Journal of Materials Research and Technology 27 (2023) 5257–5265

Contents lists available at ScienceDirect

Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Analyzing the impact of veneer layup direction and heat treatment on plywood strain distribution during bending load by digital image correlation (DIC) technique

Fang-Yu Hsu [a,1], Ke-Chang Hung [b,1], Jin-Wei Xu [a], Jian-Wei Liu [a], Yi-Hung Wu [c], Wen-Shao Chang [d], Jyh-Horng Wu [a,e,*]

[a] *Department of Forestry, National Chung Hsing University, Taichung, 402, Taiwan*
[b] *Department of Wood Based Materials and Design, National Chiayi University, Chiayi, 600, Taiwan*
[c] *Secretariat Office, National Chiayi University, Chiayi, 600, Taiwan*
[d] *Lincoln School of Architecture and the Built Environment, University of Lincoln, Lincoln, LN6 7TS, United Kingdom*
[e] *Advanced Plant and Food Crop Biotechnology Center, National Chung Hsing University, Taichung, 402, Taiwan*

A R T I C L E I N F O

Handling Editor: P.Y. Chen

Keywords:
Digital image correlation
Heat treatment
Layup direction
Plywood
Strain distribution

A B S T R A C T

In this study, radiata pine veneers and phenol-formaldehyde resin were used to prepare specimens of 5-ply plywood with different layup directions and heat treatments of veneers. The physical and flexural properties of the plywood specimens were assessed, and digital image correlation (DIC) analysis was employed to determine the strain distribution of the plywood under bending loads. The results of the static mechanical strength and DIC tests showed that the plywood with a small-angle veneer layup ($[0]_5$ and [0,22.5,0,22.5,0]) exhibited a better longitudinal modulus of rupture (MOR//), while [0,45,0,45,0] plywood showed the least bending strength and most strain. Moreover, the results revealed that for plywood composed of veneers that were fully heat treated at 200 °C ($5T_{200}$), the moisture content was efficiently decreased, and the modulus of elasticity parallel to grain (MOE//) was the highest. The DIC images indicated that the largest strain along the x-direction (ε_{xx}) was concentrated on the tensile side of untreated plywood (5N) and on the opposite side of plywood composed of heat-treated veneers, except for the plywood composed of veneers treated at 220 °C ($5T_{220}$). Of these, $5T_{200}$ plywood showed the least strain. In addition, the plywood with 200 °C heat-treated veneers instead of face and core layers ($NTNTN_{200}$) or crossband layers of untreated veneers ($TNTNT_{200}$) had larger strain values than 5N and $5T_{200}$ plywood specimens, with $NTNTN_{200}$ plywood having the greatest strain. According to the above results, appropriate layering and heat treatment of veneers can effectively improve the dimensional stability and flexural properties of plywood.

1. Introduction

In recent years, the importance of environmental protection and conservation of natural resources has gradually been recognized worldwide. The effective and reasonable use of timber resources has been widely discussed, as the supply of large logs has been decreasing year by year, and the cost of timber has been increasing. To reduce the use of logs and increase the utilization rate of fast-growing tree species, scholars and experts have developed wood-based composites such as plywood, fiberboard, particleboard, and oriented strand board (OSB), which have been widely used in daily life and the construction industry. Plywood is mainly made from odd numbers of layers of veneers in a sequence of face veneer, crossband veneer, core veneer(s), crossband veneer, and back veneer; the veneers are peeled or sliced from logs [1]. Therefore, plywood not only eliminates the natural defects and anisotropy of wood but also has the advantages of easy processing, low cost, and availability of large panels, making it a commonly used substitute for solid wood [2]. Furthermore, according to the study by Bier [3], the bending properties parallel to grain of plywood are better when layers of crossband veneer and face/back veneer are parallel, i.e., oriented in the same direction (0°), than perpendicular (90°). However, when wood-based panels are exposed to a humid environment, cracking is

* Corresponding author. Department of Forestry, National Chung Hsing University, Taichung, 402, Taiwan.
E-mail address: eric@nchu.edu.tw (J.-H. Wu).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.jmrt.2023.10.304
Received 27 April 2023; Received in revised form 2 October 2023; Accepted 29 October 2023
Available online 9 November 2023

more severe in panels made by parallel layup than perpendicular layup [4]. Therefore, plywood with parallel or perpendicular laminated veneers has its own advantages, and both forms are widely used in wooden construction [5].

In general, the veneers commonly used in plywood are obtained from small-to medium-diameter trees or fast-growing tree species. As they contain a high proportion of juvenile wood, they are particularly susceptible to degradation caused by biological, moisture, weather, stress, and human factors. Therefore, they need to be treated with special methods to improve the properties of plywood, expand their outdoor application range, and extend their service life [6–9]. Chemical modification is one of the most common and traditional methods. However, such methods are cumbersome, and they require chemical agents that can be harmful to humans and the environment. Thus, it is likely that their application will be restricted. Therefore, low-cost and environmentally friendly physical heat treatment technology has gradually received more attention [1,10–12]. Early research indicated that heat treatment not only effectively reduced the number of hydrophilic functional groups in wood but also enhanced its dimensional stability and decay resistance [13–17]. Moreover, extensive research has been conducted on the impact of heat treatment on the physical, mechanical, decay resistance, and bonding properties of plywood [1,9,18,19]. Our previous study demonstrated that the heat treatment of radiata pine (*Pinus radiata*) veneers at various temperatures improved hydrophobicity and resistance to swelling; the most significant improvement was observed veneers heat treated at 200 °C [20]. However, the internal structure of composite materials is complex, making it susceptible to defects, such as delamination between veneers and adhesive layers and cracking of veneers or adhesive layers during bending tests. These defects can lead to stress concentrations. Therefore, the evaluation of strain distributions and strain parameters in wood-based composites is important for structural applications [21–23]).

To accurately evaluate the strain of materials, many researchers have developed various methods of surface deformation and strain measurement, such as electrical resistance strain gauges, photoelasticity methods, geometric moiré techniques, and optical strain measurement methods [21]. Among them, optical strain measurement methods are most commonly used for engineering problems [24]. Currently, the most advanced optical strain measurement technique is digital image correlation (DIC). This technique does not require surface treatment of the specimen, has a simple experimental setup, and does not rely on complex optical systems. DIC offers noncontact, full-surface, high-precision strain measurement and is applicable to all types of material surfaces [24,25–28]. Therefore, in recent years, DIC has been commonly used to investigate the deformation, crack propagation, and strain fields on the surfaces of wood and wood-based composites [27,29]. Khoo et al. [21] highlighted the superior information on surface strain obtained through two-dimensional (2D) DIC techniques compared to one-dimensional techniques. However, current research on the impact of veneer layup direction on the properties of plywood is still very limited. In view of this, the main objective of this study is to systematically investigate the effects of layup sequence and direction of untreated and heat-treated veneers on physical and mechanical properties of plywood and to apply the DIC technique of VIC-2D to analyze changes in the strain distribution of plywood under bending load.

