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End effect on determining shear modulus of timber beams in torsion tests

N. Gharavi [a], H. Zhang [a,*], Y. Xie [b], T. He [c]

[a] School of Engineering and Built Environment, Edinburgh Napier University, 10 Colinton Road, EH10 5DT, UK
[b] Key Laboratory of Bio-based Material Science and Technology (Ministry of Education), College of Material Science and Engineering, Northeast Forestry University, 26 Hexing Road, Harbin 150040, China
[c] Department of Civil Engineering Shanghai Normal University, 100 Haisi Road, Fengxian District, Shanghai 20141, China

HIGHLIGHTS

- Identified the minimum gauge to end distance in the torsion test for timber beams.
- Propose a guideline for determining the minimum gauge to end distance.
- Develop non-destructive and non-contact photogrammetry technique for torsion test.

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ABSTRACT

The end effect plays an important role in determining where the rotation measuring gauges should be located in a torsion test. A thorough review on the impact of end effect in a torsion test has been conducted, followed by an experimental validation. A close-ranged photogrammetric method using binocular stereo vision technique was employed in this study. The results have indicated that the end effect has a great impact on a region of 1.5 times the cross-sectional depth of the beam from the supports. Therefore, the distance between the gauges and the supports as specified in BS EN 408:2010+A1:2012 for the torsion test setup is not sufficient for the beams with slender cross-sections. This research has also indicated that it is more appropriate to use the depth of the beam as the referencing dimension to specify this required minimum distance.

1. Introduction

The end effect plays an important role in the torsion test when determining the gauge distance, i.e. the distance that the gauges should be located away from the supports. Insufficient distance will bring an unnecessary error into the measurement, while an excessive distance will create difficulties and inconveniences for the test setup. Hence, it is fundamentally important to investigate the end effect in this type of mechanical test. According to Saint-Venant's Principle, when testing structural-sized samples the gauge sections should be located at a certain distance away from the supports or loads, where, the stress and strain in the beam are uniform and the end effect is negligible [1,10,12]. In the case of isotropic materials, studies by Horgan and Carlsson [12], Horgan [11] and Choi and Horgan [5] have shown that Saint-Venant's end effect can be neglected at a distance approximately equal to the cross-sectional depth of the beam. However, in terms of orthotropic or transversely isotropic materials, where the longitudinal modulus of elasticity (E_L) is far greater than its tangential (E_T), radial modulus of elasticity (E_R) and shear modulus (G_{LT}), the latter authors proposed that the stresses (τ) decay exponentially from the location of the support or load as follows,

$$\tau \sim Ce^{-kX} \tag{1}$$

where, $k \approx \frac{2\times\pi}{h}(G_{LT}/E_L)^{1/2}$ is the decay rate; X is the location from the support or load; C is a constant; and, h is the cross-sectional depth. Horgan and Carlsson [12], Horgan [11] and Choi and Horgan [5] proposed that the characteristic decay length (λ^*) can be determined by:

$$\lambda^* = ln(100)/k \approx ln(100)\frac{h}{2\times\pi}\left(\frac{E_L}{G_{LT}}\right)^{1/2} \tag{2}$$

* Corresponding author.
E-mail addresses: n.gharavi@napier.ac.uk (N. Gharavi), j.zhang@napier.ac.uk (H. Zhang), yxie@nefu.edu.cn (Y. Xie), taohe@shnu.edu.cn (T. He).

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According to BS EN 338:2016: Structural Timber – Strength Classes [4], for most of the structural timber classes for softwood, the mean longitudinal modulus of elasticity (E_L) ranges from 0.7 to 16 GPa, while, the mean shear modulus ranges from 0.44 to 1.00 GPa. Using Eq. (2), it can be estimated that the decay length of the end effect is between 1.8 and 3 times the cross-sectional depth (h) of the specimen.

The discrepancy identified indicates that the recommendation detailed in BS EN 408:2010+A1:2012: Timber structures – Structural Timber and Glued Laminated Timber – Determination of some Physical and Mechanical Properties [3], Clause 11.1.2 for the torsion test has limited consideration of Saint-Venant's end effect on the rotation measurements of a beam, especially for beams with a high cross-sectional aspect ratio (h/b, where h depth and; b thickness of the beam). According to this standard, the rotations should be measured at a distance of two to three times the cross-sectional thickness (b) from the supports or loads. This specification is provisionally accepted for beams with low cross-sectional aspect ratios, such as a square section. However, the most commonly used timber beams in construction have slender cross-sections with aspect ratios of 3–5. For these types of sections, the specified setup is clearly too close to the supporting or loading points which introduces unnecessary error in the rotation measurement.

