Water vapour diffusion resistance factor of *Phyllostachys edulis* (Moso bamboo)

Puxi Huang[1], Eshrar Latif[2], Wen-Shao Chang[3], Martin P. Ansell[4], Mike Lawrence[5]

Abstract

This study measured the water vapour diffusion resistance factor of the Moso bamboo specimens in all directions of the cylindrical coordinate system at both internode parts and node parts. The measurement was conducted by the dry cup method. Major findings included three aspects. The water vapour diffusion resistance factor results of Moso bamboo specimens present a decreasing trend from the external surface to the internal surface in the radial directions. This fact may be attributed to the more densified fibre cells and low quantity of pits at the external surface. The water vapour diffusion resistance factor of bamboo specimens is remarkably lower in the longitudinal direction than in the radial and tangential directions. The large diameter, high interconnectivity and straight structure of the vascular bundle vessel influence the lower water vapour diffusion resistance factor in the longitudinal direction. The majority of the node specimens demonstrated lower water vapour diffusion resistance factor values than the internode specimens in the radial and tangential directions. The irregular orientation of vascular bundle vessels in different directions can be considered as the reason.

Keywords: Water vapour diffusion resistance factor, vapour permeability, Bamboo

1. Introduction

This study measured water vapour diffusion resistance factor of *Phyllostachys edulis* (Moso bamboo) specimens in the three directions of the cylindrical coordinate system. The strengths of bamboo as a biological building material are fast reproductive capacity and competitive thermal and mechanical properties (Van Der Lugt et al. 2006, Flander and Rovers 2009, Majumdar et al. 2010). Bamboo is used as a construction material in Fareast. Using natural material to minimise environmental impact has proved to be an effective strategy in the building industry (Bribian 2011). Especially for building envelope components, the application of natural materials not only focuses on neutralising the embodied energy during the construction period but also aims to reduce the operational energy consumption during the building serving period. To evaluate the thermal and hygroscopic performance of a building material, the knowledge of heat and moisture transfer is indispensable. Moisture transfer often interacts with heat transfer for building materials. The adsorption isotherm, desorption isotherm and water vapour permeability or resistance are essential inputs for the numerical simulation of moisture transfer mechanism. Better understanding of moisture transfer mechanisms of building materials is important in terms of assessing the equivalent thermal resistance, the condition under which mould will grow and expansion will happen.

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The water vapour diffusion resistance factor is the ratio of the water vapour permeability of the air to the water vapour permeability of the specimen. The water vapour permeability of the air can be regarded as a constant if the temperature is known. Therefore, to calculate the water vapour diffusion resistance, the value of water vapour permeability of the specimen is required. The water vapour permeability of the specimen is the water vapour diffusion coefficient with vapour pressure as the driving potential in Fick's laws of diffusion (Time 1998). The physical definition of the water vapour permeability is the quantity of water vapour transmitted per unit time through a unit area of the material per unit of vapour pressure (BS EN 12086:2013).

The water vapour permeability data of bamboo is insufficient in the literature compared with related research on wood. Most of the water vapour permeability research on bamboo currently focuses on knitted fabrics rather than bamboo for construction (Majumdar *et al.* 2010, Prakash *et al.* 2011). The water vapour permeability of heat treated bamboo fibre and high density polyethylene composites has been reported by Du *et al.* (2014). The water vapour permeability of Swedish pine and spruce was investigated in the radial, tangential and longitudinal directions of the log (Wadsö *et al.* 1993). The density variation was considered in a research on the water vapour permeability of wood in the radial and tangential directions (Carmeliet and Derome 2008). The water vapour permeability values of wood fibre, wide-ring wood, narrow-ring wood and oriented strand board were measured by both dry cup and wet cup method (Vololonirina *et al.* 2014). The design values of water vapour permeability for general building materials can be found in a standard (BS EN 12524:2000).