2. Materials and methods

2.1. Materials

Defect-free rotary-cut radiata pine (*Pinus radiata*) veneers with a thickness of 2.2 mm (density: 406 ± 30 kg/m^3; moisture content: 9.7 ± 0.3 %) were kindly supplied by Prime Fortune Co., Ltd. (Kaohsiung, Taiwan). Phenol-formaldehyde resin (PF125; solid content: 46 %, viscosity: 757 cps, curing temperature: 150 °C) was purchased from Chang Chun Plastics Co., Ltd. (Hsinchu, Taiwan).

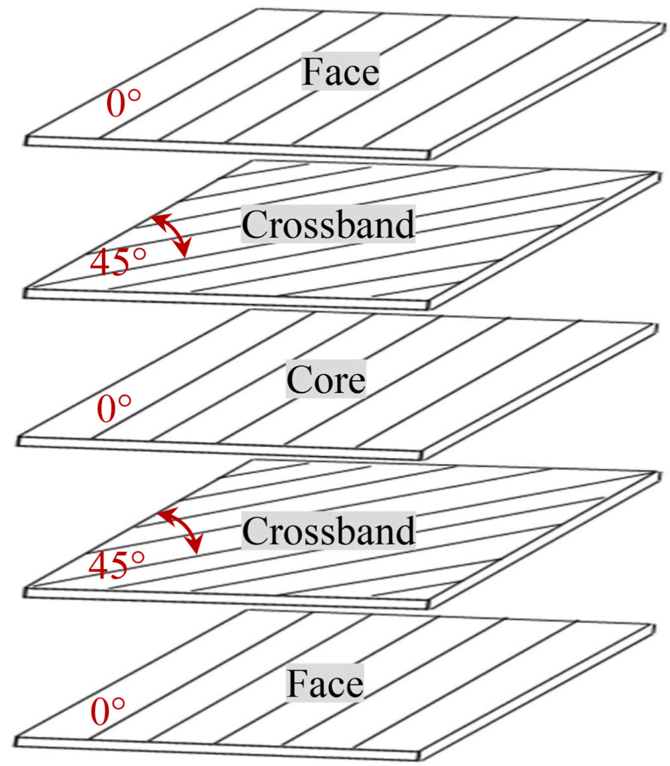

Fig. 1. Schematic diagram of [0,45,0,45,0] plywood layup.

2.2. Heat treatment of veneers

The veneers were kept in a hot air circulating oven (JB-27, Prokao, Kaohsiung, Taiwan) under a continuous flux of nitrogen (20 mL/min) and then oven-dried at 105 °C for 24 h. Subsequently, the veneers were divided into five groups: one acted as a control, and the other four were heat treated at the desired temperature (160, 180, 200, and 220 °C) for 2 h. Finally, the veneers were cooled to room temperature for more than 40 min.

2.3. Preparation of plywood

To investigate the effect of veneer layup directions on the properties of plywood, this study used veneers with different grain angles (0, 22.5, 45, 67.5, and 90°) as crossband veneers and layered them to prepare 5-ply plywood. Fig. 1 illustrates the layup diagram for [0,45,0,45,0] plywood as an example. In addition, plywood with partially ($TNTNT_{xxx}$ and $NTNTN_{xxx}$) and fully heat-treated ($5T_{xxx}$) veneers were prepared where N represents untreated veneers, T represents heat-treated veneers, and subscript xxx denotes the temperature (160–220 °C) at which the veneer was heat-treated. Five-ply plywood panels with a glue spread level of 140 g/m^2 were produced by combining untreated and heat-treated veneers. The panels were subjected to cold pressing at 1.5 MPa for 1 min and subsequently hot-pressed at 160 °C and 1.5 MPa for 7.5 min using a flat-platen press without press stops. The default dimensions of the plywood specimens were 300 mm × 300 mm with a thickness of approximately 10 mm.

2.4. Determination of plywood properties

To compare the plywood specimens, their physical properties (density and moisture content) and flexural properties were measured under stress parallel to the grain of the face veneer according to CNS 1349 [30] and ASTM D3043 [31], respectively. In brief, the modulus of rupture (MOR//) and modulus of elasticity (MOE//) of the specimens with

Journal of Materials Research and Technology 27 (2023) 5257–5265

Table 1
Effects of veneer layup angle and heat treatment on the physical and flexural properties of 5-ply plywood.

Specimen[a]	Density (kg/m^3)	MC (%)	MOR// (MPa)	MOE// (GPa)
$[0]_5$	600 ± 17^A	11.0 ± 0.1^A	76 ± 2^A	8.9 ± 0.5^A
[0,22.5,0,22.5,0]	576 ± 14^{AB}	11.0 ± 0.7^A	73 ± 5^A	8.9 ± 0.9^A
[0,45,0,45,0]	556 ± 21^B	11.0 ± 0.3^A	48 ± 3^C	6.4 ± 0.8^B
[0,67.5,0,67.5,0]	544 ± 14^B	11.3 ± 0.2^A	63 ± 1^B	6.8 ± 0.1^B
[0,90,0,90,0]	554 ± 19^B	11.2 ± 0.3^A	54 ± 4^C	7.1 ± 0.3^B
5N	554 ± 19^{ab}	11.1 ± 0.3^b	54 ± 4^b	7.1 ± 0.3^{abc}
5T$_{160}$	540 ± 31^{ab}	11.1 ± 0.3^{ab}	54 ± 8^b	5.1 ± 1.3^c
5T$_{180}$	520 ± 9^b	11.5 ± 0.4^a	50 ± 6^{bc}	6.2 ± 0.4^{bc}
5T$_{200}$	555 ± 25^{ab}	9.8 ± 0.3^c	50 ± 6^{bc}	9.2 ± 0.9^a
5T$_{220}$	543 ± 22^{ab}	9.2 ± 0.1^d	40 ± 4^c	7.2 ± 1.4^{abc}
NTNTN$_{200}$	593 ± 29^a	7.3 ± 0.2^e	72 ± 4^a	6.9 ± 0.3^{bc}
TNTNT$_{200}$	539 ± 11^{ab}	7.2 ± 0.1^e	53 ± 5^{bc}	7.9 ± 0.7^{ab}

Values are mean ± SD (n = 5). Different letters within the column indicate statistically significant differences at $p < 0.05$.

[a] The numbers within square brackets indicate the angle at which the veneers were laid in a 5-ply plywood. N: untreated veneer. T: heat-treated veneer. Subscript numbers (160, 180, 200, and 220) denote the temperature (°C) at which the veneer was heat treated. 5N, 5T, NTNTN, and TNTNT plywood all adopt a consistent [0,90,0,90,0] configuration.

dimensions of 290 mm × 50 mm × ~10 mm were evaluated by the three-point flexural test with a loading speed of 10 mm/min and a span of 240 mm. Before the test, all samples were conditioned at 20 °C/65 % relative humidity for 2 weeks.

2.5. Digital image correlation analysis for the flexural test

The noncontact technique of digital image correlation (DIC) was employed to measure the surface deformation of a sample. This involved correlating sub-images of a sequence of images captured both before loading and during loading [22,27]. Prior to the experiment, white sprayed paint was used to paint the side face of flexural test specimens, and then black paint was sprayed randomly to create an adequate speckle pattern. In this study, the flexural test was performed by a universal testing machine (Shimadzu AG-10kNX, Tokyo, Japan) equipped with FlyCapture2 (Point Grey, Vancouver, Canada), VIC-2D DIC analysis software (Correlated Solution Inc., Irmo, USA), and a digital camera measurement system [22,28].

