APPLICATION OF DIGITAL SPECKLE CORRELATION METHOD FOR EXAMINING DEFORMATION BEHAVIOUR OF MOSO BAMBOO (*PHYLLOSTACHYS PUBESCENS*)

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LI XZ, REN HQ, ZHOU QY & ZHONG Y. 2013. Application of digital speckle correlation method for exmining deformation behaviour of moso bamboo (*Phyllostachys pubescens*). We studied the deformation behaviour of bamboo under loading. Modulus of elasticity (MOE) in tension parallel to grain with respect to age, damage behaviours during tension and compression loading of moso bamboo (*Phyllostachys pubescens*) were recorded via digital speckle correlation method (DSCM). DSCM could be successfully used in determining MOE because the differences in results compared with those obtained using conventional extensometer were within 5%. MOE in tension parallel to grain obtained by DSCM maintained an increasing trend with increasing age. During the tension and compression processes, samples had large strain concentrations and gradients before damage. Since DSCM could be used in advance for reflecting damage behaviours and predicting failure site, it was possible to show the whole complex damage process.

Keywords: DSCM, modulus of elasticity (MOE), extensometer, dynamic damage, tension, compression

LI XZ, REN HQ, ZHOU QY & ZHONG Y. 2013. Penggunaan kaedah korelasi bintik digital untuk mengkaji kelakuan kerosakan buluh *Phyllostachys pubescens*. Kami mengkaji ciri ubah bentuk buluh yang dikenakan bebanan. Modulus kekenyalan (MOE) dalam keadaan tegangan selari ira bagi buluh *Phyllostachys pubescens* direkod menggunakan kaedah korelasi bintik digital (DSCM) berdasarkan usia, kelakuan kerosakan semasa tegangan serta mampatan beban. DSCM dapat diguna dengan jayanya untuk menentukan MOE kerana perbezaan antara keputusan yang diperoleh menggunaan kaedah ini tidak melebihi 5% berbanding dengan kaedah ekstensometer konvensional. MOE dalam tegangan selari ira yang diperoleh menggunakan DSCM menunjukkan trend meningkat apabila usia buluh bertambah. Semasa proses tegangan serta mampatan, sampel menunjukkan tumpuan terikan serta cerun yang besar sebelum rosak. Memandangkan DSCM dapat diguna lebih awal untuk menggambarkan kelakuan kerosakan serta meramal kawasan kegagalan, seluruh proses kerosakan dapat ditunjukkan.

INTRODUCTION

Bamboo is one of the most important non-timber forest resources in many tropical and subtropical countries. Its fast growth rate, high strength and stiffness, easy machinability and local availability have made bamboo a widely used traditional material. Recently, bamboo has gained increasing attention as an alternative structural material to wood or wood-based materials. To maximise the utilisation of bamboo, many studies have been performed on its fundamental anatomical, physical and mechanical properties.

Electrical measurement is a traditional method for determining wood deformation. Although it shows high maturity in mechanical determination, total information on deformation could not be obtained since it is based on point measurement. Therefore, there are certain limitations in wood mechanical researches. With the development of computer technology, optoelectronics and digital image processing theory, the digital speckle correlation method (DSCM) has become an important method in experimental mechanics area (Sutton et al. 2000, Ma 2003). Besides its full-scale, non-contact and high precision, there are many other advantages such as simple optical measurement device, no special requirements on samples, and simple experiment procedures and data processing. Recently, DSCM was used for investigating deformation behaviours of rock (Ma 2004,

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Chen et al. 2005). This technology has also been introduced into wood science for the study of deformation behaviours of tension, compression and bending of wood or wood-based materials (Xu et al. 2003, Deng et al. 2010, Schoenmakers & Svensson 2011). All works showed that results from DSCM were precise and reliable.

In this experiment, we determined the modulus of elasticity (MOE) of 4-year-old moso bamboo (*Phyllostachys pubescens*) by conventional extensometer method. The MOE of bamboo of five ages was investigated using DSCM. In addition, the displacement movement of the whole tension and compression loading, which contributed to the deformation and the whole dynamic damage of tension and compression loading, was recorded in real time.