The water vapour permeability of bamboo has not been measured in the three directions of the cylindrical coordinate system. A previous study noted that a density gradient exists in the radial direction of bamboo (Huang *et al.* 2015). This density gradient may lead to a variation in the water vapour permeability. The aim of this paper is to investigate the water vapour permeability or water vapour diffusion resistance factor of Moso bamboo in both internode and node specimens. A basic physical property database has been created for the numerical study of the coupled heat and moisture transfer through Moso bamboo specimens. As a result moisture movement mechanisms within bamboo panels may be elucidated when the spatial arrangement of the raw materials is considered.

2. Methodology

2.1 Specimen preparation and water vapour diffusion resistance factor measurement

Fig 1 illustrates the cutting position of specimens. The radial direction refers to the direction of the bamboo culm wall thickness. The longitudinal direction is the bamboo vertical growing direction. The tangential direction is along the radian direction of the bamboo culm wall. Three types of cylindrical specimens were prepared for water vapour permeability measurement. The measurement direction is perpendicular to the circular surface. For example, the tangential-longitudinal surface is perpendicular to the radial direction. The cylindrical specimen with circular tangential-longitudinal surface is the specimen for the radial direction measurement of water vapour permeability because the water vapour is transmitted in the radial direction. The cutting position is described in detail in Figs. 2, 3 and 4.
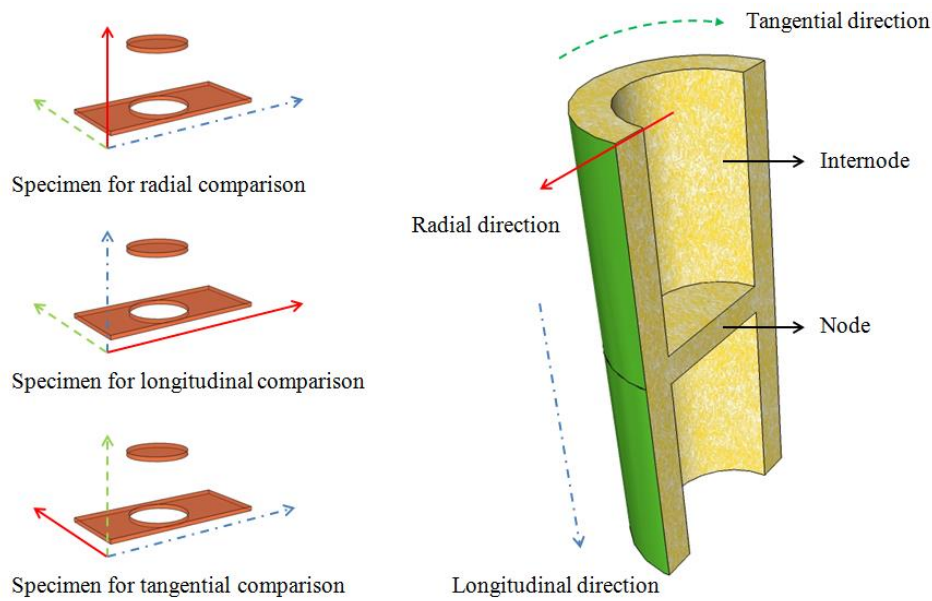

Fig 1. Nomenclature for a bamboo culm and orientation of specimens

In the radial direction (Fig. 2), specimens were cut from internode and node position respectively. Three cutting positions are defined as internal, middle and external positions from the internal surface to the external surface of the bamboo culm wall. Five specimens were prepared for each position. These specimens were prepared to demonstrate the water vapour permeability trend of the bamboo in the radial direction.
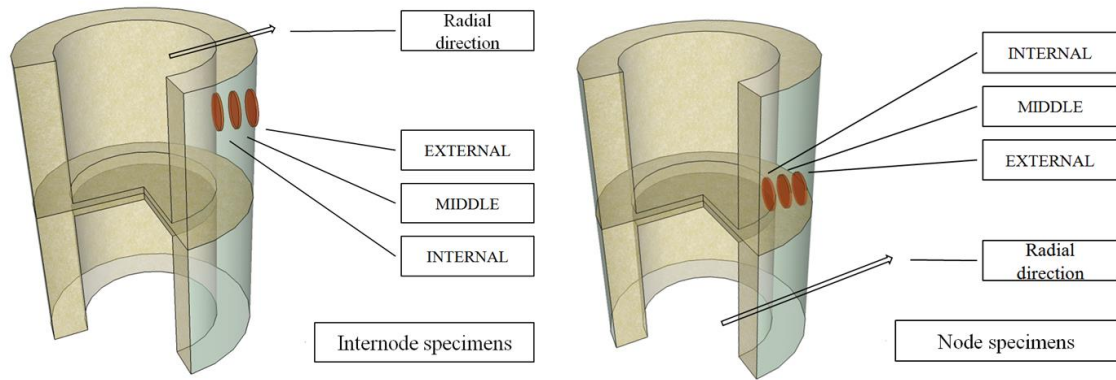
Fig 2. The cutting position of bamboo specimens in the radial direction

