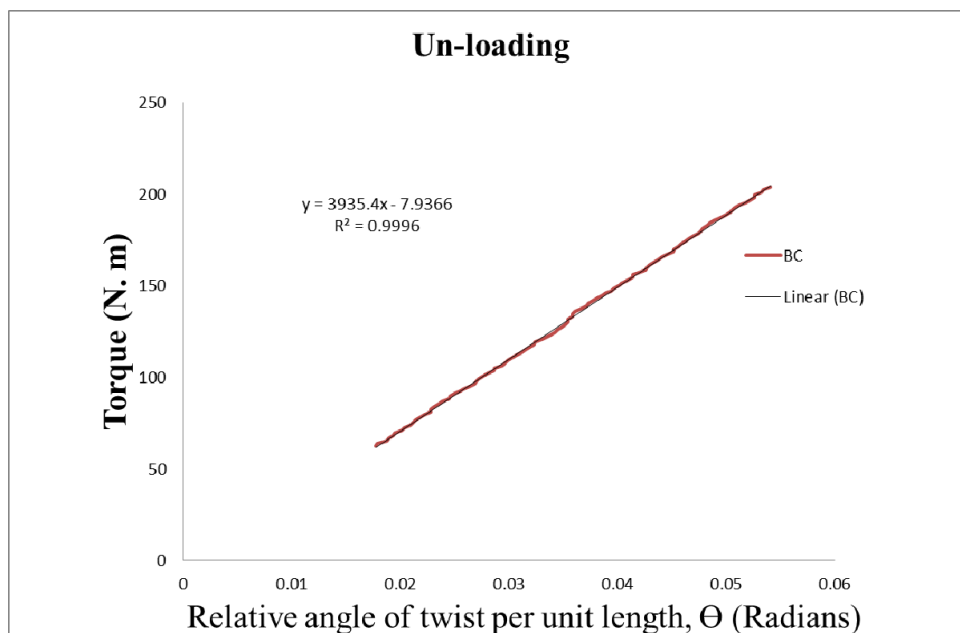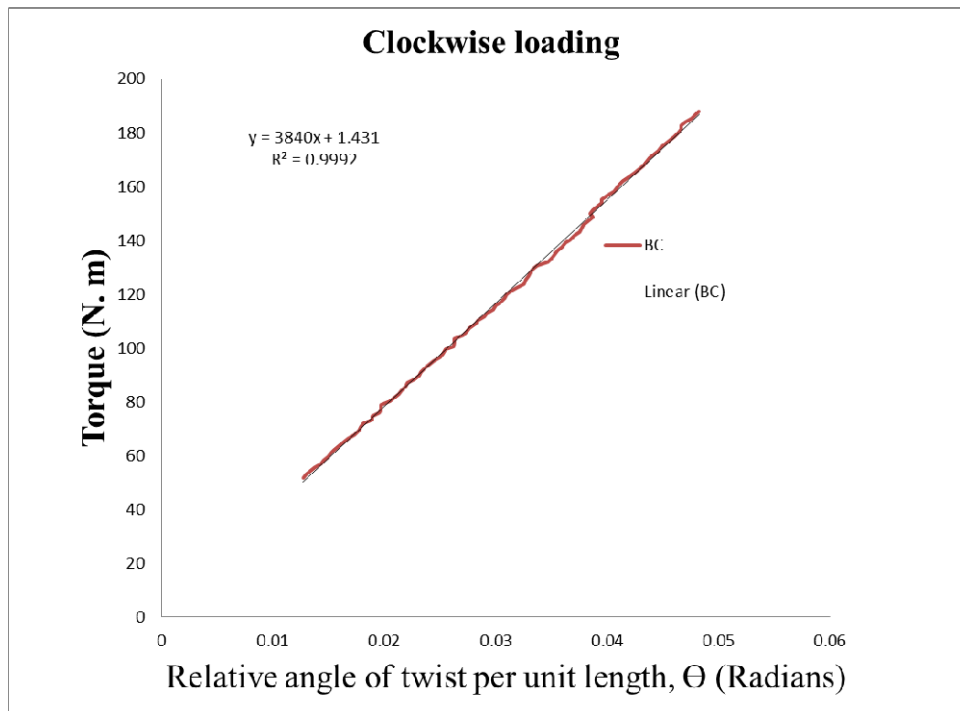
Figure 15: Torque-twist plot of the sample HT002 subjected to torques applied in a clockwise direction under torque loading (top) and unloading (bottom) phases.