MATERIALS AND METHODS

Sampling

Moso bamboo culms were collected from an experimental forest located in Zhejiang Province, China. Five representative culms for each age group (0.5, 1, 2, 4 and 6 years) were harvested for this study. According to the national standard GB/T15780-1995 (Zhang et al. 1995), the 13th internode of each culm was selected as

experiment material after air-drying for three months. The dimension for tension test was 280 mm (longitudinal) × 10 mm (tangential) × T mm (radial) while that for compression, 20 mm × 10 mm × T mm. The tension sample was further processed as shown in Figure 1. All specimens were conditioned at 20 °C and 65% relative humidity until moisture content of approximately 10% was achieved.

The five-age groups of bamboo were measured for MOE in tension parallel to grain. Before the test, three pairs of markers were labelled near the outer, inner and middle layers of the culm on each sample (Figure 2). Moso bamboo aged 4 years was selected for dynamic damage analysis. Samples were sprayed with white paint in radial direction as the base colour, then sprayed black to form uniform distribution speckles. The samples were tested after the paint had dried completely.

Equipment

Mechanical test machine with accuracy of 0.5% and maximum testing force of 50 kN was controlled by a microcomputer. Loading speed was set at 0.3 mm min^{-1}. Experimental apparatus included a digital charge-coupled device (CCD) camera (resolution 1280 × 1024, frame rate 7.5 fps) and zoom lens (variable focus range
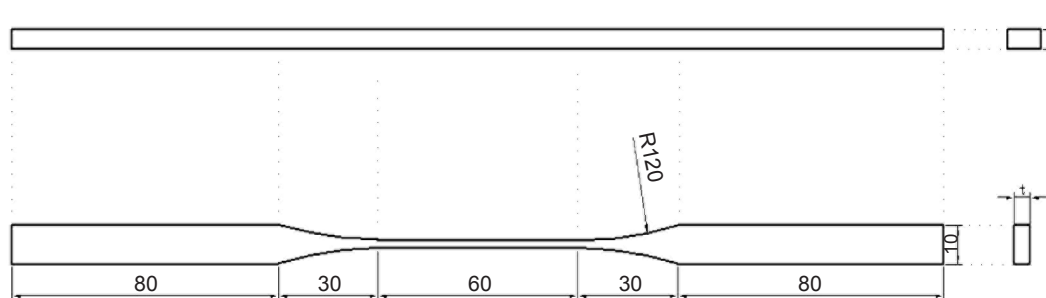

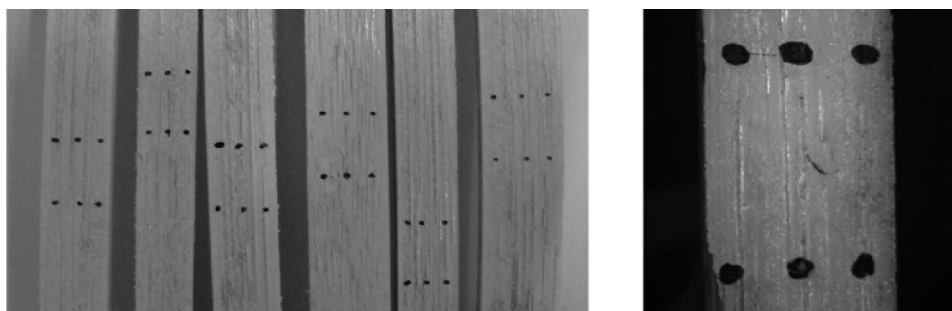**Figure 1**   Shape of tension specimen

Figure 2   Labelling of tension sample

17–102 mm). Images were taken from test areas of specimens using the effective-megapixel CCD camera which recorded real-time displacements in the whole process.

Principle of grey weighted centroid algorithm

The distance between the pair of markers was about 10 mm, which ensured that all markers were in the camera observing scope and allowed displacements to be recorded. Tension strains were calculated from displacement of each pair using the grey weighted centroid algorithm. Finally, MOE in tension parallel to grain of bamboo was determined according to the strains.

