FLATTENING OF HALF TUBULAR BAMBOO CULMS AND FIXATION OF BAMBOO BOARDS

T Parkkeeree[1], N Matan[1,] *, N Matan[2] & B Kyokong[1]

[1]*Materials Science and Engineering, School of Engineering and Resources, Walailak University, Thasala District, Nakhon Si Thammarat 80160, Thailand*
[2]*Food Technology, School of Agricultural Technology, Walailak University, Thasala District, Nakhon Si Thammarat 80160, Thailand*

Received November 2012

PARKKEEREE T, MATAN N, MATAN N & KYOKONG B. 2014. Flattening of half tubular bamboo culms and fixation of bamboo boards. The objective of this work was to maximise the utilisation of bamboo (*Dendrocalamus asper*) by overcoming constraints due to its tubular form in producing flat bamboo board. Water-saturated half tubular bamboo specimens (thickness of 3 mm and length of 150 mm) were pressed under various loads (10 to 25 N) while being immersed in hot linseed oil at different temperatures (120 to 180 °C). The height of each specimen was measured as a function of time. The flattened bamboo boards were hot pressed at 0.65 MPa at temperatures between 180 and 240 °C for up till 40 min. Springback of fixed bamboo boards in ambient air (28 °C and 75% relative humidity) and in water was assessed. The half tubular bamboo culms were best flattened in hot linseed oil under applied load of 15 N and 160 °C. Without an additional fixation at high temperature, final springback levels of 52% in ambient air and 73% in water were observed. These springback levels were reduced to below 5% in ambient air and 40% in water by hot pressing the flattened bamboo boards at 240 °C for at least 20 min. After fixation, the colour change of bamboo specimens was a good indicator of the springback observed.

Keywords: *Dendrocalamus asper*, flat bamboo board, linseed oil, springback, colour change

PARKKEEREE T, MATAN N, MATAN N & KYOKONG B. 2014. Meleperkan buluh yang dibelah dua dan pengikatan papan buluh. Kajian ini bertujuan untuk memaksimumkan penggunaan buluh *Dendrocalamus asper* dengan mengatasi kekangan bentuk tiubnya untuk penghasilan papan buluh yang leper. Spesimen buluh berbelah dua (tebal 3 mm dan panjang 150 mm) yang tepu air direndam dalam minyak biji rami panas pada suhu 120 °C hingga 180 °C dan dikenakan beban antara 10 N hingga 25 N. Tinggi setiap specimen disukat mengikut masa. Papan buluh yang leper dikenakan tekanan panas pada 0.65 MPa pada suhu antara 180 °C hingga 240 °C sehingga 40 min. Anjal balik dalam udara ambien (28 °C dan 75% kelembapan relatif) dan dalam air bagi buluh yang telah diikat disukat. Kulma buluh yang dibelah dua paling baik dileperkan dalam minyak biji rami panas di bawah beban 15 N pada 160 °C. Pada suhu tinggi tanpa pengikatan tambahan, aras akhir anjal balik dalam udara ambien dan dalam air adalah masing-masing 52% dan 73%. Aras anjal balik berkurangan sehingga di bawah 5% dalam udara ambien dan 40% dalam air apabila papan buluh yang leper dikenakan tekanan panas pada 240 °C selama sekurang-kurangnya 20 min. Selepas pengikatan, perubahan warna spesimen buluh menjadi petunjuk yang baik bagi anjal balik yang dicerap.

INTRODUCTION

To meet the growing global demand for good quality timber, searching for alternative sources of wood material is vital to relieve the pressure of logging from the existing natural forests. Owing to faster growth, shorter rotation and higher mechanical strength compared with other species (Aminuddin & Abdul Latif 1991, Lee et al. 1994, Dransfield & Widjaja 1995), bamboo has the potential to supplement timber in the near future. Unlike other solid sections of a tree trunk, bamboo culm is a cylindrical tube that is divided at intervals by nodes. The culm comprises mainly parenchyma cells and vascular bundles, which are largely made up of thick-walled fibres with high strength (Grosser & Liese 1971). As a result, the utilisation of bamboo until recently has been focused mainly on various types of wood composite products such as plybamboo (Anwar et al. 2011), oriented strand board (Sumardi et al. 2007, Malanit et al. 2011), particleboard (Biswas et al. 2011) and bamboo fibre reinforced polymer (Khalil et al. 2012). For the manufacturing of these products, energy is required to break the bamboo culm down into veneer, strands, particles or fibres and an additive is needed to bond

---

*mnirundo@wu.ac.th

these elements together again to form products (Maloney 1993). In the case of bamboo, it will be more efficient to develop a technique that softens and flattens its tubular culm directly into flat lumber which is the purpose of this study.

Softening the cell wall of wood is possible because it is a polymeric material containing amorphous phases of hemicelluloses, lignin and non-crystalline cellulose components (Haygreen & Bowyer 1989), which exhibits viscoelastic and plastic behaviours when exposed to increasing temperature (Glasser et al. 1998). At low temperatures, amorphous wood constituents are in a 'glassy state' exhibiting high strength and modulus. However, as the temperature increases to the glass transition temperature, amorphous wood constituents attain a softer 'rubbery' state (Wolcott et al. 1990). The glass transition temperature of bamboo, ranging from 80 to 200 °C, was reported to depend mainly on moisture content (Matan et al. 2007). Moisture acts as a plasticiser, reducing the glass transition temperature of wood material (Obataya et al. 1998). However, moisture loss during heating of bamboo tends to increase its glass transition temperature (Matan et al. 2007, Liu et al. 2012). It is, therefore, state of the art to maintain moisture within bamboo during heating to keep the rubbery state of the specimen long enough for the process of flattening to be completed. It should be noted that thermal degradation of wood constituents will take place during heating, especially at high temperatures during long treatment period (Windeisen et al. 2007).

Various techniques for softening bamboo culms have been reported; for example, dipping pieces of bamboo strips (*Phyllostachys pubesens*) into boiling water for several hours followed by paraffin immersion at 130 °C for 10 min (Chen 1987). Li et al. (1994) heated bamboo strips (*Bambusa pervaribilis*) in a container to adjust the moisture content and then compressed them into plates. Cherdchim et al. (2004) successfully softened and flattened half-tubular bamboo culms (*Dendrocalamus asper*) by immersion in hot (> 115 °C) linseed oil, a common wood surface coating. The impregnation of linseed oil into wood and heat treatment of wood in linseed oil have been reported to improve the dimensional stability and durability of wood (Olsson 1999). Softening and flattening bamboo culms in hot oil is an attractive technique because it is simple and low cost. Moreover, it can improve the durability of bamboo (Manalo & Acda 2009, Dubey et al. 2011).

The main objectives of this research were to optimise the process parameters of flattening half-tubular bamboo culms (*D. asper*) into flat bamboo boards using hot linseed oil and to examine the process of fixation in order to reduce springback of the bamboo boards.