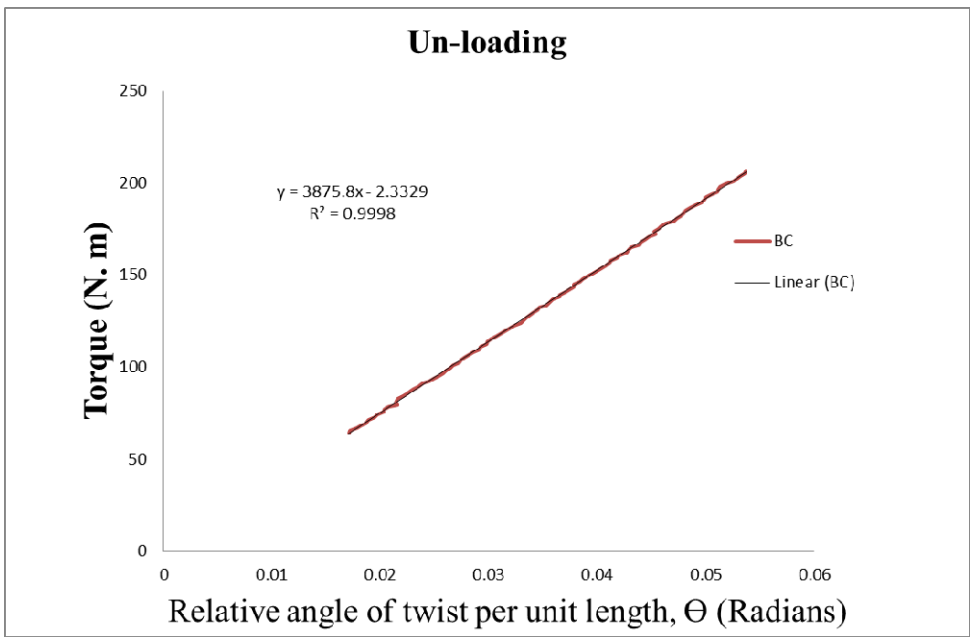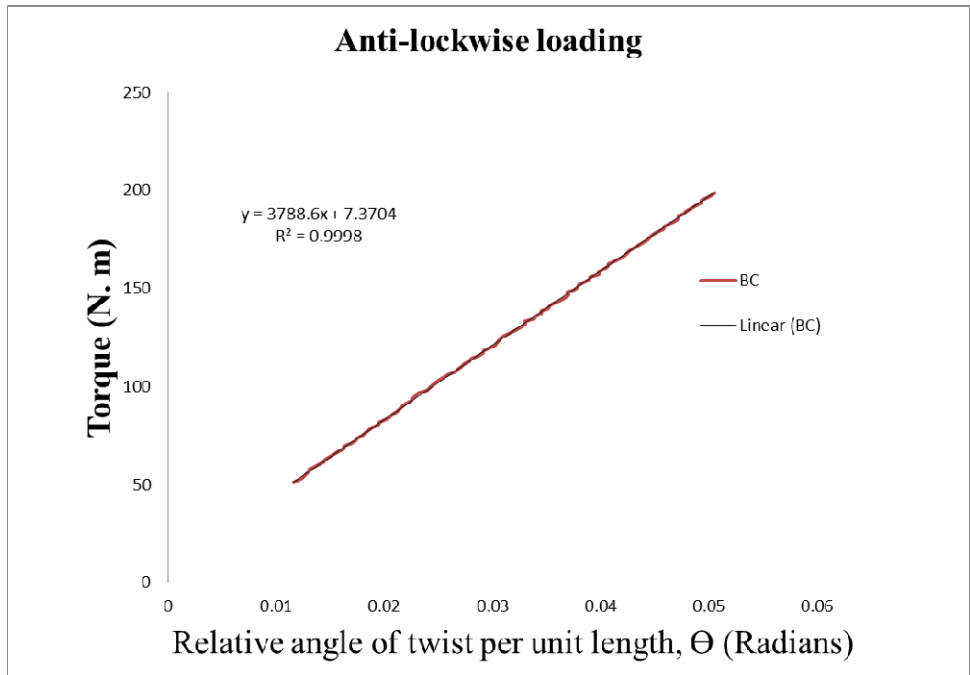
Figure 16: Torque-twist plot of the sample HT002 subjected to torques applied in an anticlockwise direction under torque loading (top) and unloading (bottom) phases.