For grey weighted centroid algorithm, the grey scale of the digital image pixel was considered as density of the image and the marker at the centre of the image was considered as centroid. For a two-dimensional object, a closed surface area D was assumed in the coordinate system. If the surface density of the marker (x, y) was ρ (x, y), its centroid coordinate would be:

$$x_c = \frac{\iint\limits_D x\rho(x,y)dxdy}{\iint\limits_D \rho(x,y)dxdy}, y_c = \frac{\iint\limits_D y\rho(x,y)dxdy}{\iint\limits_D \rho(x,y)dxdy} \tag{1}$$

Assuming the size of the grey image area was M × N and the grey scale of each pixel was I(i, j), the centroid coordinate was defined as (2):

$$x = \frac{\sum\limits_1^{M\times N} i \cdot I(i \times j)}{\sum\limits_1^{M\times N} I(i,j)} \quad y = \frac{\sum\limits_1^{M\times N} j \cdot I(i \times j)}{\sum\limits_1^{M\times N} I(i,j)} \tag{2}$$

where M, N, i, j are all integers, 0 < i < m, 0 < j < n and I ranged from 0 to 255.

Tension strain determination

The applicability of the DSCM was verified prior to the experiment. Four-year-old bamboo was chosen for this validation test, done in triplicates. MOE in tension parallel to grain was calculated by stress and strain which were obtained by the grey weighted centroid algorithm. In addition, two extensometers with 50 mm retaining distances

were fixed at both sides of the sample. These were used for measuring the strain (Figure 3). Results from the two different methods were then compared.

The tension model of bamboo sample is shown in Figure 4. Strain was obtained by processing the two markers measured in the DSCM and conventional extensometers method. First, two closed surface areas (A and B) were chosen for the determination of their densities. Then, centroids of the two markers (x_A, y_A) and (x_B, y_B) were determined. Due to horizontal load, only the deformation in x direction was considered. The distance (l) and strain (ε) between the two grey weighted centroid algorithms were obtained according to the geometric relationships as shown in equations (3) and (4). The experimental design is shown in Figure 5.

$$l = l_2 - l_1 + X_B - X_A \tag{3}$$

$$\varepsilon = \frac{l' - l_0}{l_0} \tag{4}$$

where l' = distance after test and l_0 = distance before test.

RESULTS AND DISCUSSION

Analysis on validation test

Mean MOE values obtained using DSCM and extensometer method ranged from 11.7 to 15.6 GPa (Table 1). It has been reported that MOE in compression of *Pinus taeda* by DSCM and traditional method varied between 1 and 7% (Xu et al. 2003). This proves that both methods are reliable and can be used successfully. In the current research, differences between DSCM
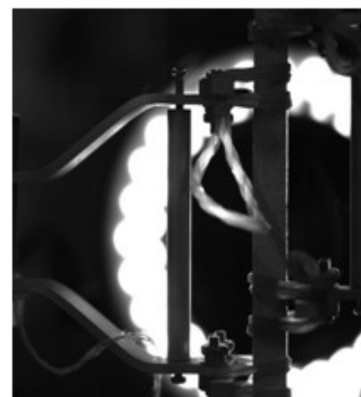

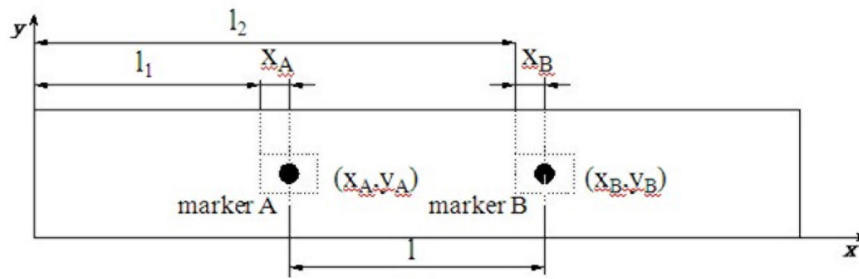**Figure 3**   Extensometers fixing on sides of sample