In the tangential direction (Fig. 3), specimens were designated Nos.1 to 4. The interval of two adjacent cutting positions is 90°. Five specimens were prepared for each position. The middle point of the node specimens were aligned with the node line of the bamboo culm wall. These specimens were utilised to identify the water vapour permeable trend of the bamboo in the tangential direction.
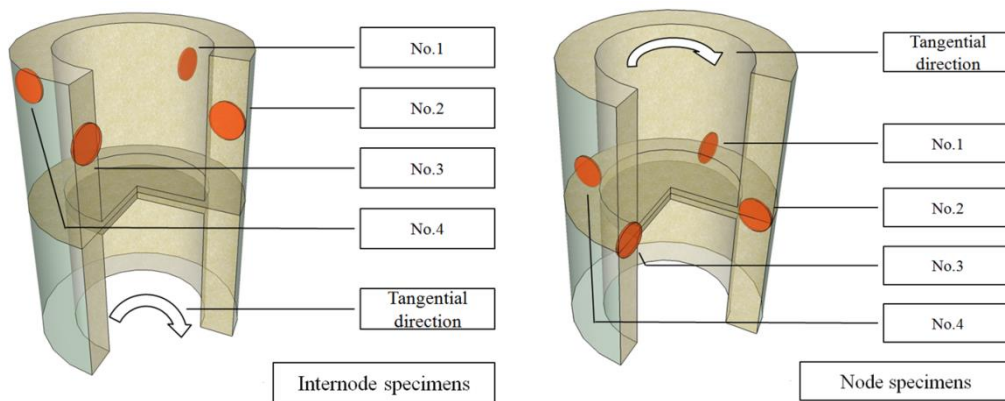

Fig 3 The cutting position of bamboo specimens in the tangential direction

In the longitudinal direction (Fig. 4), specimens were designated Nos.1 to 3. The distance between two adjacent specimens was equal. Five specimens were prepared for each position. These specimens were prepared to assess the water vapour permeable trend of the bamboo in the tangential direction.
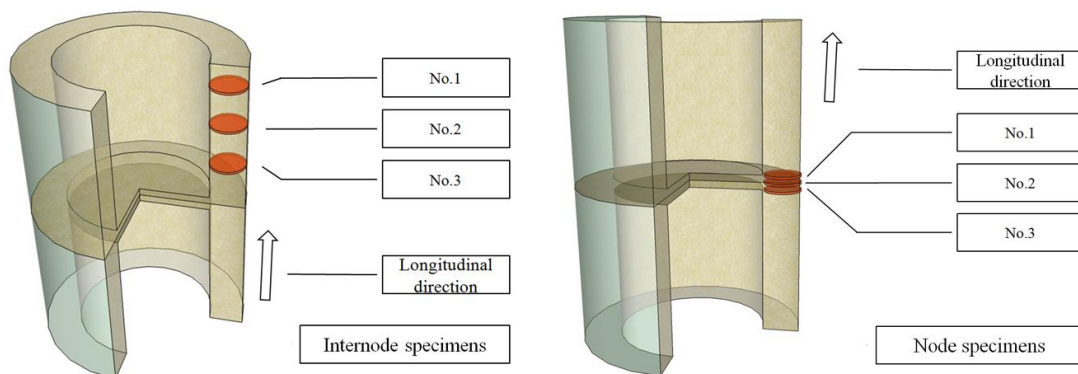

Fig 4. The cutting position of bamboo specimens in the longitudinal direction

The diameter of all specimens was 14 ± 1 mm and the thickness was 3 ± 0.5 mm. These specimens were stored in a climate chamber for 24 hours with a temperature and relatively humidity of $23 \pm 1°C$ and 50% respectively.