MATERIALS AND METHODS

Specimen preparation

Black sweet bamboo culms (*D. asper*) of 3 to 4 years old were collected from a plantation in the Thasala district of Nakhon Si Thammarat in Thailand. The culms were separated into three sections (bottom, middle and top) at 4-m intervals starting from 0.5 m above the ground level. Each culm was cross-cut into hollow specimens of 150 mm long to remove the nodes before splitting it longitudinally into half. The outer surface was removed and the specimen thickness was reduced from the inner surface to the required size of 3 mm. A sharp curved gouge was used to ensure that the surface finish was in good condition. Prior to testing, all specimens were dipped into water at room temperature to adjust the moisture content to water saturated condition of 46 ± 8%. The volume fraction of vascular bundles for each specimen was evaluated according to Sutnaun et al. (2005).

Flattening of bamboo specimens

A pressing test set up containing two flat stainless steel plates was used to apply force to the bamboo (Figure 1). This force generated compressive stress at the outer surface and tensile stress at the inner surface causing the specimen to deform into flatter shape while being softened in hot linseed oil. The pressing test rig with the bamboo specimen was immersed in hot linseed oil and heated to the required temperature in a heating bath which was capable of heating linseed oil up to 200 °C. Two thermocouples were used to measure temperatures of the linseed oil and bamboo specimen. The linear variable differential transformer, fixed to the top steel plate of the pressing test rig, was used to monitor specimen height during the flattening process. A data logger was used to record and transfer data to the computer.

The degree of flatness F was calculated from specimen height h using equation $F = (r_0 - h)/(r_0 - d)$ where r_0 = initial height and d = specimen thickness. At the initial condition, $h = r_0$ and $F = 0$. After flattening, if the specimen is completely deformed into a plate with $h = d$, then $F = 1$ (Figure 2a). The final value of degree of flatness F_F was derived from the analysis of the thermal softening behaviour of the half tubular bamboo

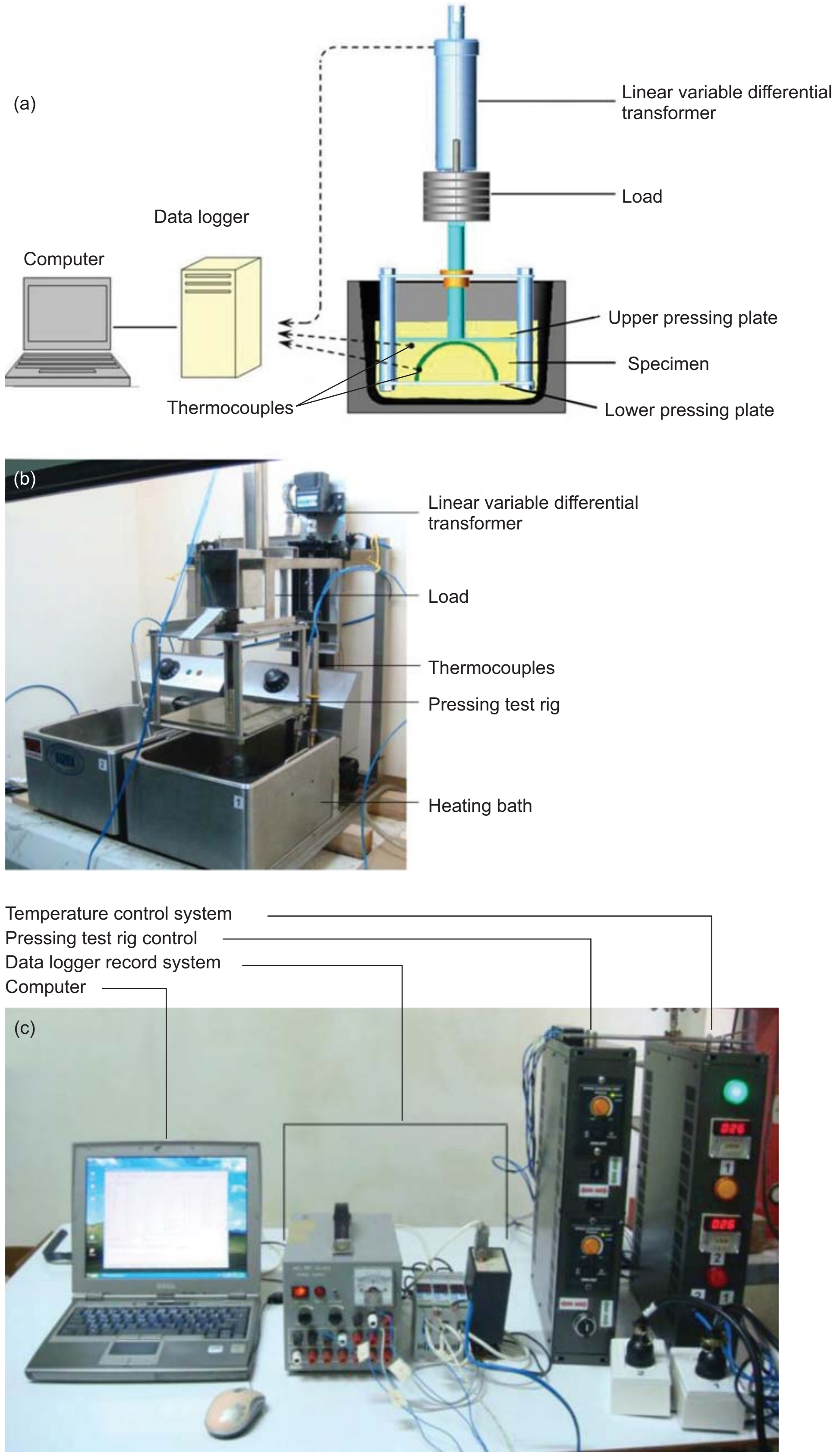

Figure 1 (a) Schematic diagram showing the flattening apparatus system and photographs showing (b) the flattening apparatus consisting of the pressing rig, heating bath and linear variable differential transformer used to monitor the specimen height in real time and (c) the recording and controlling system