A camera (GS3-US-51S5M – C, Point Grey, Vancouver, Canada) with 2448-pixel × 2048-pixel resolution was placed in front of the sample to record the side face image of plywood in TIFF format. FlyCapture2 software (Point Grey, Vancouver, Canada) was used to acquire and prepare images. The unit pixel displacements and strain distributions of the samples were calculated using VIC-2D DIC analysis software. The selected region for DIC analysis was centered around the load cell as the reference point, with a resolution of 1800-pixel × 460-pixel for the experiment.

2.6. Analysis of variance

The results are presented as the mean ± standard deviation (SD). The significance of differences was determined using the Scheffé test, with p values of less than 0.05 indicating statistical significance.

3. Results and discussion

3.1. The effect of veneer layup direction and heat treatment on the physical and flexural properties of plywood

The physical and mechanical properties of the plywood are shown in Table 1. Accordingly, the densities of the $[0]_5$, [0,22.5,0,22.5,0], [0,45,0,45,0], [0,67.5,0,67.5,0], and [0,90,0,90,0] plywood specimens were 600, 576, 556, 544, and 554 kg/m^3, respectively. Except for the $[0]_5$ plywood, there was no statistically significant difference in density among the plywoods. The main reason was that the $[0]_5$ plywood (8.5–9.6 mm) was thinner than the other groups (9.5–10.7 mm), which increased its density. In contrast, the moisture content of all plywood groups was in the 11.0–11.3 % range, and there was no statistically significant difference among them; all specimens met the standard of CNS 1349 [30] for general plywood. In addition, the bending test results of the plywood in Table 1 show that the values of the MOR// were the largest for the small-angle layup plywood ($[0]_5$ and [0,22.5,0,22.5,0]) with values of 76 and 73 MPa, respectively. Similarly, the MOE// showed a similar trend, with both values at 8.9 GPa. In contrast, the MOR// and MOE// of the [0,45,0,45,0] plywood were the smallest, with values of 48 MPa and 6.4 GPa, respectively. This result was similar to the results reported by Bier [3], where the MOE// of plywood decreased as the veneer layup angle increased from 0° to 45° for a 5-ply plywood, and the MOE// slightly increased when the veneer layup angle increased from 45° to 90°. According to the above results, the bending strength parallel to the span direction of the surface veneer was best achieved with a plywood with small-angle veneer layup.

However, to understand the effects of veneers with different heat treatment temperatures and layup sequences on the physical and bending properties of plywood, this study used veneers treated at different temperatures to prepare composite panels and tested their density, moisture content, and flexural properties. As shown in Table 1, the average density of untreated plywood was 554 kg/m^3, while the densities of plywoods composed of veneers heat-treated at 160–220 °C were in the range of 520–555 kg/m^3. However, a statistical analysis did not show statistically significant differences between the densities of heat-treated and untreated plywoods. This result was consistent with those of Ferreira et al. [1], who found that heat-treated veneers had no significant effect on the density of plywood. However, the density of NTNTN$_{200}$ was 593 kg/m^3, which was greater than that of 5T$_{160}$, 5T$_{180}$, and TNTNT$_{200}$. In addition, the moisture content of each plywood in Table 1 showed that the moisture content of the untreated plywood was 11.1 %. When preparing plywood from veneers, heat treating the veneers at 200 and 220 °C could reduce the moisture content of the plywood by 9.8 % and 9.2 %, respectively. The moisture contents of the NTNTN$_{200}$ and TNTNT$_{200}$ plywoods prepared from untreated and 200 °C heat-treated veneers were 7.3 % and 7.2 % less than that of untreated plywood, respectively. This result was similar to the results of Ferreira et al. [1] and Lovrić et al. [19], who found that preparing plywood from veneers heat-treated at higher temperatures could effectively reduce their moisture content. The main reason was that the veneers underwent thermal degradation during heat treatment, which reduced their hemicellulose and hydroxyl content and thus decreased their moisture absorption. Moreover, after heat treatment, the crystallinity of cellulose in veneers increases, and lignin undergoes cross-linking reactions, further reducing the possibility of water molecules entering the veneers [10, 32–35].

Additionally, as shown in Table 1, the MOR// of the untreated plywood was 54 MPa, while the MOR// values of the plywood made from veneers heat-treated at 160, 180, 200, and 220 °C were 54, 50, 50, and 40 MPa, respectively. Except for the group treated at 220 °C, there was no statistically significant difference between the heat-treated groups (5T$_{160–200}$) and the untreated group. However, when the plywood was composed of partially heat-treated veneers, the MOR// of NTNTN$_{200}$ (72 MPa) was greater than that of TNTNT$_{200}$ (53 MPa).

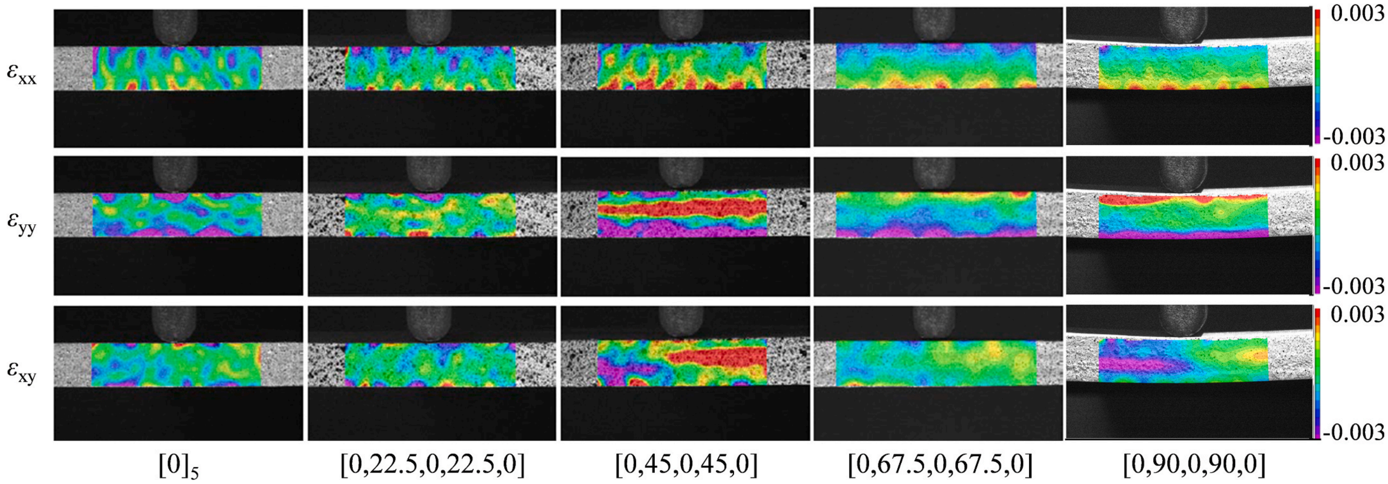

Fig. 2. Strain contours of plywood composed of various veneer layup directions at the destruction state.