The water vapour permeability measurement was conducted by the dry cup method. Bamboo specimens were assembled within glass containers. Calcium chloride ($CaCl_2$) was prepared as the desiccant to provide 0% RH within the glass containers. The air space between the desiccant and the test specimen was 15 ± 5 mm. Crystalline wax was utilised to seal the gap between the bamboo specimen and the glass container (Fig 5). After measuring the initial mass with an electronic scale, the sealed assemblies were stored in the climate chamber. The weight of every assembly was monitored every 24 hours. The monitoring was terminated when the rate of mass change was less than 5%. The readability of the electronic scale is 0.001g.
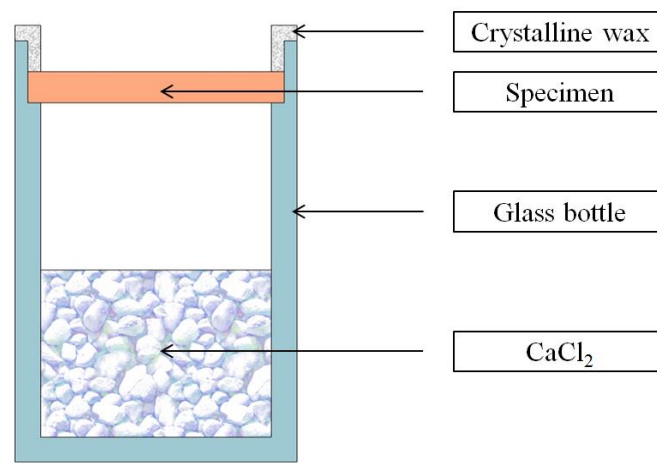

Fig 5. Assemblies for water vapour diffusion resistance factor measurement

2.2 Water vapour permeability calculation

The water vapour permeability was calculated by equation 1 (BS EN 12086:2013).

$$\delta_p = \frac{\Delta m \cdot d}{\Delta t \cdot A \cdot \Delta p} \tag{1}$$

δ_p: Water vapour permeability (kg/m·s·Pa)

Δm: Mass change in 24 hours (kg)

d: Thickness of the specimen (m)

Δt: Time interval=24 (h)

A: Exposed area (m^2)

Δp: The water vapour pressure difference=1400 (Pa)

The water vapour permeable capability of a construction material is often expressed by the water vapour diffusion resistance factor. The water vapour diffusion resistance factor was calculated by equation 2 (BS EN 12086:2013).

$$\mu = \frac{\delta_{air}}{\delta_p}$$ (2)

μ: Water vapour diffusion resistance factor, dimensionless

δ_{air}: Water vapour permeability of air (kg/m·s·Pa)

δ_p: Water vapour permeability of the specimen (kg/m·s·Pa)

The water vapour permeability of air can be calculated by equation 3 (Schirmer 1938).

$$\delta_{air} = \frac{2.306 \cdot 10^{-5} \cdot P_0}{R_v \cdot T \cdot P_a} \left(\frac{T}{273.13}\right)^{1.81}$$ (3)

δ_{air}: Water vapour permeability of air (kg/m·s·Pa)

P_0: Standard atmospheric pressure (101325 Pa)

R_v: Gas constant for water (461.5 J/K·kg)

T: The Kelvin temperature (K)

P_a: Ambient air pressure (Pa)