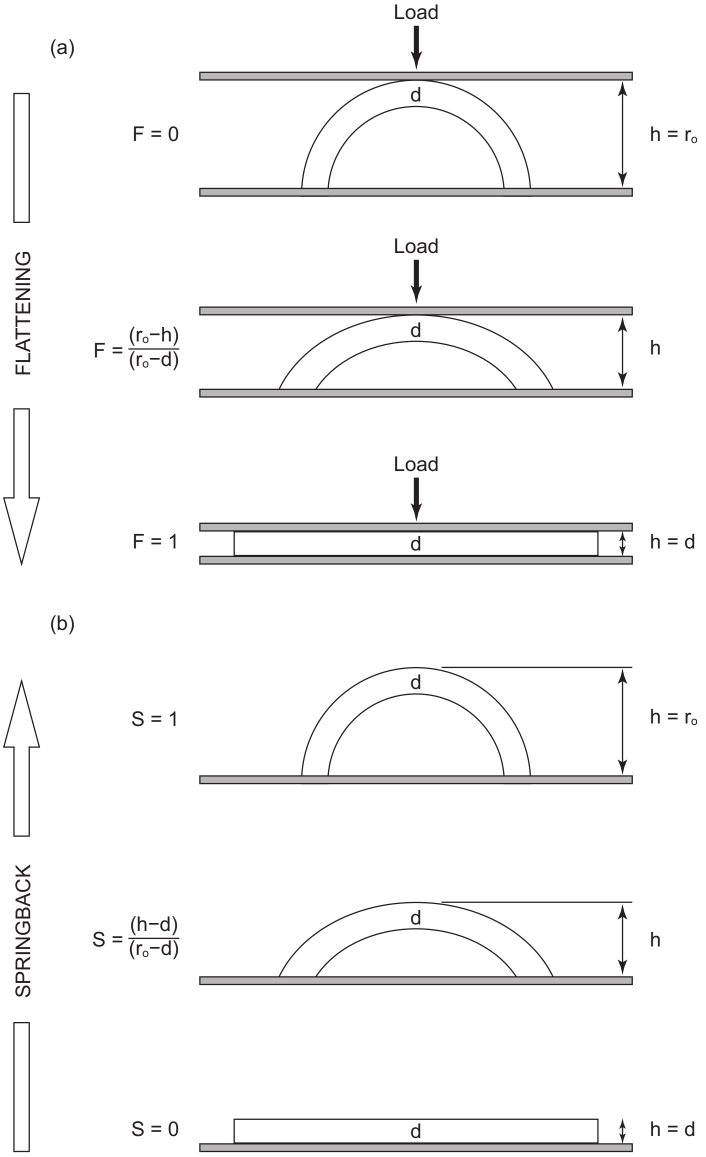

Figure 2 Schematic representation of the definitions of the (a) degree of flatness (F) during the flattening process and the (b) degree of springback (S) after the fixation process; h = height, d = thickness, r_0 = outer radius

specimen. A total of 144 specimens prepared from three sections of the culm (bottom, middle and top) were tested at four linseed oil temperatures (120, 140, 160 and 180 °C) and four loads (10, 15, 20 and 25 N). Three replicate specimens were tested per condition.

Fixation of bamboo specimens

Half cylindrical cross-section bamboo specimens were flattened in hot linseed oil at 160 °C using applied load of 15 N for 5 min. The flattened bamboo specimens were subsequently pressed at 0.65 MPa in a single-opening hydraulic laboratory press at four temperatures (180, 200, 220 and 240 °C) for four treatment times (5, 10, 20 and 40 min). Three replicate specimens were tested per condition including the control (without fixation). Each sample was cut into three sections of 50 mm in length. Two sections were used to study specimen springback and another section was used to measure colour change. The first and second sections, which were end-coated with industrial lacquer to prevent moisture gain or loss in the longitudinal direction, were conditioned in ambient air (28 ± 2 °C and 75 ± 6% RH) and submersed in water respectively for up to 4 months. The recorded height at any given time h was used to calculate the degree of springback S according to $S = (h - d)/(r_0 - d)$, where r_0 = initial height prior to flattening and d = specimen thickness. After fixation, h = d and S = 0, so there was no springback. If the specimen completely springs back to reach its initial height prior to flattening where $h = r_0$, then $S = 1$ (Figure 2b). The final value of the degree of springback S_F was derived from the analysis of the springback behaviour of the fixed bamboo specimens.

Colour measurement was performed using a tristimulus colour analyser. A total of three replicates per treatment were carried out. Hunter colour coordinates were used to determine the degree of lightness (L*), redness–greenness (+ or -a*) and yellowness–blueness (+ or -b*). The total colour difference (ΔE*) between treatments and control was calculated using the equation:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Statistical analysis

The data were evaluated by analysis of variance (ANOVA) at the 0.01 and 0.05 levels of significance. The Duncan's multiple range tests were conducted to determine significant differences between mean values. Response surface methodology (RSM) was employed to describe various variables (dependent variables) examined during the flattening and fixation processes as functions of statistically significant independent variables. The behaviour of the system was described using the following second-order polynomial:

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \beta_{ij} x_i x_j \qquad (1)$$

where Y = predicted response, x_i and x_j = independent variables, β_o = interception coefficient, β_i = linear terms, β_{ii} = quadratic term and β_{ij} interaction term. The models of the two responses were expressed in terms of two independent variables. The quality of fit was checked with coefficient of determination r^2 and its statistical significance was determined by F-test. The statistical analysis was performed using Statistica software.

RESULTS AND DISCUSSION

Flattening of half tubular bamboo culms

Specimen configurations after the flattening process could be classified into three categories, namely, rolled, flat and broken (Figure 3). ANOVA revealed that the applied load had strong influence ($p < 0.01$) on bamboo specimen configurations (Table 1). Figure 4a shows the percentage of bamboo specimens at each configuration plotted as a function of the applied load. At a low applied load of 10 N, about 10% of the bamboo specimens had rolled configuration and about 90% had flat configuration. As the applied loads increased to 15 N, the percentage of flat specimens increased towards 100% with rolled and broken specimens at approximately minimal percentage. At applied loads higher than 15 N, the percentage of broken specimens increased from zero to about 50% while those of the flat configuration decreased from about 100 to 50%. The optimum applied load for a 3-mm thick bamboo specimen to have maximum percentage of flat configuration was 15 N.

The percentage of rolled, flat and broken bamboo specimens at different temperatures is shown in Figure 4b. With increasing temperature from 120 to 160 °C, the per cent values of flat specimens increased from 64 to 86% while those for broken and rolled specimens decreased from 28 to 14% and from 8 to 0% respectively. All bamboo specimen configurations remained unchanged above 160 °C. Therefore, the suitable linseed oil temperature for the flattening process was 160 °C.

Bamboo culm height had little effect on final specimen configuration after the flattening process (Figure 4c). This might be because all specimens used were prepared from the outer portion of the bamboo culm. An examination of the fibre volume fraction found that there were no significant differences ($p < 0.01$) between bamboo specimens (result not shown).

Figure 5 shows the typical evolution of the height of a bamboo specimen during the flattening process in hot linseed oil. Temperatures of the bamboo specimen and linseed oil were also displayed. Once the temperature of the bamboo specimen reached the glass transition temperature of around 115–120 °C for a moist bamboo specimen (Cherdchim et al. 2004, Cheng et al. 2006, Matan et al. 2007), the specimen started to develop into a flatter shape under the applied load. The height of the measured specimen (h) gradually decreased with time, approaching the thickness (d) of the bamboo specimen. The corresponding degree of flatness (F) calculated and the final degree of flatness (F_F) derived from the graph are also shown. Linseed oil, which is hydrophobic, should act mainly as a heat convection substance in the flattening process since the molecular size of linseed oil is too large to penetrate into the wood cell wall (Olsson et al. 2001, Dubey et al. 2011). The absorbed linseed oil was

Figure 3 Photographs showing (a) rolled, (b) flat and (c) broken specimens of half tubular bamboo specimens obtained after the flattening process in hot linseed oil

expected to be in the cell lumen and did not contribute to the softening of the bamboo cell wall. Softening of bamboo during treatment in hot linseed oil could, therefore, be largely a function of an effect of moisture within the bamboo cell wall, which acted as a plasticising agent, and the heat carried by the hot linseed oil. Plasticisation of lignin and hemicelluloses was reported to be responsible for the softening of wood cell wall in hydro-thermolysis process (Hillis & Rozsa 1985, Östberg et al. 1990)

ANOVA revealed that applied load and linseed oil temperature had significant effects ($p < 0.01$ with F values of 23.74 and 7.30 respectively) on final degree of flatness (Table 1). Response surface analysis was, therefore, performed on these two independent parameters (Table 2): x_1 (applied

Table 1 Analysis of variance for final bamboo specimen configuration and final degree of flatness