The torsion test was conducted on the full-size glulam beams to determine their response to torsional loading and unloading phase in the clockwise and anticlockwise directions. The test results showed applying torques to timber specimens in either clockwise or anti-clockwise direction does not influence the torque stiffness and hence the shear modulus. It was also observed that loading and unloading in either of the two directions does cause a significant change on the torque stiffness.

The performance of the developed approach on measuring the actual angles of twist of the torsion specimen was evaluated by comparing the angular data recorded by inclinometers with those calculated utilizing the photogrammetric targets acquired by the stereo camera systems. A good agreement established between the two methods. The results showed that the contact-free measurement systems not only allowed evaluating the performance and reliability of inclinometers but also allowed monitoring the torsional deformations of the samples at various locations by providing more information which would not be possible to obtain using the traditional techniques.

References

[1]   EN 408:2010 Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties, CEN, Brussels, 2010.

[2]   Forest Products Laboratory. Wood handbook: wood as an engineering material, United States Government Printing, 1987.

[3]   Gupta, R., Heck, L. R. & Miller, T. H. Experimental evaluation of the torsion test for determining shear strength of structural lumber. Journal of testing and evaluation, 30(4), (2002): 283-290.

[4]   Gupta, R., Siller, Tobias. Shear strength of structural composite lumber using torsion tests. Journal of testing and evaluation, 33(2), (2005): 110-117.

[5]   Hindman, D., Manbeck, H. B. & Janowiak, J. J. Torsional rigidity of rectangular wood composite materials. Wood and fibre science, 37(2), (2005): 283-291.

[6]   IS-2-30_Inclinometer-Sensor, available from
       http://www.leveldevelopments.com/PDF_Documents/IS-2-30_Inclinometer Sensor.pdf   [accessed 11/04/2013].

[7]   Khokhar, A., Zhang, H. & Ridley-Ellis, D. Shear strength of timber joists obtained from torsion tests. WG meetings COST Action E53-Quality Control for Wood and Wood Products, 2009, Lisbon, Portugal.

[8]   Khokhar, A., Zhang, H., Ridley-Ellis, D. & MOORE, J. Year. The shear strength, and failure modes, of timber joists obtained from the torsion test method. In: Proceedings of the 11th World Conference of Timber Engineering, 20-24th June, Riva del Garda, Italy, 2010.

[9]   MVTech Software GmbH. Halcon. The software for Machine Vision Applications. http:// www.mvtech.com/halcon/

[10] MVTech Software GmbH 2010. Halcon 11.0 - the Power of Machine Vision - HDevelop User's Guide, München, Germany.

[11] R. Hartley and A. Zisserman. Multiple View Geometry in Computer Vision. Cambridge University Press, 2003.

[12] Torsion tester--Tinius Olsen, available from http://www.tiniusolsen.com/pdf/Torsion-Testers.pdf [accessed 11/04/2013]

[13] Zhang, H., Mohamed, A., Smith, I. & Xiao, Z. Evaluation of shear constant of timber glulam composite with photogrammetric approach. The 13th International Conference on Civil, Structural and Environmental Engineering Computing. Crete, Greece,2011.