3. Results and discussion

The results of the dry cup tests of the Moso bamboo specimens are expressed as the water vapour diffusion resistance factor (µ) in Fig 6. The horizontal axis represents the µ value. The vertical axis displays the group name of bamboo specimens from different directions in both internode and node parts. The variation ranges of each group were provided. See Fig 6.
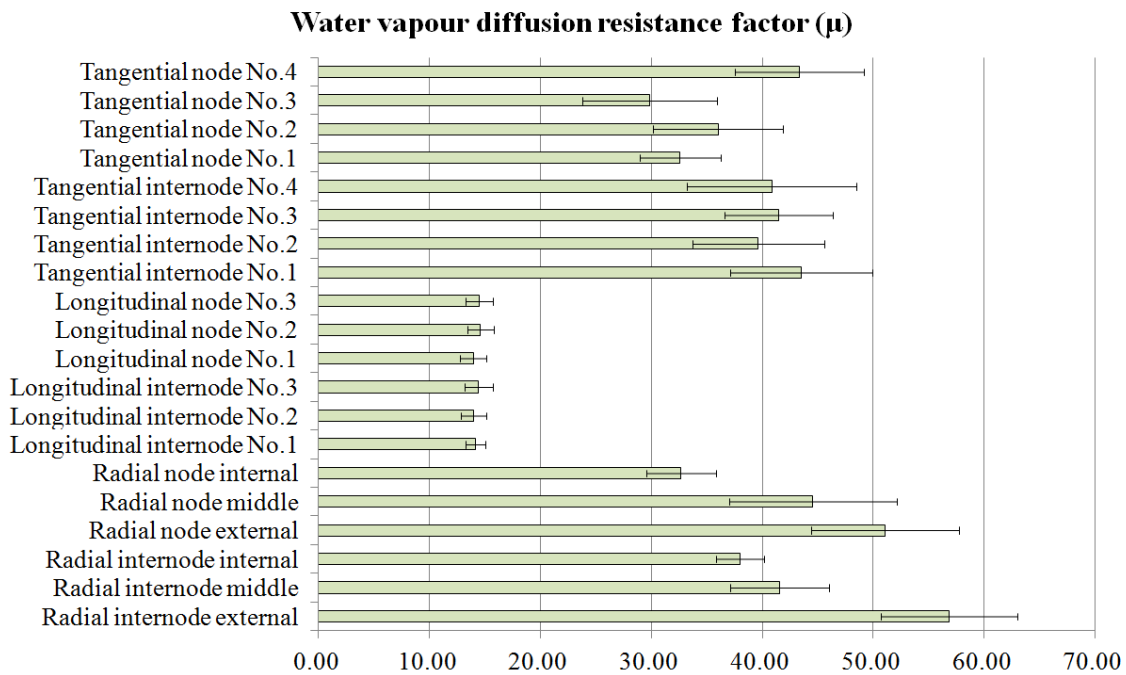
Water vapour diffusion resistance factor (µ)

Fig 6. Water vapour diffusion resistance factor (µ)

The water vapour diffusion resistance factor results for Moso bamboo specimens in the radial direction exhibit an obvious decreasing trend from the external surface to the internal surface for both internode and node parts which is explained by the morphological features of bamboo. The main structure of the bamboo culm can be regarded as a mixture of vascular bundle tissue and the parenchyma ground tissue. From the external surface to the internal surface, the content of vascular bundle tissue decreases while the content of parenchyma ground tissues increases (Fig 7). Large numbers of fibre cells around the vascular bundle vessels are highly lignified with relatively small cavities and thick cell walls. Even the parenchyma ground cells between two vascular bundles are smaller than the parenchyma ground cells in other parts of the bamboo culm wall (Fig 8). On the external side, the vascular bundle tissues occupy a large proportion of the area. The gap between parenchyma ground cells is much larger than the tightly arranged fibre cells   at 600 times magnification (Fig 8 and Fig 10). Furthermore, many tiny pits are distributed on the cell wall of the parenchyma ground tissue cells. The diameter of these pits is around 1µm. However, these pits are rarely found on the cell wall of the vascular bundle cells. In addition, the quantified bulk density data demonstrates a decreasing trend from the external surface to the internal surface (Huang *et al*. 2015). Therefore, the difficulty for water vapour to diffuse through the external side of bamboo culm wall is higher than that through the internal side.