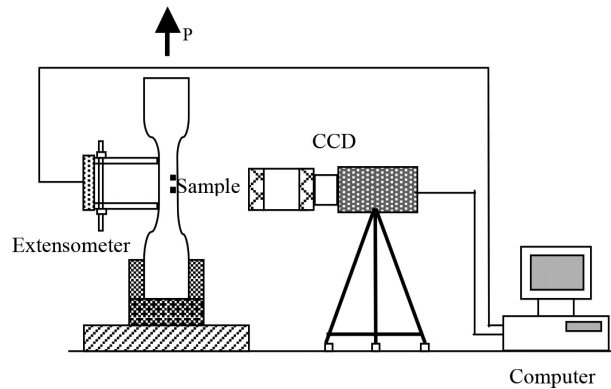**Figure 4**   The tension model of bamboo sample

Figure 5   Experimental design using extensometer for bamboo sample; CCD = charge-coupled device

Table 1   MOE values obtained using conventional and DSCM

Method/layer	MOE (MPa)		
	Outer	Middle	Inner
Extensometer	15601	-	12262
DSCM	14810	12268	11740
Error (%)	5.0%	-	4.2%

Data are means of three samples; DSCM = digital speckle correlation method, MOE = modulus of elasticity

and extensometer were within 5%, which fully validated that DSCM could be used for determining MOE. Therefore, only DSCM was used in the following experiments.

MOE in tension parallel to grain

MOE obtained by DSCM ranged from 9.40 to 12.2 GPa (Figure 6). Except for the 2-year-old bamboo, MOE was higher with increase in age. Similar trend was repored by Lin et al. (2002), Yu et al. (2004) and Ren et al. (2008). Lower MOE in the 2-year-old bamboo was due to off year for bamboo which resulted in weak growth and small

quantity of bamboo (Xu et al. 2008, Chen 2010). Diameter at breast height (dbh) of the 2-year-old bamboo was reported to be less than those of 0.5- and 1-year-old bamboos (Ren et al. 2008). The authors also concluded that MOE values obtained by DSCM were the same as those obtained by conventional mechanical testing method.

Dynamic damage of tension

Bamboo cell wall is mainly composed of three substances, namely, cellulose, hemicellulose and lignin. The property of bamboo is neither like elastic nor plastic material; instead it is
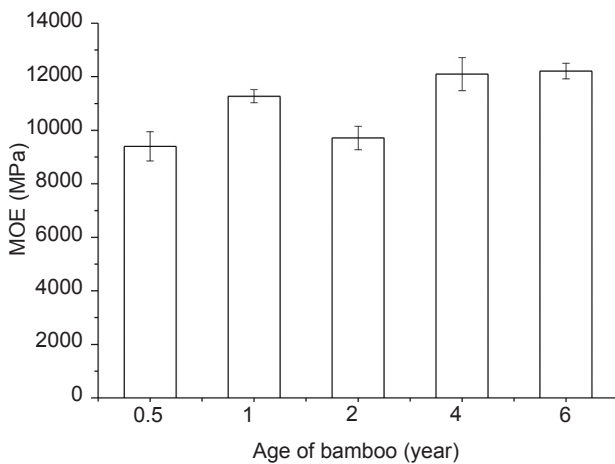
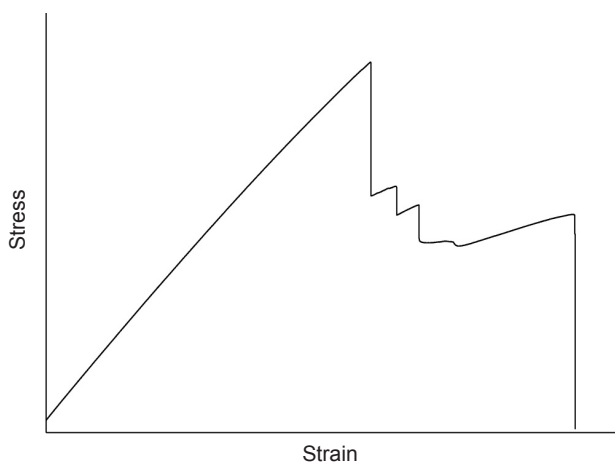**Figure 6** Trend in MOE at different ages; MOE = modulus of elasticity

Figure 7 The stress–strain curve of bamboo tension damage

a typical viscoelastic material. Although it is viscoelastic, the tension stress–strain curve shows brittle damage in tension test (Figure 7). The slippage between adjacent fibres led to tearing damage with needle-shaped cross-section. Initial subtle cracks perpendicular to the fibre appeared near the inner layers and increased with increasing load until vertical tearing occurred. Moreover, the horizontal tension that appeared within the tearing damage processes in longitudinal direction led to interfaces damage, shearing damage between parenchyma and vascular bundles simultaneously.