Source of variation	F value	
	Final bamboo specimen configuration	Final degree of flatness (%)
Load	9.83[a]	23.74[a]
Temperature	2.15	7.30[a]
Height	0.42	5.38[a]
Load × temperature	0.47	1.40
Load × height	0.68	4.97[a]
Temperature × height	3.21[a]	1.07
Load × temperature × height	2.55[a]	0.86

[a] $p < 0.01$

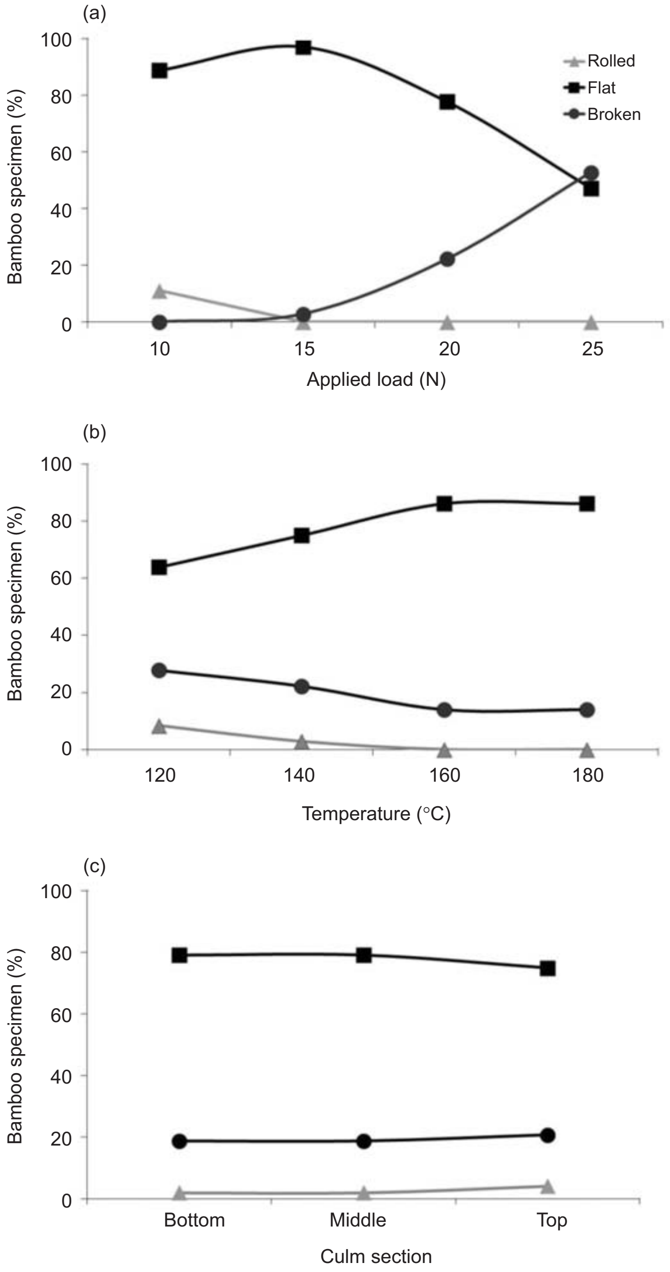

Figure 4 Percentage of bamboo specimens in rolled, flat and broken configurations after the flattening process in hot linseed oil plotted against (a) applied load, (b) linseed oil temperature and (c) bamboo culm section

load) and x_2 (linseed oil temperature). Multiple regression coefficients, fitted using a second-order polynomial model for F_F, are summarised in Table 3. The goodness of fit represented by r^2 was 0.65 (result not shown).

The response surface plot of the F_F of bamboo specimens after the flattening process as a function of applied load and linseed oil temperature is shown in Figure 6. The final degree of flatness increased from about 80% at the lowest temperature (120 °C) and lowest applied load (10 N) to ~100% towards the highest temperature (180 °C) and highest applied load (25 N). From our preliminary test, it was found that the final degree of flatness required for the fixation process must be above 90%. As a result, the conditions for flattening bamboo specimens were 15 N for the applied load and 160 °C for the temperature of linseed oil.

Figure 7 shows the corresponding initial stress of the applied load that is suitable for flattening half tubular bamboo culms. Circumferential stress occurring within the bamboo culm as a result of an

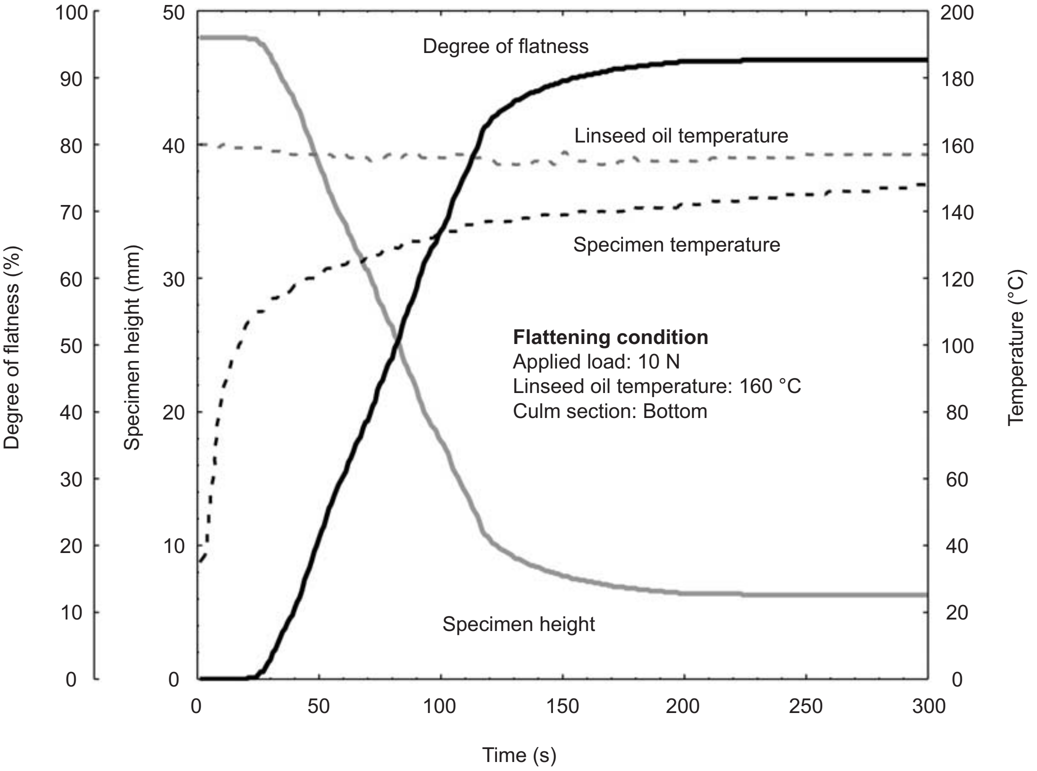

Figure 5 The typical evolution of the height of a bamboo specimen and the corresponding degree of flatness calculated during the flattening process of a half tubular culm in hot linseed oil

applied load P at radius r can be calculated according to the equation $\sigma = \frac{PR(r_n - r)}{2\ bdr\ (R - rn)}$ where R = radius of the centroid $R = \frac{r_o + r_i}{2}$ and r_n = radius of the neutral axis $r_n = \frac{d}{\ln(r_o/r_i)}$ (Boresi et al. 1993). By substituting P = 15 N, b = 15 cm, d = 3 mm, r_o = 49 mm and r_i = 46 mm, circumferential stresses at the outer surface and at the inter surface were obtained at -1.55 (compressive stress) and 1.60 MPa (tensile stress) respectively. It should be noted that these are the stresses generated at beginning of the flattening process. Once the bamboo specimen has changed its shape under constant applied load, the magnitude of stress within bamboo specimen is altered, which should lead to different configurations (i.e. rolled, broken or flat) observed at the end of the flattening process (Figure 3).