Another feature of the results is that the water vapour diffusion resistance factor of bamboo specimens in the longitudinal direction is remarkably lower than the water vapour diffusion resistance factor of bamboo specimens in the radial and tangential directions. The water vapour diffusion resistance factor of bamboo specimens in the longitudinal direction is around 14. The values in the radial and tangential

directions range from 30 to 57. The main reason is that vascular bundle vessels provide many straight conduits for the transportation of water vapour. The interconnectivity of the vascular bundle vessel is considerable in the longitudinal direction (Fig 9). The vascular bundle vessel can be regarded as a tube with many tiny pits. No obvious partition appears in the longitudinal direction of the vascular bundle vessel. The diameter of the vascular bundle vessels can reach 100 µm. However, no tissue with straight conduits and high interconnectivity can be found in the radial and tangential directions (Liese 1985 and Wang 2010).

In addition, the results indicate that the majority of the node specimens possess a lower water vapour diffusion resistance factor than internode specimens in the radial and tangential directions. This phenomenon may be attributed to the irregularly growing vascular bundle tissues in the node parts of the bamboo culm. Fig 11 is a computed tomography (CT) image of a bamboo specimen from the node parts. The greyscale of the image clearly showed the density difference between the vascular bundle tissues and the parenchyma ground tissues. Figs. 11 and 12 illustrate that the growth of the vascular bundle tissue in the node part is not as straight as it is in the internode part. The direction of the vascular bundle tissue also changes from the longitudinal direction to other directions. Therefore, water vapour may be transported via these irregularly growing vascular bundle vessels which can provide higher interconnectivity than other tissues.
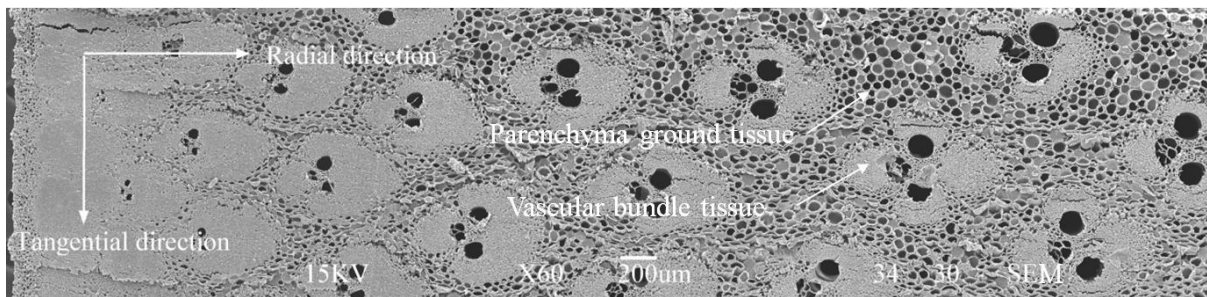

Fig 7. The scanning electron microscope image of a bamboo specimen (×60)
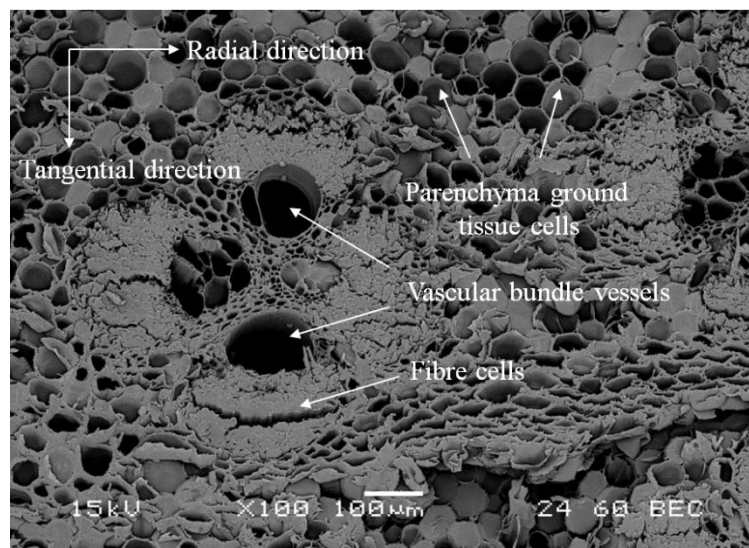