The irregular degree of damaged surfaces was dependent on the ratio of tension strength and shear strength parallel to grain. Generally, the higher the ratio, the more damage at the

inner layers and the more extremely irregular the damaged cross-section (Liu & Zhao 2004).

The whole damage process of the tension specimen, which changed with increase in loading is shown in Figure 8. The damage began at the edge of the inner layer of specimen and expanded inward gradually until the longitudinal tearing damage appeared (Figures 8e–j). The corresponding strain distribution of tension specimen is shown in Figure 9. There was low matching correlation coefficient because of the large displacement in longitudinal tearing damage (Figure 8j). Thus, the strain distribution was omitted.

Colour index in the strain distribution (colour changed from red to blue and strain decreased gradually) is shown in Figure 9. An even distribution of colour was observed in the initial stages (Figures 9a and b), which reflected low load, small deformation and absence of strain concentration in initial tension. When the load reached a certain value (which nearly equal the critical value of maximum load), the colour in the lower right corner turned red (Figure 9c). This indicated that the strain was higher at this point than other areas. Correspondingly, a subtle crack appeared at the lower right corner and the specimen was damaged. However, the damage was not visible in Figure 8c. The crack gradually expanded with constant loading (Figures 8d–j). Moreover, the strain concentration at the right corner was more obvious than the other areas (Figures 9c–j) where the specimen was damaged. It was concluded that strain distribution could reflect specimen damage in the tension process earlier than the naked eyes.

Dynamic damage of compression

Bamboo is made up of vascular bundles and parenchyma cells which form a unique structural characteristic. Therefore, analysis on compression phenomenon could be explained by composite material theory (Ren et al. 2007). In initial compression process, parenchyma and vascular bundles bear vertical pressure. Deformation is proportional to load where the curve increases in a linear upward trend. During this process, the parenchyma becomes the weak surface due to its low rigidity and the increasing load. Consequently, a horizontal compression band
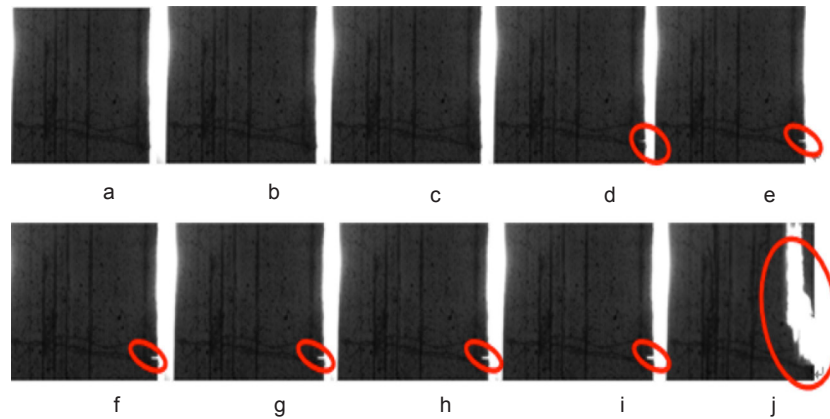
Figure 8   Crack extend images of bamboo dynamic tension sample; the right side is the inner layer and the left side is the outer layer of sample
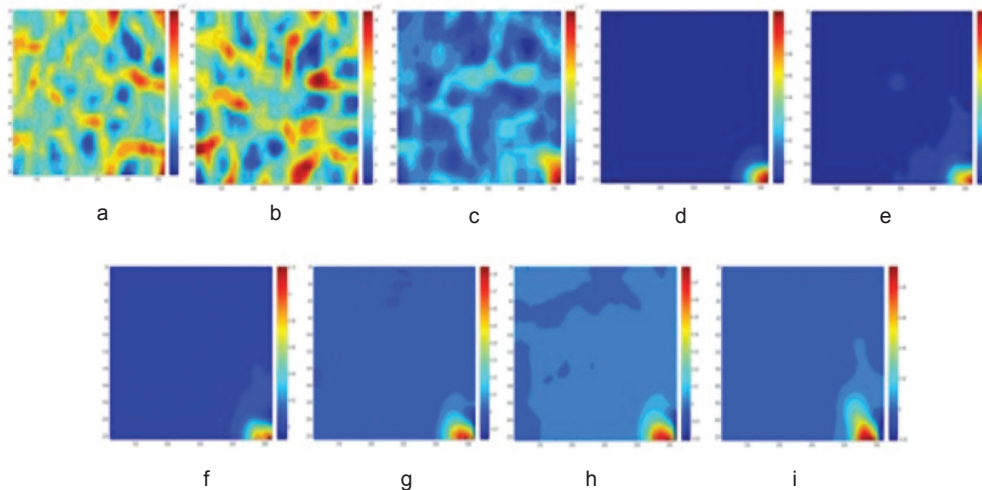