Fixation and its effect on springback and colour changes of the flattened bamboo specimens

Figure 8 shows the typical flattening and fixation of a bamboo specimen. Evolution of the calculated degree of springback (S) of the fixed bamboo specimens during incubation in ambient air (28 ± 2 °C and 75 ± 6% RH) and during submersion in water is also shown. Immediately after the fixation process, the bamboo specimen sprung in the

Table 2 Independent variables and levels in a two-factor, four-level (4^2) full factorial design of flattening and fixation processes employed

Flattening process (F_F)		Level			
Applied load (N)	x_1	10	15	20	25
Temperature (°C)	x_2	120	140	160	180
Fixation process (S_F, ΔE*)		Level			
Temperature (°C)	x_1	180	200	220	240
Time (min)		5	10	20	40
1n Time (min)	x_2	1.61	2.30	3.00	3.69

Table 3 Regression coefficients of the second-order polynomial equations describing the final degree of flatness (F_F) for the flattened half tubular bamboo culms and final degree of springback (S_F) and colour changes (ΔE^*) for the fixed bamboo boards

Factor	F_F (%)	S_F in ambient air (%)	S_F in water (%)	ΔE^*
β_0	-6.9078	-209.6660^a	-393.2500^a	97.8218^b
β_1	0.9148^a	2.2802^a	4.5616^a	-0.9371^b
β_2	0.9727	15.6558^b	33.9044^b	-17.3392^b
β_{11}	-0.0023^b	-0.0055^a	-0.0109^a	0.0024^b
β_{12}	-0.0004	-0.0890^a	-0.1810^a	0.0991^a
β_{22}	-0.0093	-0.1124	-0.4745	-0.0755

$^a p < 0.01$, $^b p < 0.05$

opposite direction with a negative springback value. The different structures of outer and inner layers of bamboo (Amada et al. 1996, Sutnaun et al. 2005) were probably responsible for this negative springback effect of the flattened bamboo board after hot pressing. The magnitude of degree of springback gradually decreased to zero (completely flat) before changing to positive value during incubation in ambient air or submersion in water. Figure 9 shows bamboo specimens after various conditions of the fixation process. In general, the higher the pressing temperature and the longer the treatment time during the fixation process, the darker the colour obtained. This is in agreement with many published works (Bekhta & Niemz 2003, González-Peña & Hale 2009) on the effect of heat treatment on colour changes in wood. ANOVA revealed that pressing temperature and treatment time had strong influence ($p < 0.01$) on the final degree of springback in ambient air and in water, as well as the value of colour changes of the fixed bamboo specimens (Table 4).

The effect of treatment temperature and logarithm of treatment time (designated as x_1 and x_2 respectively in Table 2) employed in the fixation process on the final values of the degree of springback and colour changes of the bamboo specimens were quantitatively analysed using response surface methodology. Multiple regression coefficients fitted using a second-order polynomial model are summarised in Table 3. The predicted response values of the final degree of springback S_F in ambient air and in water and the values of colour changes ΔE^* were in good agreement with the experimental data having r^2 values of 0.84, 0.85 and 0.91 respectively (result not shown). Response surface plots of S_F in ambient air and in water and

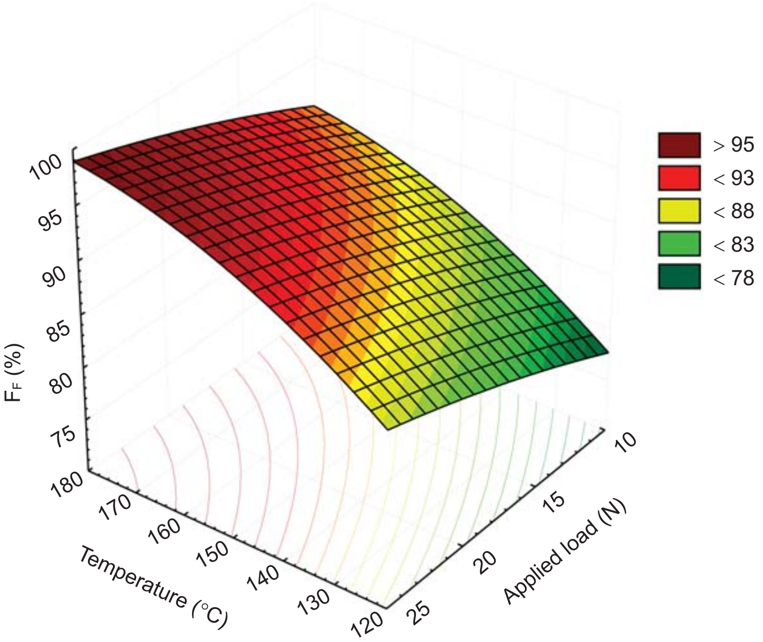

Figure 6 Response surface plot of the final value of degree of flatness (F_F) of half tubular bamboo specimens flattened in hot linseed oil at temperatures between 120 and 180 °C under applied load of 10 to 25 N

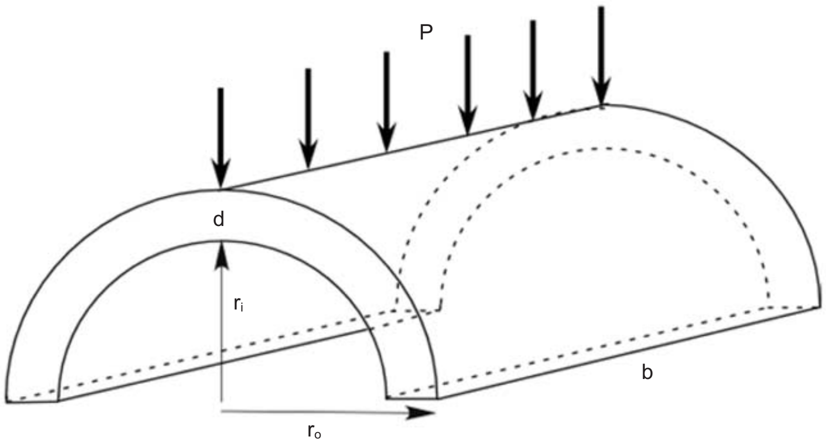

Figure 7 Schematic diagram showing dimension of half tubular bamboo specimens under applied load; P = applied load, d = thickness, b = length, r_i = internal radius, r_o = outer radius