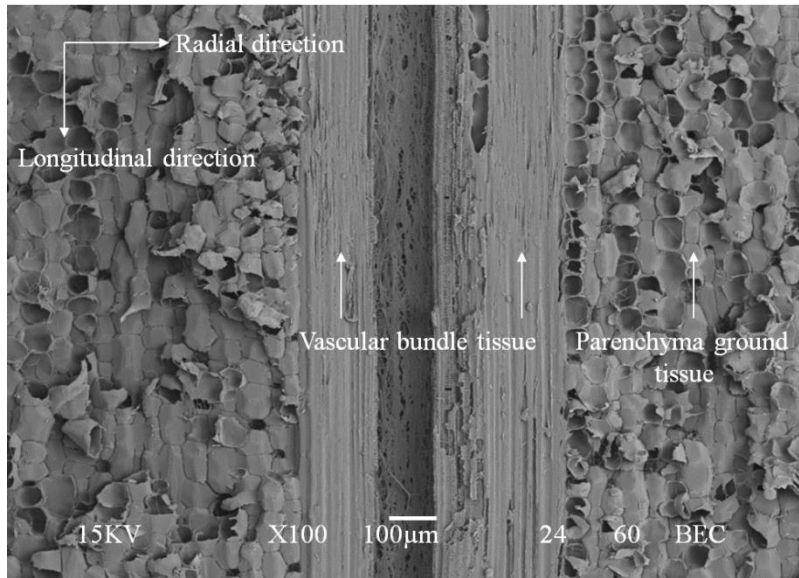Fig 8. A backscattered electron image of a bamboo cross-section (×100)

Fig 9. A backscattered electron image of a bamboo radial-longitudinal section (×100)
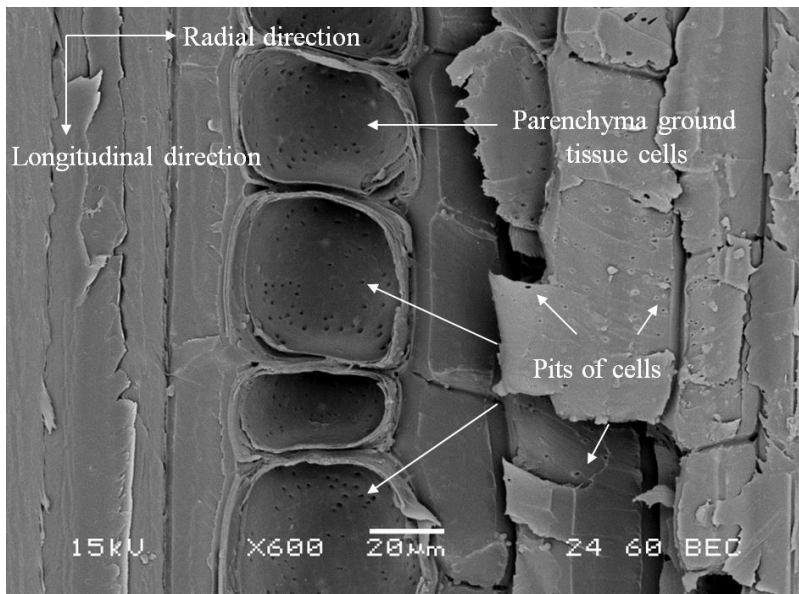