Gupta et al. [8] conducted a finite element analysis of stress distribution on a timber beam subjected to a torque at one end. Their study indicated that a distance of two times the cross-sectional depth, plus the grip distance needs to be excluded from both ends of the beam in order to obtain a uniform shear stress distribution. Compared to the distance recommended by BS EN 408 [3] there is a significant difference for beams with slender cross-sections. The torsion test is widely recognised as a suitable test method for evaluating the shear properties of the timber beams as it creates a perfectly pure shear status in the specimen [16,7,6,9,13], therefore, it is important to investigate how the end effect propagates from the ends of the beam. To provide proper guidelines for the industry in measuring the shear properties using the torsion test method, there is a need to better understand the Saint-Venant's end effect in torsion test. The aim of this study is to experimentally evaluate the propagation of this effect along the beam using a tailor-made and close-range photogrammetric technique. To achieve this aim, two objectives were targeted as follows:

1. To evaluate the end effect in a torsion test method when determining the shear modulus of a timber beam and to improve the current practice adopted by the industry;
2. To develop a state-of-art photogrammetric technique for determining the shear modulus using torsion test method and to circumvent the limitation of the test setup recommended by the current code of practice.

Compared to the proposed photogrammetric technique, the conventional inclinometers or modified inclinometers as indicated in BS EN 408 [3] possess several limitations. For instance, they are limited to record only the rotation of a specific plane at a predetermined location. Hence, it is difficult to use these types of devices/designs to measure the distribution of the rotation on a specimen during the test. Therefore, a more advanced and accurate close-range photogrammetry technology based on stereo vision was employed to capture this rotation. Using the triangulation algorithm, the displacement of any point in the cameras' field-of-view can be measured with two or more sets of photos taken before and after the loading. A well-known method for acquiring the 3-D coordinates of an object is Binocular Stereo Vision. This is a passive triangulation technique where two images taken from two different viewpoints are analysed to extract a depth map of the scene [15,17]. This system is similar to simplified human visual perception. Unlike the early version of this system where some setups are very strict, such as the cameras having to be mounted exactly parallel to each other, the most up-to-date system offers more flexibility and is capable of handling the camera/lens imperfections more easily.

2. Materials and methods

2.1. Materials

With a view to that the cross-sectional aspect ratio is an important parameter in determining the impact of the end effect, 12 timber beams with the aspect ratios ranging from 1 to 4.89 were selected and tested. All beams are rectangular, structural-sized and kiln dried with a testing length of at least 19 times the largest cross-sectional dimension. Based on BS EN 408 [3], the samples were conditioned at the standard environment of 20 °C ± 2 °C and 65% ± 5% relative humidity for about four weeks before testing. The moisture content of the samples was measured in accordance with BS EN 13183-1:2002, Moisture content of a piece of sawn timber. Determination by oven dry method [2], the results and beams specifications are presented in Table 1.

2.2. Methods

In the example of the torsion test setup, illustrated in BS EN 408 [3], the gauges and rotation measuring system are not well designed. The circular gauge may not rotate the same angle as the specimen due to the possible warping in the cross-section (Fig. 1). In addition, the LVDTs used in the system will not be able to handle a slightly larger rotations. Therefore, there is a need to develop a more suitable method to overcome the above limitations.

2.2.1. Stereo vision system

Humans and most animal's visual perception are through a highly sophisticated 3D vision system. The binocular stereo vision system is able to compute disparity, distance and 3D coordinates of any object by simulating the human eyes. In this system, two cameras simultaneously capture the images of an object from different positions and angles [14]. The basic principle behind the employed binocular stereo vision is illustrated in Fig. 2.

In the Fig. 2, assume $oxyz$ is the cameras coordinate systems (CCS), XOY is left and right image coordinate system and f is the effective focal length, which is the distance between camera coordinate system (lenses) and image coordinate system (image sensor within the camera). Parameters that are related to left and right images are subscripted by l and r, respectively. For convenience,

Table 1
Material information.[a]

Nominal dimensions						
b [mm]	h [mm]	L [m]	QTY	A.R.	M.C. [%]	Specie
95	95	1.9	2	1	12.8	RP
45	95	1.9	2	2.11	10.4	RP
75	225	4.3	2	3	11.2	WW
45	170	3.4	2	3.78	10.4	WW
45	195	3.9	2	4.33	12	RP
45	220	4.3	2	4.89	12.5	WW

[a] A.R. = Aspect Ratio (h/b); M.C. = Moisture Content; RP = Redwood (Pine); WW = WhiteWood (Spruce).