Furthermore, the MOE// of untreated plywood was 7.1 GPa, while the MOE// of the plywood made from veneers that were fully heat-treated at 160–220 °C were in the 5.1–9.2 GPa range; the largest MOE// value was obtained for the 200 °C group. This trend was similar to the results of Kubojima et al. [36], where the Young's modulus of heat-treated Sitka spruce (*Picea sitchensis*) increased with increasing heat treatment temperature from 120 to 200 °C and reached its maximum value at 200 °C. The MOE// values of $NTNTN_{200}$ (6.9 GPa) and $TNTNT_{200}$ (7.9 GPa) did not differ significantly from that of untreated plywood.

3.2. Influence of veneer layup angle on the bending strain distribution of plywood

To investigate the strain distributions of the specimens under different loads during the bending test, this study used DIC to monitor the variations. Through this approach, this study aimed to understand the influences of the veneer layup angle and heat treatment on strain in plywood. The strain of a test specimen was mainly divided into normal strain and shear strain, and the normal strain included components in the x-direction (ε_{xx}) and the y-direction (ε_{yy}). In the case of ε_{xx}, when the strain was a positive value, the strain contour appeared in red, indicating that the test specimen was undergoing tensile deformation. Conversely,

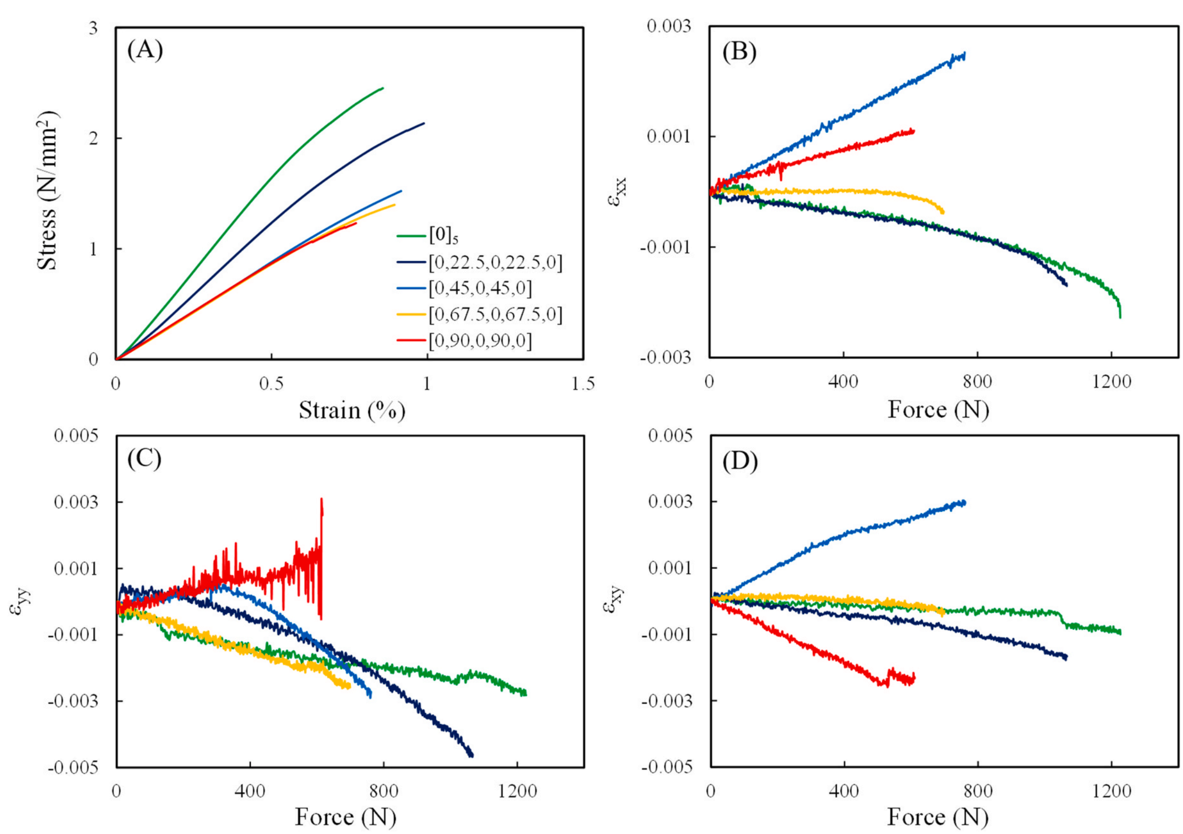

Fig. 3. Stress–strain curve (A), normal strains in the x- and y-directions (ε_{xx}, ε_{yy}) (B, C), and xy-plane shear strain (ε_{xy}) (D) of plywood with various layup directions of veneer at different load levels.

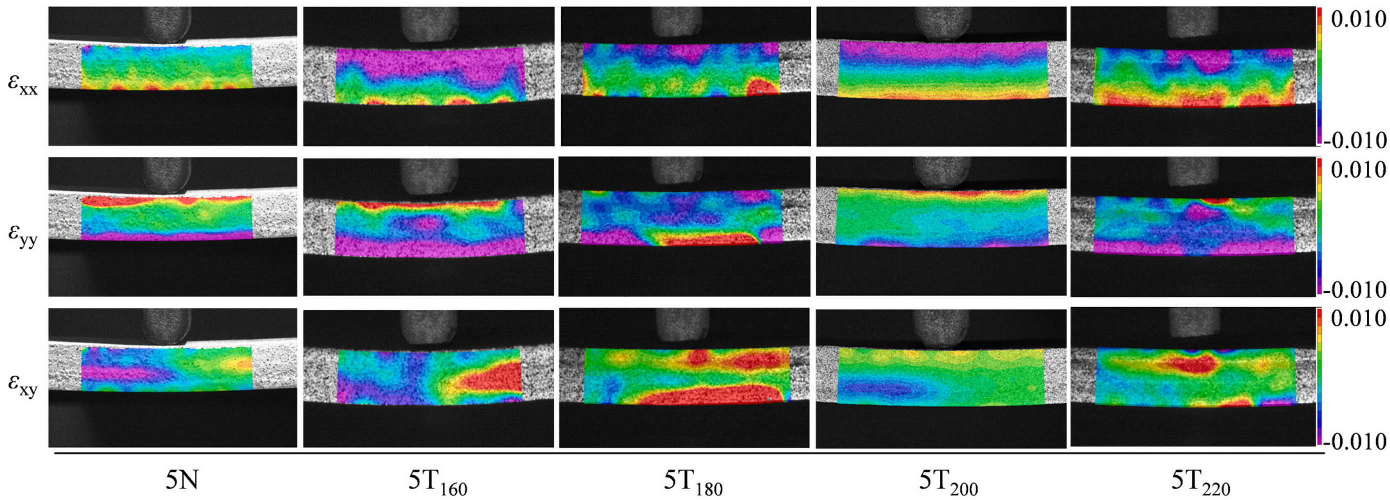

Fig. 4. Strain contours of plywood composed of fully heat-treated veneers with different temperatures at the destruction state.

when the contour appeared in purple, it indicated that the strain was negative, showing a compressive phenomenon. The distribution of the ε_{yy} contour was opposite to that of ε_{xx}. After the bending test, when the tensile or compressive phenomena were observed in the x-direction, the opposite phenomena were observed in the y-direction. The main reason for this phenomenon was that the material did not have a long-axis stress during bending, and its strain was affected by horizontal normal stress and related to Poisson's ratio of the material [37]. For the shear strain (ε_{xy}) in the xy-plane, the contour distributions on both sides of the neutral axis were symmetrical, and the strain increased with increasing load.