Figure 9   Strain field of dynamic tension specimen; the right side is the inner layer and the left side is the outer layer of sample; bar on the right side of each image is the colour index

called micro-compression wrinkle is formed. The wrinkle becomes more obvious with increasing load. With increasing load, the stress–strain curve showed a yield phase where the stress and strain were not in a linear relationship (Figure 10) and the growth rate of strain was faster than stress. When load is applied constantly, horizontal compression band will not experience further deformation, thus, a second linear increase is observed on the stress–stain curve (Jiang et al. 2000). However, the second linear increase was not observed in this experiment because a large deformation appeared when load reached a certain extent. A longer loading time might be required to achieve complete destruction of the specimen.

A total of 10 typical images were selected for compression damage analysis. The specimen did not show significant change (Figures 11a–c) in the initial compression stage. Distortion had taken place at the side of inner layers and became obvious with load increasing (Figures 11d and e). Moreover, the distortion of the inner layers caused crushing damage at the end of the specimen, so large stress concentration occurred at the outer layers on the interface of load head and specimen. In addition, strain near the inner layers was much more than that at the outer layers, thus, the compression surface inclined towards the inner layers. Therefore, tension internal stress appeared near the inner layer while compression internal stress appeared

near the outer layer. Due to the sparse vascular bundles, inner layer with weak carrying capacity was vulnerable to crushing. Furthermore, because vascular bundles decreased from outer to inner layers in specimen wall thickness direction, the specimen produced tangential shearing damage gradually with load increasing. From microscopic images, some single, dystopic and crack-like thin lines appeared on fibre cells (Liu & Zhao 2004). The number of lines increased with increasing load until a criss-cross reticulate pattern was formed. The shearing damage that appeared along the direction of thin lines contributed to distortion of cell wall (Liu & Zhao 2004). At the end of experiment, the whole specimen was distorted. Accordingly, it was concluded that damage was attributed to the accumulation of strain. When accumulation extent reached its

bearing capacity, damage would appear at some part of the sample.

Subimages of Figure 11 are given in Figure 12. There were no significant changes at the beginning of the experiment (Figures 11a–c), which corresponded with the stages of Figures 12a–c. The uniform blue colour in the whole distribution in Figure 12a and b indicated small and uniform strain. Figure 12c shows a lighter colour to reflect that strain has begun to increase. Slight distortion was found at the top left corner of the specimen during loading (Figure 12d). Distortion became obvious with increasing load (Figures 12e–j). The colour at the top left corner in the stain field turned to red gradually, which indicated that strain was increasing in the region until the specimen damaged.