ΔE* for the fixed bamboo specimens as functions of temperature and logarithm of treatment time are shown in Figures 10a–c respectively. Fixation treatment with higher temperature and longer treatment time appeared to reduce the values of S_F in ambient air (Figure 10a) and S_F in water (Figure 10b) but increased the value of ΔE* (Figure 10c). These effects were in agreement with other studies (Bekhta & Niemz 2003, González-Peña & Hale 2009). The time dependency of S_F in ambient air, S_F in water and ΔE* were more pronounced at higher fixation temperatures. At 180 °C, S_F in ambient air and water, and ΔE* were insensitive to treatment time at 23%, 76% and 7 respectively. These values changed linearly from 10 to 1%, 50 to 30% and 15 to 35 with an increasing logarithm of treatment time from 1.61 (5 min) to 3.69 (40 min) under treatment temperature of 240 °C. The values of S_F in ambient air and in water decreased from 23 to 1% and 76 to 30% while the value of ΔE* increased from 7 to 35 upon increasing treatment temperature from 180 to 240 °C at 40 min of treatment time. This temperature dependency declined with treatment time at 5 min. Without an additional fixation at high temperature, final degrees of springback in ambient air and in water were 52 ± 10% and 73 ± 9% respectively. Linear

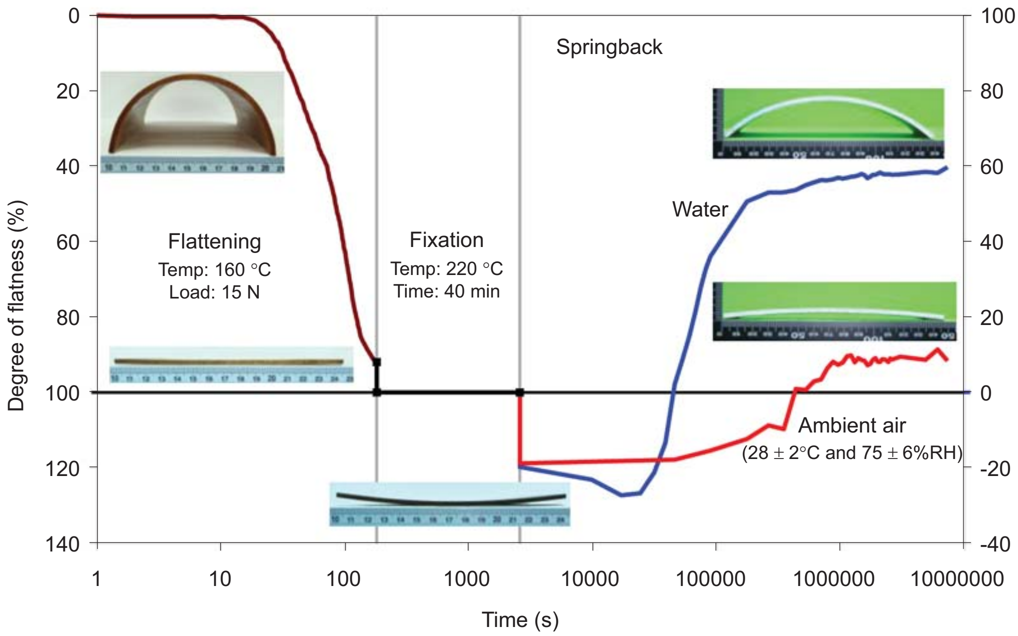

Figure 8 A typical evolution of degree of flatness and degree of springback of bamboo specimen during flattening, fixation and springback periods; photographs of bamboo specimen in each period are also shown; RH = relative humidity

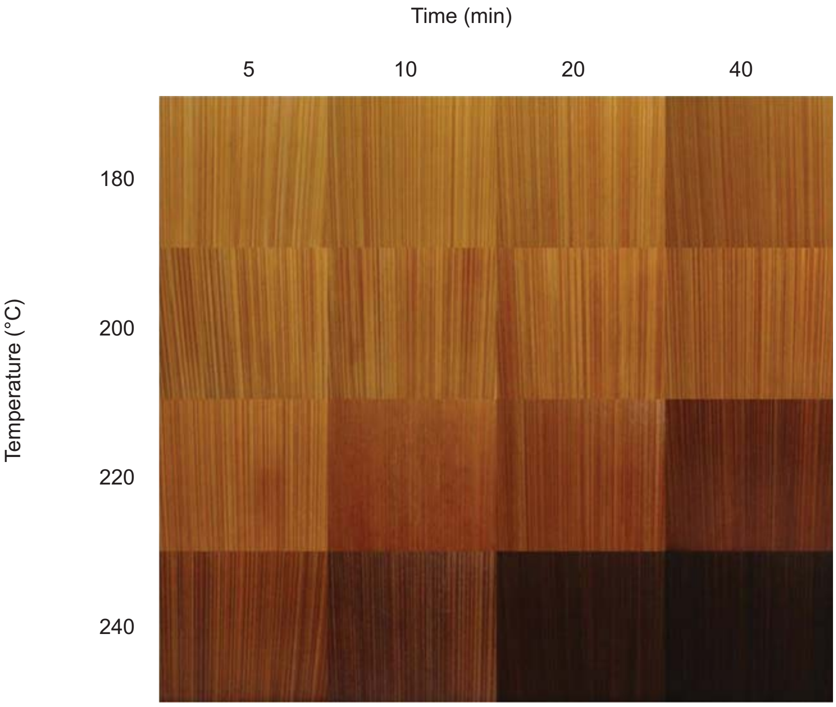

Figure 9 Photographs showing bamboo boards after being fixed at temperatures between 180 and 240 ºC for 5 to 40 min

correlations were also found between ΔE* and S_F in ambient air ($r^2 = 0.71$) and between ΔE* and S_F in water ($r^2 = 0.71$) (Figure 11). As a result, in practice, colour changes may be used as an indicator for springback values.

Chemical changes during thermal treatment have been extensively studied (Sivonen et al. 2005, Tjeerdsma & Militz 2005, Boonstra & Tjeerdsma 2006). Thermal treatment at high temperature has been reported to increase relative crystallinity of cellulose (Sivonen et al. 2005) and depolymerise hemicelluloses into oligomers and monomers. Cleavage of acetyl groups of hemicelluloses leads to formation of carbonic acids, largely acetic acid. These acids further catalyse the cleavage of carbohydrates to form formaldehyde, furfural and other aldehydes and cause some lignin cleavage and aldehyde production from lignin units (Tjeerdsma & Militz 2005, Boonstra & Tjeerdsma 2006). Condensation reactions of lignin fragments with high reactivity and degradation products of hemicelluloses result in an increased cross-linking of the lignin network (Sivonen et al. 2005, Boonstra & Tjeerdsma 2006). In the presence of moisture such as in wood compressed under saturated steam, reduction of springback was reported to be the result of break-down of the crosslinks responsible for the memory effect in wood coupled with lignin softening and perhaps the formation of covalent bonds in the deformed position (Inoue et al. 2008). On the other hand, the degradation of hemicelluloses was reported to be the main mechanism in the reduction of springback in the absence of moisture (Morsing 2000). Strong correlations between colour changes and springback might be a consequence of hemicellulose degradation during fixation at high

Table 4 Analysis of variance for final degree of springback (S_F) and colour changes (ΔE*) of the fixed bamboo boards

Source of variation	F value		
	S_F in ambient air	S_F in water	ΔE*
Temperature	91.227^a	23.547^a	263.397^a
Time	22.522^a	5.709^a	26.054^a
Temperature × time	3.523^a	0.906	8.210^a