Based on the strain contours of the plywood with different veneer layup directions at the point of failure, as presented in Fig. 2, when the load reached the critical value of the specimen, the compression side of small-angle layup plywood ($[0]_5$ and [0,22.5,0,22.5,0]) exhibited a concentration of ε_{xx}, whereas for crossband veneer layup angles greater than 45°, ε_{xx} concentrated on the tensile side. It was hypothesized that the main reason for this phenomenon was that the $[0]_5$ and [0,22.5,0,22.5,0] plywood specimens were stiffer (Table 1), and thus the compressive strain was greater. Conversely, when the crossband veneer layup angle was greater than 45°, the MOE// value of the plywood was smaller (Table 1), which was prone to elastic deformation, and thus the strain was concentrated on the tensile side. For ε_{yy}, the strain of small-angle layup plywood ($[0]_5$ and [0,22.5,0,22.5,0]) was mostly concentrated on the tensile side, while it was concentrated on the compression side of the [0,90,0,90,0] plywood, and its strain distribution was opposite to that of ε_{xx}. Regarding ε_{xy}, the [0,45,0,45,0] plywood exhibited the largest shear strain, and in its ε_{yy} contour, the strain was concentrated not only on the tensile side but also at the center of the samples. This may be influenced by the weaker bond strength between individual veneers. In general, the failure of samples is mainly attributed to structural changes caused by shear stress. Therefore, it can be inferred that the [0,45,0,45,0] plywood should have lower flexural properties, which was consistent with the results shown in Table 1. In addition, this test result conformed to the trend that when the shear strain of the test specimen was small, its flexural properties tended to be greater, as noted by Guan et al. [38] and Bardak [22].

To understand the changes in strain values of the test specimen under different loads, this study investigated the average normal strain (ε_{xx} and ε_{yy}) and plane shear strain (ε_{xy}) on the surface of the test specimen, and the results are shown in Fig. 3. In the stress−strain curve of the plywood in Fig. 3A, at the same strain and point of failure, small-angle layup plywood ($[0]_5$ and [0,22.5,0,22.5,0]) had more stress, indicating excellent flexural properties, which was consistent with the bending strength of the plywood shown in Table 1. Furthermore, as shown in Fig. 3B, the ε_{xx} values of small-angle layup plywood ($[0]_5$ and [0,22.5,0,22.5,0]) were negative, indicating that their strain was mainly compressive strain, and thus the strain was concentrated on the compression side. However, when the crossband veneer layup angle was greater than 45°, ε_{xx} was positive, indicating that the strain was mainly tensile strain, and the strain was concentrated on the tensile side, which was consistent with the result for the ε_{xx} contour in Fig. 2. In addition, Fig. 3C shows that the ε_{yy} of the [0,90,0,90,0] plywood had an unstable distribution, but the strain was still concentrated on the compression side. According to the diagram of ε_{xy} in Fig. 3D, the absolute values of ε_{xy} for [0,45,0,45,0] and [0,90,0,90,0] plywood were larger. Moreover, the ε_{xy} contours of both plywood types exhibited a phenomenon of strain concentration in the center of samples (Fig. 3), which was speculated to be a significant factor contributing to their weaker bending strength. Based on the above test results, plywood with smaller angle layering ($[0]_5$ and [0,22.5,0,22.5,0]) was stiffer and had superior mechanical properties, while [0,45,0,45,0] plywood had less bending strength and maximum strain. These results were consistent with the static bending strength results (Table 1), indicating the reliability of DIC in monitoring wood-based composite strain.

3.3. Influence of veneers heat treated at different temperatures on the bending strain distribution of plywood

Based on the ε_{xx} contours at the moment of failure for plywood made from untreated and various heat-treated veneers treated in Fig. 4, the strain concentration of untreated plywood (5N) mainly occurred on the tensile side when it reached the critical load. This result was similar to the findings of Bardak [22]. In contrast, except for $5T_{220}$, the strains of all other groups of heat-treated plywood were concentrated on the compression side, with the smallest strain being that of $5T_{200}$. It was inferred that the main reason for this phenomenon was that the plywood made from 200 °C heat-treated veneer was stiffest (Table 1), resulting in smaller strains on the compression side. However, from the strain contours of ε_{yy} at the moment of failure of each group of heat-treated plywood, the strains were mainly concentrated on the tension side, which was opposite to the trend of ε_{xx}. For ε_{xy}, the strains of 5N and $5T_{160}$ were mainly concentrated on both sides of the neutral axis. This result was consistent with the finding by Bodig and Jayne [39] that the maximum shear stress occurred in the neutral axis during bending tests for wood and wood-based composites. In contrast, the shear strains of $5T_{180}$ and $5T_{220}$ were concentrated on the glue line and tension side with larger strain values, which led to their weaker bending strength. However, the shear strain of $5T_{200}$ was the smallest, and its distribution was similar to that of the untreated plywood, mainly concentrated on the left

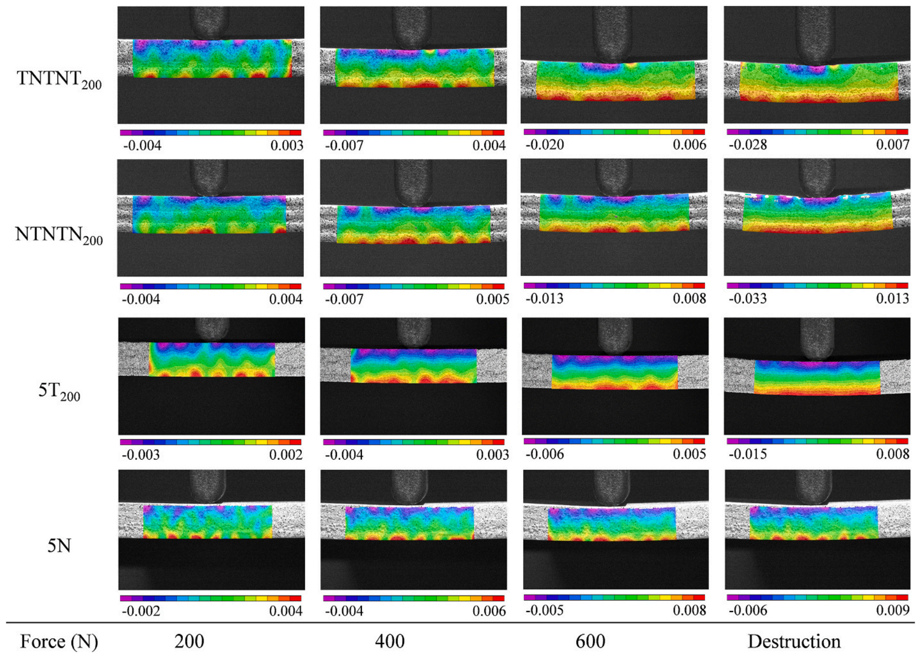

Fig. 5. ε_{xx} contours of plywood composed of fully and partially 200 °C heat-treated veneers at various load levels.