Fig 10. The backscattered electron image of a radial-longitudinal section (×600)
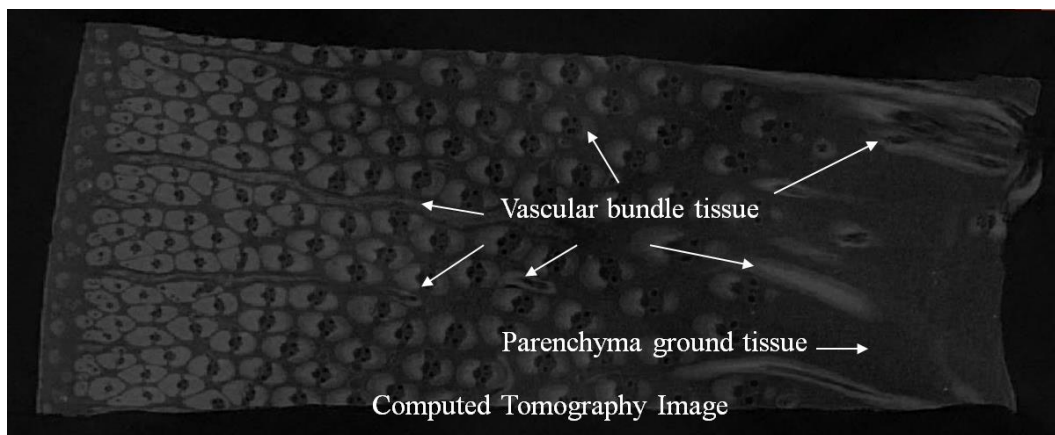

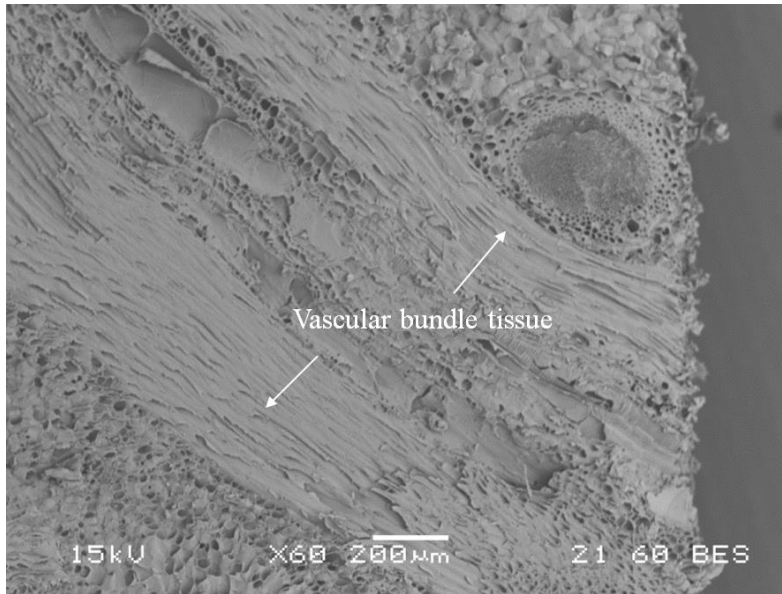Fig 11. A computed tomography image of a bamboo cross-section.

Fig 12. A backscattered electron image of a section through a node. (×60)

The results of the water vapour diffusion resistance factor indicate that different fibre directions can lead to significant variation of the water vapour diffusion performance. The variation needs to be noticed in the manufactureing of bamboo-based building envelope components. In addition, the wide variation range of the water vapour diffusion factors imply that simply using average value is not appropriate in the heat and moisture transfer research. The selection of the water vapour diffusion factors should consider the fibre direction and cutting postion of bamboo specimens.

4. Conclusions

The water vapour diffusion resistance factor of the Moso bamboo specimens was measured by a dry cup method. The specimens were measured in all directions of the cylindrical coordinates system at both internode parts and node parts. The water vapour diffusion resistance factor results for Moso bamboo specimens demonstrate a decreasing trend from the external surface to the internal surface in the radial directions. This fact may be attributed to the more densified fibre cells and low quantity of pits at the external surface. The water vapour diffusion resistance factor of bamboo specimens is remarkably lower in the longitudinal direction than in the radial and tangential directions. The large diameter, high interconnectivity and straight structure of the vascular bundle vessels are the factors which determine the lower water vapour diffusion resistance factor in the longitudinal direction. The majority of the node specimens demonstrated lower water vapour diffusion resistance factor values than internode specimens in the radial and tangential directions due to the irregularly growing vascular bundle vessels which are oriented in different directions.

Acknowledgements

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