$^a p < 0.01$

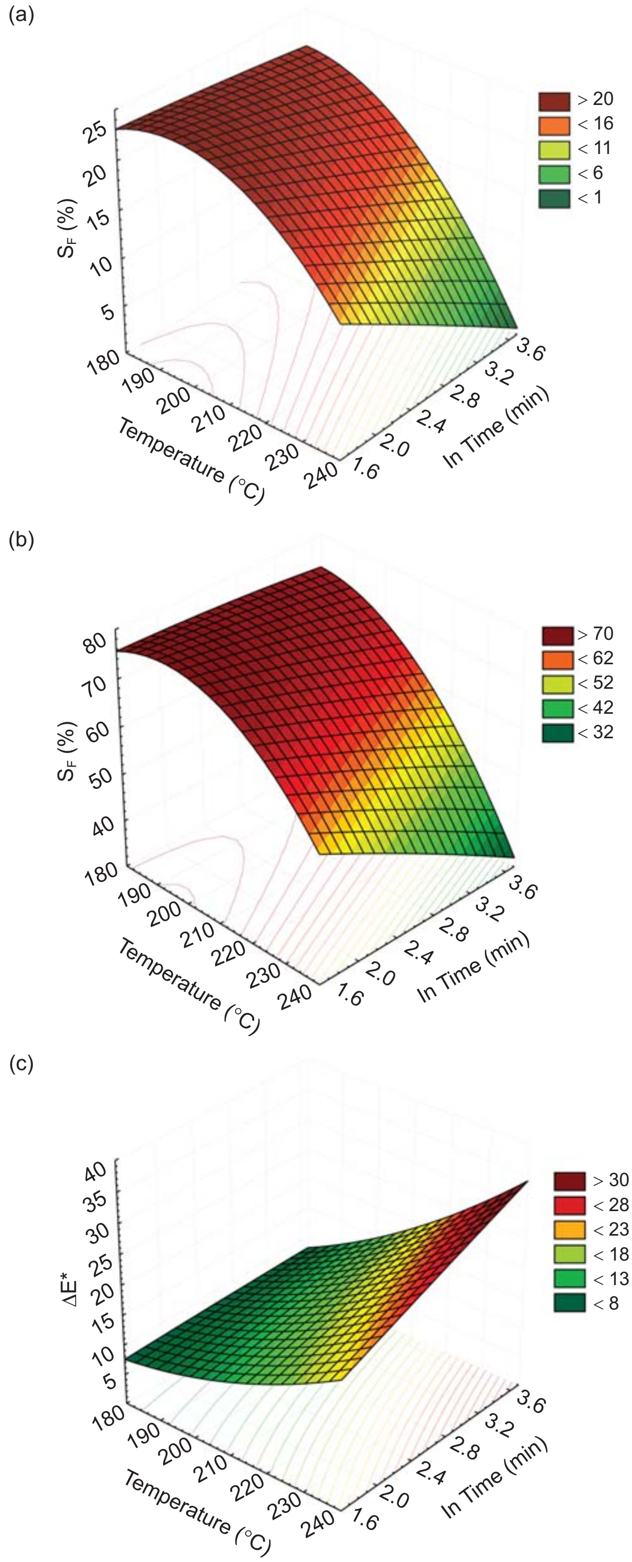

Figure 10 Response surface plots of springback (S_F) of bamboo specimens (a) incubated in ambient air (28 ± 2 °C, 75 ± 6% RH) and (b) immersed in water together with (c) their colour changes (ΔE*) after being fixed at temperatures between 180 and 240 °C for 5 to 40 min; RH = relative humidity

temperature. Colour change of heat-treated wood has been attributed to leaching and/or caramelising of cleaved products from hemicelluloses (Sehlstedt-Persson 2003, Sundqvist 2004, Boonstra & Tjeerdsma 2006). Thermal hemicellulose degradation in wood cell wall was reported to be responsible for reduction of springback of the heat-treated wood (Morsing 2000).

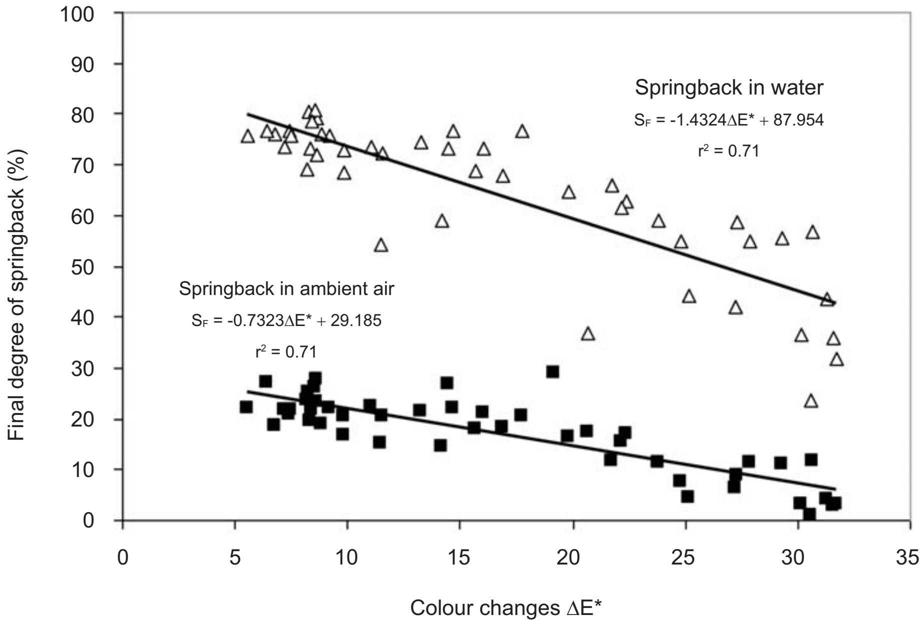

Figure 11 Correlations between colour changes (ΔE*) and final degree of springback (S_F) of fixed bamboo specimens incubated in ambient air (28 ± 2 °C and 75 ± 6% RH) and immersed in water; RH = relative humidity

CONCLUSIONS

The water-saturated half tubular bamboo culm of dimensions 3 mm (thickness) and 150 mm (length) was best flattened in hot linseed oil at 160 °C and under applied load of 15 N with corresponding initial circumferential stress of 1.6 MPa. Degree of flatness, final springback and colour change behaviour were successfully described by a multi-parameter model which would be helpful in finding the appropriate parameter settings during practical application.

Without an additional fixation at high temperature, final springback levels of 52 ± 10% in ambient air and of 73 ± 9% in water must be accepted. These levels can be reduced to below 5% in ambient air and 40% in water by hot-pressing the flattened bamboo boards at 240 °C for at least 20 min.

Strong correlations between colour changes and final degree of springback in ambient air and in water of fixed bamboo specimens ($r^2 = 0.71$) were obtained. Therefore, colour change could be used as an indicator of the level of springback in fixed bamboo boards.

ACKNOWLEDGEMENTS

The authors acknowledge the support from the Walailak University Fund and the Wood Science and Engineering Research Unit, Walailak University, Thailand. The first author wishes to thank King Mongkut's University of Technology North Bangkok, Thailand for a PhD scholarship at Walailak University.

REFERENCES

Amada S, Munekata T, Nagase Y, Ichikawa Y, Kirigai A & Zhifei Y. 1996. The mechanical structures of bamboos in viewpoint of functionally gradient and composite materials. *Journal of Composite Materials* 30: 800–819.