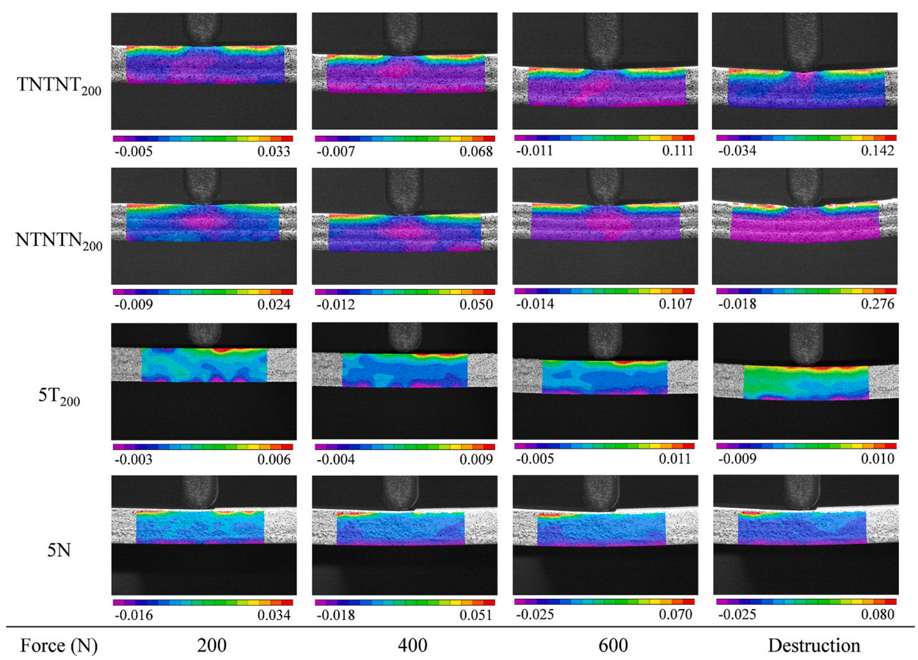

Fig. 6. ε_{yy} contours of plywood composed of fully and partially 200 °C heat-treated veneers at various load levels.

side of the neutral axis. In addition, this test result was consistent with the findings of Guan et al. [38] and Bardak [22], which indicated that heat treatment may improve the bonding quality, resulting in greater flexural properties when the shear strain was smaller. The bonding quality may be attributed to the reduction of the O/C ratio and increase of C1/C2, which improve and activate the veneer surface [40]. Additionally, Chotikhun et al. [41] noted that the appropriate heat treatment reduces the occurrence of lathe checks on the veneer's surface and minimizes surface roughness. This, in turn, ensures continuous bond lines, leading to a stronger plywood. Furthermore, phenol-formaldehyde resin is cured through an acid- or base-catalyzed polycondensation. Therefore, the acetic acid generated from wood heat treatment may promote the curing of acid-catalyzed phenol-formaldehyde resin [41, 42]. However, the shear bond strength of plywood decreases with an increase in treatment temperature, because the surface of heat-treated veneer is more hydrophobic and thus results in a greater decline in bonding performance between veneers [43]. Based on the above results, it was concluded that plywood composed of 200 °C heat-treated veneer exhibited greater stiffness and superior mechanical properties. Therefore, the subsequent investigation of the effect of veneer layup sequence on plywood strain focused only on the veneer that was heat-treated at 200 °C.

In the strain contours of ε_{xx} at different loads of the plywood in Fig. 5, the strains of all groups of plywood increased with increasing load. However, the strain of the untreated plywood was mainly concentrated on the tension side, while the strains of the plywood made from partially

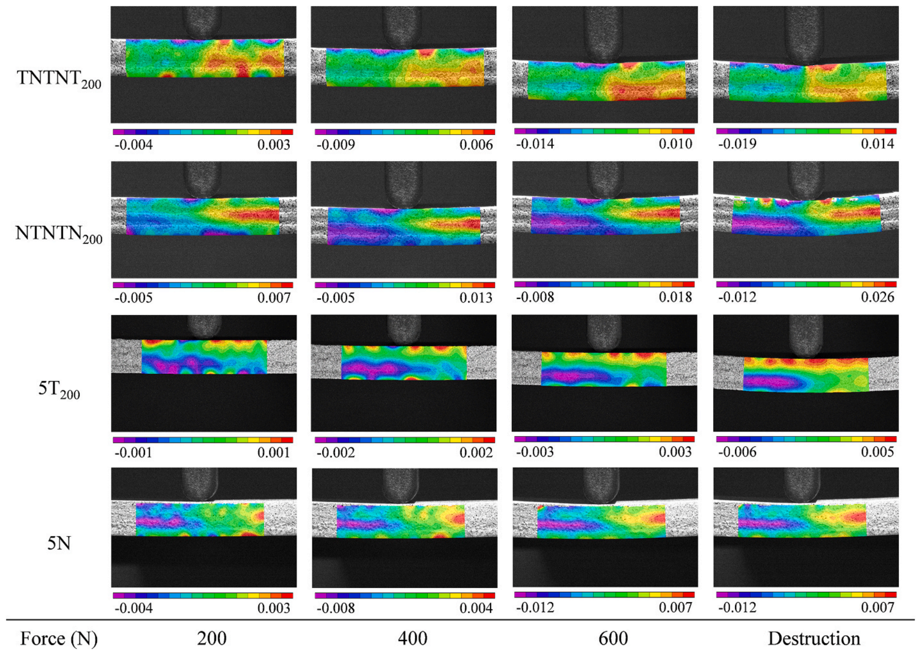

Fig. 7. ε_{xy} contours of plywood composed of fully and partially 200 °C heat-treated veneers at various load levels.