CONCLUSIONS

MOE in tension parallel to grain increased with increasing age. Deformation behaviours of tension and compression were quite complex, which attributed to complicated dynamic damage modes. In tension process, initial subtle cracks perpendicular to the fibre appeared near the inner layers and increased with the increasing load until vertical tearing occurred. In compression process, crushing damage mainly occurred at the end of the specimen and sample was distorted near the load header. It was concluded that DSCM could reflect specimen damage in advance and predict the damage site of the sample.
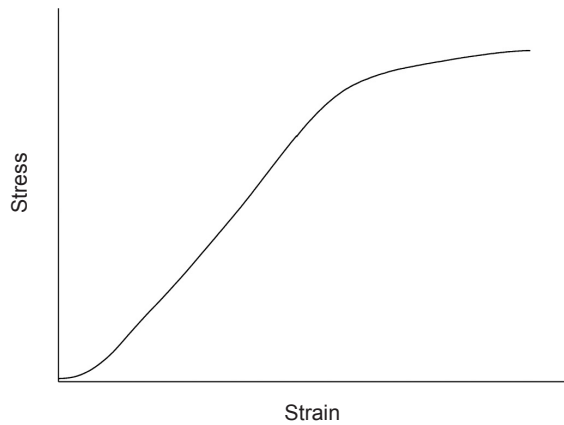

Figure 10   Stress–strain curve of bamboo compression damage
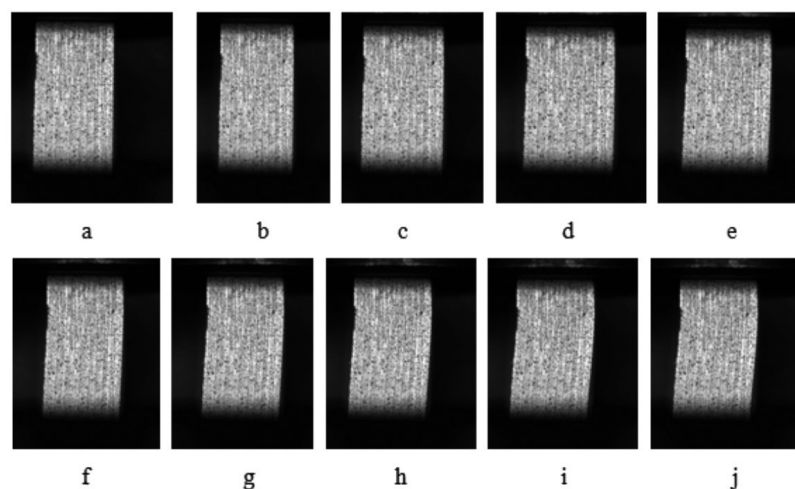

Figure 11   Distortion images of bamboo dynamic compression sample; the right side is the outer layer and the left side is the inner layer of sample
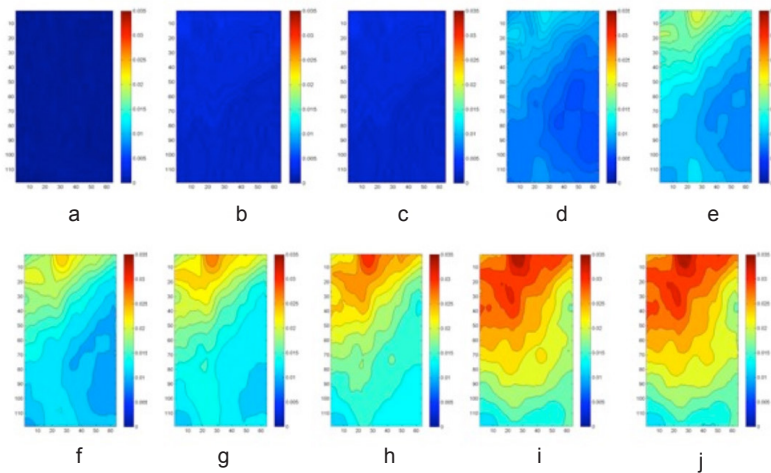
Figure 12   Strain field of dynamic compression specimen; the right side is the outer layer and the left side is the inner layer of sample; bar on the right side of each image is the colour index

The application of DSCM in the conventional mechanical testing for moso bamboo gave significant important results which would benefit our understanding of mechanical properties of bamboo and solve some practical problems in processing techniques. Non-uniform feature of wood and bamboo require special test methods. DSCM is reliable in determining mechanical parameters and properties of biomass materials.

ACKNOWLEDGEMENTS

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