Aminuddin M & Abdul Latif M. 1991. Bamboo in Malaysia: past, present and future research. Pp 349–354 in *Proceedings of the Fourth International Bamboo Workshop: Bamboo in Asia and the Pacific.* 27–30 November 1991, Chiang Mai.

Anwar UMK, Hiziroglu S, Hamdan H & Abdul Latif M. 2011. Effect of outdoor exposure on some properties of resin-treated plybamboo. *Industrial Crops and Products* 33: 140–145.

Bekhta P & Niemz P. 2003. Effect of high temperature on the change of color, dimensional stability and mechanical properties of spruce wood. *Holzforschung* 57: 539–546.

Biswas D, Bose SK & Hossain MM. 2011. Physical and mechanical properties of urea formaldehyde-bonded particleboard made from bamboo waste. *International Journal of Adhesion and Adhesives* 31: 84–87.

Boonstra MJ & Tjeerdsma BF. 2006. Chemical analysis of heat treated softwoods. *Holz als Roh- und Werkstoff* 64: 204–211.

Boresi AP, Schmit RJ & Sidebottom OM. 1993. *Advanced Mechanics of Materials.* John Wiley and Sons, New York.

Chen GS 1987. *Bamboo Production and Utilization.* Nanjing Forestry University, Nanjing.

Cherdchim B, Matan N & Kyokong B. 2004. Effect of temperature on thermal softening of black sweet-bamboo culms (*Dendrocalamus asper* Backer) in linseed oil. *Songklanakarin Journal of Science and Technology* 26: 855–866.

Cheng RX, Zhang QS & Sui SJ. 2006. Improvement of softening treatment technology of bamboo. *Wood Science and Technology* 40: 327–335.

Dransfield S & Widjaja EA. 1995. *Plant Resources of South-East Asia 7: Bamboos.* Backhuys Publishers, Leiden.

Dubey MK, Pang S & Walker J. 2011. Changes in chemistry, color, dimensional stability and fungal resistance of *Pinus radiata* D. Don wood with oil heat-treatment. *Holzforschung* 66: 49–57.

Glasser WG, Rials TG, Kelley SS & Dave V. 1998. Studies of the molecular interaction between cellulose and lignin as a model for the hierarchical structure of wood. Pp 265–282 in Heinze TJ & Glasser WG (eds) *Cellulose Derivatives Modification, Characterization, and Nanostructures.* American Chemical Society, Washington.

González-Peña M & Hale M. 2009. Colour in thermally modified wood of beech, Norway spruce and Scots pine. Part 2: property predictions from colour changes. *Holzforschung* 63: 394–401.

Grosser D & Liese W. 1971. On the anatomy of Asian bamboos, with special reference to their vascular bundles. *Wood Science and Technology* 5: 290–312.

Haygreen JG & Bowyer JL. 1989. *Forest Products and Wood Science.* Iowa State University Press, Ames.

Hillis WE & Rozsa AN. 1985. High temperature and chemical effects on wood stability. Part 2. The effect of heat on the softening of radiata pine. *Wood Science and Technology* 19: 57–66.

Inoue M, Sekino N, Morooka T, Rowell RM & Norimoto M. 2008. Fixation of compressive deformation in wood by pre-steaming. *Journal of Tropical Forest Science* 20: 273–281.

Khalil AHPS, Bhat IUH, Jawaid M, Zaidon A, Hermawan D & Hadi YS. 2012. Bamboo fibre reinforced biocomposites: a review. *Materials and Design* 42: 353–368.

Lee AWC, Xuesong B & Perry NP. 1994. Selected physical and mechanical properties of giant timber bamboo grown in South Carolina. *Forest Products Journal* 44: 40–46.

Li SH, Fu SY, Zhou BL, Zeng QY & Bao XR. 1994. Reformed bamboo and reformed bamboo/aluminium composite. *Journal of Materials Science* 29: 5990–5996.

Liu Z, Jiang Z, Cai Z, Fai B, Yu Y & Liu X. 2012. Dynamic mechanical thermal analysis of moso bamboo (*Phyllostachys heterocycla*) at different moisture. *BioResources* 7: 1548–1557.

Malanit P, Frühwald A & Barbu MC. 2011. Physical and mechanical properties of oriented strand lumber made from an Asian bamboo (*Dendrocalamus asper* Backer). *European Journal of Wood and Wood Products* 69: 27–36.

Maloney TM. 1993. *Modern Particleboard and Dry-Process Fiberboard Manufacturing.* Miller Freeman Inc, San Francisco.

Manalo RD & Acda MN. 2009. Effect of hot oil treatment on physical and mechanical properties of three species of Philippine bamboo. *Journal of Tropical Forest Science* 21: 19–24.

Matan N, Kyokong B & Preechatiwong W. 2007. Softening behavior of black sweet-bamboo (*Dendrocalamus asper* Backer) at various initial moisture contents. *Walailak Journal of Science and Technology* 4: 225–236.

Morsing N. 2000. Densification of wood-the influence of hygrothermal treatment on compression of beech perpendicular to the grain. PhD thesis, Technical University of Denmark, Kgs. Lyngby.

Obataya E, Norimoto M & Gril J. 1998. The effects of adsorbed water on dynamic mechanical properties of wood. *Polymer* 39: 3059–3064.

Olsson T. 1999. Physical and morphological aspects of linseed oil impregnated pine. PhD thesis, University of Lulae, Lulae.

Olsson T, Megnis M, Varna J & Lindberg H. 2001. Measurement of the uptake of linseed oil in pine by the use of an X-ray microdensitometry technique. *Journal of Wood Science* 47: 275–281.

Östberg G, Salmen L & Terlecki J. 1990. Softening temperature of moist wood measured by differential calorimetry. *Holzforschung* 44: 223–225.

Sehlstedt-Persson M. 2003. Colour responses to heat-treatment of extractives and sap from pine and spruce. Pp 459–464 in Ispas M & Chiriacescu ST (eds) *Proceedings of the 8th IUFRO International Wood Drying Conference.* 24–29 August 2003, Brasov.

Sivonen H, Maunu SL, Sundholm F, Jämsä S & Viitaniemi P. 2005. Magnetic resonance studies of thermally modified wood. *Holzforschung* 56: 648–654.

Sumardi I, Ono K & Suzuki S. 2007. Effect of board density and layer structure on the mechanical properties of bamboo oriented strandboard. *Journal of Wood Science* 53: 510–515.

Sundqvist B. 2004. Colour changes and acid formation in wood during heating. PhD thesis, Lulea University of Technology, Lulea.

Sutnaun S, Srisuwan S, Jindasai P, Cherdchim B, Matan N & Kyokong B. 2005. Macroscopic and microscopic gradient structures of bamboo culms. *Walailak Journal of Science and Technology* 2: 81–97.

Tjeerdsma BF & Militz H. 2005. Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. *Holz als Roh- und Werkstoff* 63: 102–111.

Windeisen E, Strobel C & Wegener G. 2007. Chemical changes during the production of thermo-treated beech wood. *Wood Science and Technology* 41: 523–536.

Wolcott MP, Kamke FA & Dillard DA. 1990. Fundamentals of flake board manufacture: viscoelastic behavior of the wood component. *Wood and Fiber Science* 22: 345–361.