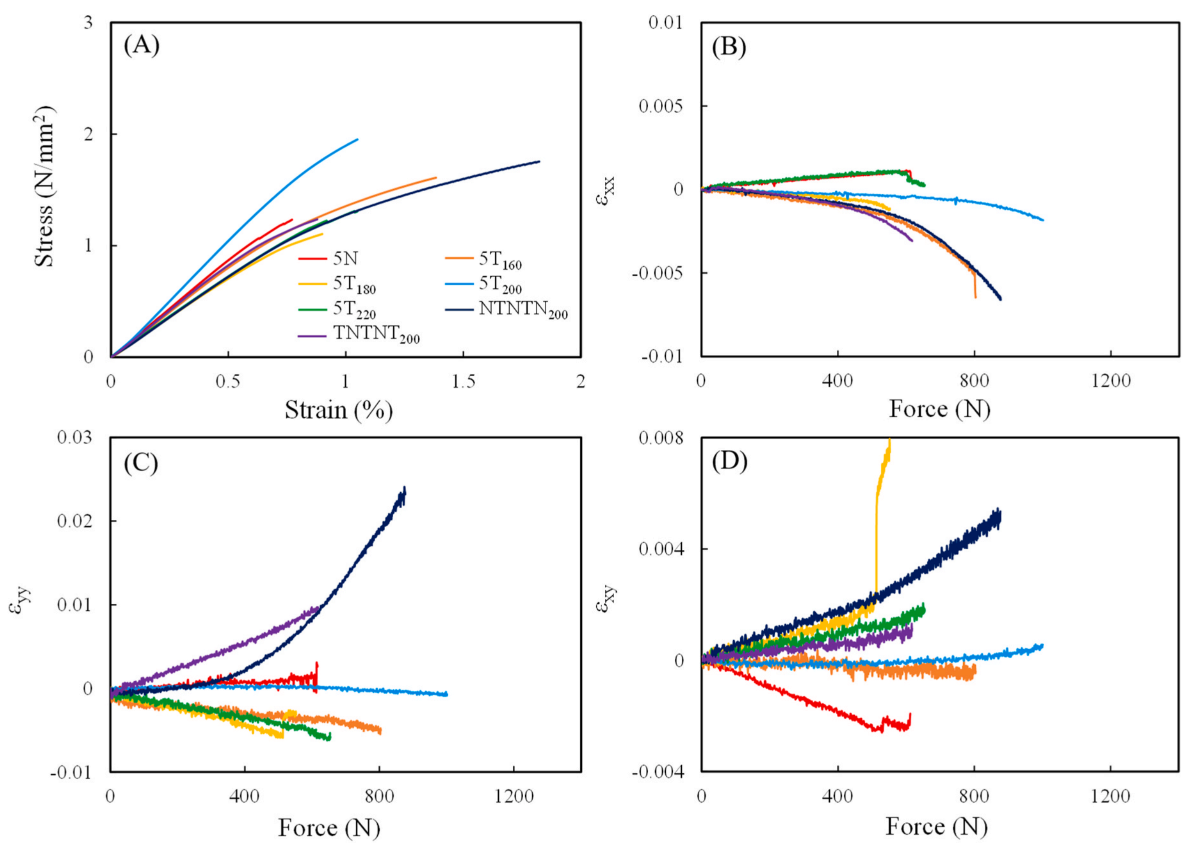

Fig. 8. Stress−strain curve (A), normal strains in the x- and y-directions (ε_{xx}, ε_{yy}) (B, C), and xy-plane shear strain (ε_{xy}) (D) of plywood composed of fully and partially heat-treated veneers at different load levels.

and fully 200 °C heat-treated veneers were distributed on the compression side. Among them, the ε_{xx} strain of the $5T_{200}$ plywood was the smallest, and this result was similar to the MOE// test results shown in Table 1. Similarly, the ε_{yy} strain of all groups of plywood increases with increasing load, as shown in Fig. 6, but the strain distribution of ε_{yy} was opposite to that of ε_{xx}. The strain of the untreated plywood was mainly concentrated on the compression side, while the strains of the plywood made from partially and fully heat-treated veneers were distributed on the tensile side, which was consistent with the results of Lyu [37]. For the strain of ε_{xy} in each group of plywood, Fig. 7 shows that the strains of $NTNTN_{200}$ and $TNTNT_{200}$ were larger than those of the untreated plywood and $5T_{200}$, and the strain value of $NTNTN_{200}$ (with lower MOE//) was the highest, while that of $5T_{200}$ was the lowest.

The stress–strain curves of each plywood are shown in Fig. 8A. The results revealed that the strain of $5T_{200}$ was the lowest under the same stress, indicating that the plywood had the best stiffness, while the $5T_{180}$ specimen was less stiff. However, comparing the strain values of each group of plywood at the moment of failure showed that $NTNTN_{200}$ had the largest strain value. Furthermore, as depicted in Fig. 8B, the compression side bore the bulk of the normal strain in the x-direction for all heat-treated plywood groups except for $5T_{220}$, where the tensile side bore the major strain, which was consistent with the results in Figs. 4 and 5. For the normal strain in the y-direction, the strain was greater for $TNTNT_{200}$ and $NTNTN_{200}$ than 5N and $5T_{200}$ and concentrated on the compression side (Fig. 8C). Furthermore, the average strain of $NTNTN_{200}$ was the largest in the xy-plane shear strain curve in Fig. 8D, which was consistent with the result of the ε_{xy} strain in Fig. 7. In summary, the average ε_{xx}, ε_{yy}, and ε_{xy} values of the plywood made from fully 200 °C heat-treated veneers were the smallest among all plywood specimens, which was consistent with the MOE// results in Table 1, indicating that the $5T_{200}$ plywood had the greatest MOE// and was not prone to elastic deformation.

4. Conclusions

This study mainly investigated the effects of different veneer layup directions and heat treatment temperatures (160, 180, 200, and 220 °C) on the physical and mechanical properties of *radiata pine* veneer-based plywood. DIC was used to analyze the global strain distribution changes and strain concentration areas during bending tests. The results showed that small-angle layup plywood ($[0]_5$ and [0,22.5,0,22.5,0]) had better flexural properties than large-angle layup plywood. The DIC results also showed that the stiffness of plywood with a small-angle layup caused ε_{xx} to concentrate on the compression side, while [0,45,0,45,0] plywood had less bending strength and maximum strain. However, the densities of the untreated (5N) and heat-treated (5T) plywood specimens ranged from 520 to 555 kg/m^3, and the density was higher for the NTNTN plywood prepared from veneer that was partially treated at 200 °C than the plywood composed of fully heat-treated veneer ($5T_{200}$). In addition, when the veneer heat treatment temperature was increased to above 200 °C, the moisture content of the plywood was effectively reduced. Regarding the flexural properties of the untreated and heat-treated plywood, the MOE// of the untreated plywood was 7.1 GPa, while the MOE// of the heat-treated plywood ranged from 5.1 to 9.2 GPa, with $5T_{200}$ having the greatest MOE// (9.2 GPa). Finally, the DIC test results showed that when a specimen reached the critical failure load, the strain was smallest for $5T_{200}$ and concentrated on the compression side, while the strain was largest for $5T_{180}$ plywood. Additionally, the ε_{xx} results for the $NTNTN_{200}$ and $TNTNT_{200}$ plywood specimens concentrated on the compression side, and the strain concentrations were more pronounced than that of $5T_{200}$. Accordingly, it was concluded that plywood composed of veneers with a smaller-angle layup was stronger and had less strain. Moreover, the use of heat-treated veneers effectively improved the dimensional stability and strength properties plywood; the best effects were achieved by using veneers heat-treated at 200 °C.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jyh-Horng Wu reports financial support was provided by Ministry of Science and Technology, Taiwan. Jyh-Horng Wu reports financial support was provided by Forestry Bureau of the Council of Agriculture, Taiwan.

Acknowledgments

This work was financially supported by a research grant from the Ministry of Science and Technology (MOST 108-2313-B-005-023-MY3) and partially by the Forestry Bureau of the Council of Agriculture, Taiwan (110AS-7.4.4-FB-e1).

References

[1] Ferreira BS, Silva JVF, Campos CI. Static bending strength of heat-treated and chromated copper arsenate-treated plywood. Bioresources 2017;12(3):6276–82.
[2] Hoadley RB. Understanding wood: a craftsman's guide to wood technology. Newtown: The Taunton Press; 2006.
[3] Bier H. Strength properties of *Pinus radiata* plywood at angles to face grain. N Z J Forestry Sci 1984;14(3):349.
[4] Rindler A, Vay O, Hansmann C, Muller U. Dimensional stability of multi-layered wood-based panels: a review. Wood Sci Technol 2017;51:969–96.
[5] Tenorio C, Moya R, Muñoz F. Comparative study on physical and mechanical properties of laminated veneer lumber and plywood panels made of wood from fast-growing *Gmelina arborea* trees. J Wood Sci 2011;57:134–9.
[6] Saka S, Ueno T. Several SiO_2 wood-inorganic composites and their fire-resisting properties. Wood Sci Technol 1997;31:457–66.
[7] Li YF, Dong XY, Liu YX, Li J, Wang FH. Improvement of decay resistance of wood *via* combination treatment on wood cell wall: swell-bonding with maleic anhydride and graft copolymerization with glycidyl methacrylate and methyl methacrylate. Int Biodeterior Biodegrad 2011;67:1087–94.
[8] Gérardin P. New alternatives for wood preservation based on thermal and chemical modification of wood–a review. Ann For Sci 2016;73:559–70.
[9] Zanuttini R, Castro G, Cremonini C, Negro F, Palanti S. Thermo-vacuum treatment of poplar (*Populus* spp.) plywood. Holzforschung 2020;74:60–7.
[10] Hill CAS. Wood modification: chemical, thermal and other process. John Wiley & Sons; 2006.
[11] Kaboorani A, Faezipour M, Ebrahimi G. Feasibility of using heat treated wood in wood/thermoplastic composites. J Reinforc Plast Compos 2008;27:1689–99.
[12] Chien Y-C, Yang T-C, Hung K-C, Li C-C, Xu J-W, Wu J-H. Effects of heat treatment on the chemical compositions and thermal decomposition kinetics of Japanese cedar and beech wood. Polym Degrad Stabil 2018;158:365–78.
[13] Tjeerdsma BF, Boonstra M, Pizzi A, Tekely P, Militz H. Characterisation of thermally modified wood: molecular reasons for wood performance improvement. Eur J Wood Wood Prod 1998;56:149.
[14] Kamdem DP, Pizzi A, Jermannaud A. Durability of heat-treated wood. Eur J Wood Wood Prod 2002;60(1):1–6.
[15] Pétrissans M, Gérardin P, El bakali I, Serraj M. Wettability of heat-treated wood. Holzforschung 2003;57(3):301–7.
[16] Gosselink RJA, Krosse AMA, Van der Putten JC, Van der Kolk JC, de Klerk-Engels B, Van Dam JEG. Wood preservation by low-temperature carbonisation. Ind Crop Prod 2004;19(1):3–12.
[17] Yildiz S, Gezer ED, Yildiz UC. Mechanical and chemical behavior of spruce wood modified by heat. Build Environ 2006;41(12):1762–6.
[18] Goli G, Cremonini C, Negro F, Zanuttini R, Fioravanti M. Physical-mechanical properties and bonding quality of heat treated poplar (I-214 clone) and ceiba plywood. iForest 2014;8:687–92.
[19] Lovrić A, Zdravković V, Popadić R, Milić G. Properties of plywood boards composed of thermally modified and non-modified poplar veneer. Bioresources 2017;12(4):8581–94.
[20] Hsu F-Y, Hung K-C, Xu J-W, Wu T-L, Wu J-H. Physicomechanical properties and creep behavior of plywood composed of fully and partially heat-treated veneers. Wood Sci Technol 2021;55:445–60.
[21] Khoo S-W, Karuppanan S, Tan C-S. A review of surface deformation and strain measurement using two-dimensional digital image correlation. Metrol Meas Syst 2016;23(80):461.
[22] Bardak T. Effects of different advanced engineering materials on deformation behaviour of wood structure materials. Bioresources 2019;14:180–92.
[23] Lee T-I, Jo W, Kim W, Kim J-H, Paik K-W, Kim T-S. Direct visualization of cross-sectional strain distribution in flexible devices. ACS Appl Mater Interfaces 2019;11 (22):13416.
[24] Valle V, Laou L, Léandry I, Yotte S, Rossignol S, Hedan S. Crack analysis in mudbricks under compression using specific development of stereo-digital image correlation. Exp Mech 2018;58(3):475–86.
[25] Kwon OH, Kim ST, Kang JW. A study of the strain measurement for Al6061-T6 tensile specimen using the digital image correlation. J Korean Surg Soc 2013;28(4): 26–32.
[26] Mahal M, Blanksvärd T, Täljsten B, Sas G. Using digital image correlation to evaluate fatigue behavior of strengthened reinforced concrete beams. Eng Struct 2015;105:277–88.
[27] Bardak T, Bardak S, Sözen E. Determination of strain distributions of solid wood and plywood in bending test by digital image correlation. Kastamonu University Journal of Forestry Faculty 2017;17(2):354–61.
[28] Nguyen VT, Kwon SJ, Kwon OH, Kim YS. Mechanical properties identification of sheet metals by 2D-digital image correlation method. Procedia Eng 2017;184: 381–9.

[29] Ling H, Samarasinghe S, Kulasiri GD. Modelling variability in full-field displacement profiles and Poisson ratio of wood in compression using stochastic neural networks. Silva Fenn 2009;43:871–87.
[30] CNS Standard. 1349, Plywood. 2014.
[31] ASTM standard. D3043–06, Standard test methods for structural panels in flexure. 2006.
[32] Esteves BM, Pereira HM. Wood modification by heat treatment: a review. Bioresources 2009;4(1):370–404.
[33] Windeisen E, Bächle H, Zimmer B, Wegener G. Relations between chemical changes and mechanical properties of thermally treated wood. Holzforschung 2009;63:773–8.
[34] Wentzel M, Fleckenstein M, Hofmann T, Militz H. Relation of chemical and mechanical properties of *Eucalyptus nitens* wood thermally modified in open and closed systems. Wood Mater Sci Eng 2019;14:165–73.
[35] Zhou F, Fu Z, Gao X, Zhou Y. Changes in the wood-water interactions of mahogany wood due to heat treatment. Holzforschung 2020;74:853–63.
[36] Kubojima Y, Okano T, Ohta M. Vibrational properties of Sitka spruce heat-treated in nitrogen gas. J Wood Sci 1998;44:73–7.
[37] Lyu W-D. Using digital image correlation method to investigate the rolling shear properties of cross-laminated timber. Thesis: National Taiwan University; 201888pp [in Chinese)].
[38] Guan M, Yong C, Wang L. Microscopic characterization of modified phenol-formaldehyde resin penetration of bamboo surfaces and its effect on some properties of two-ply bamboo bonding interface. Bioresources 2014;9:1953–63.
[39] Bodig J, Jayne BA. Mechanics of wood and wood composites. Krieger Publishing Company; 1993.
[40] Ji Y, Qi Y, Zhu R, Ma H, Zhang Y, Yu W. Thermophysical molding treatments on thick wood veneer. Polymers 2022;14(17):3516.
[41] Chotikhun A, Kittijaruwattana J, Lee SH, Salca EA, Arsyad WOM, Hadi YS, et al. Characterization of plywood made from heat-treated rubberwood veneers bonded with melamine urea formaldehyde resin. J Wood Sci 2023;69(1):1–9.
[42] Sharshira EM, Ataalla AA, Hagar M, Salah M, Jaremko M, Shehata N. Novel novolac phenolic polymeric network of chalcones: synthesis, characterization, and thermal–electrical conductivity investigation. Molecules 2022;27(17):5409.
[43] Candana Z, Büyüksarı U, Korkut S, Unsal O, Çakıcıer N. Wettability and surface roughness of thermally modified plywood panels. Ind Crop Prod 2012;36:434–6.