Research paper

Bending Strength Mechanism and Acoustic Emission Behavior of Heat-treated Wood

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【Abstract】Air-dried clear spruce (*Picea sitchensis*) specimens after heat-treated under various temperature and time conditions were used to clarify the bending strength mechanisms and the Acoustic Emission (AE) characteristics during static bending tests. The specimens were heat-treated using 20 different conditions with combination of temperatures (40, 80, 120, 160 and 200℃) and time (8, 24, 72 and 120 h). In these experiments an AE sensor with a resonant frequency of 140 kHz was mounted onto the tensile side of the specimen. The AE sensor location was about 30 mm left side from the center of the specimen. The modulus of rupture (σ), static Young's modulus (E), deflection and AE events were measured. The σ decreased with the increase in heating time at temperatures above 160℃. The E insignificantly varied the heat-treated woods in the range from 40 to 160℃ with the heating time from 8 to 120 h. However, the E was remarkably influenced under the treatments at 200℃ with heating duration. The AE events continuously accumulated from the initial minute fracture to the load at failure according to the structural mechanics of the wood that were changed as a result of the heat treatment effect. Moreover, AE events before reaching the failure load level increased relatively, recognizing that the strain energy stored in the heat-treated wood due to the reduction in toughness (the decrease of the deflection in plastic region) decreased. These results indicate that using AE monitoring techniques in the static bending tests to evaluate the heat-treated woods could assess the variations in the bending strength mechanism.

【Key words】 Heat treatment, Bending strength, Static Young's modulus, Acoustic Emission (AE), Acoustic Emission events (AE events).

研究報告

熱處理木材的彎曲強度機構與其 AE 行爲

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【摘要】本研究係以無瑕疵之雲杉（*Picea sitchensis*）氣乾材，作爲評估木材受熱處理後之彎曲強度機構與其在彎曲強度試驗時所發生的音射（AE）行為。試材在不同溫度（40、80、120、160 及 200℃），加熱時間（8、24、72 及 120 h）等條件組合熱處理後，測定其彎曲強度，彈性係數及變形量，並同時偵測在彎曲強度試驗所發生之音射事件（AE events）。AE 試驗使用共振周波數 140 kHz 之 AE 感應器（sensor），將其裝置於試材下方離載重 3 公分處。結果顯示，在溫度超過 160 ℃ 以上，彎曲強度隨加熱時間增加而降低。彈性係數於加熱溫度 40 至 160℃ 與其加熱時間爲 8 至 120 h 時無明顯變化，但在溫度 200℃ 時，隨加熱時間增加則有顯著影響。同時得知，試材受熱處理，AE 事件由最初微小破壞開始發生並連續累積直到最大（破壞）載重。又知材內之應變能量因其韌性降低（即塑性領域之變形量減少）而減少，因此導致在破壞載重前，AE 事件相對的增加。本研究得知應用 AE 偵測技術在彎曲強度試驗時，能進一步探討木材經熱處理後之彎曲強度機構的破壞行爲。

【關鍵字】 熱處理、彎曲強度、彈性係數、音射（AE）、音射事件（AE events）

I. INTRODUCTION

In wood research a great deal of attention is paid to the influence of heat treatment on the wood properties. Woods are generally heated when dried to obtain various good quality characteristics and mechanical properties that are beneficial for many industrial and domestic applications, such as the structural members in furniture or architecture. (Kollmann *et al.*, 1967; Suzuki *et al.*, 1993). These changes in the mechanical properties depend on temperature and the timing of the drying process. Temperature can cause changes in the anatomical structure, chemical composition, and physical and mechanical properties of the wood (Sumi, 1978; 1982). The properties of heat-treated wood are usually improved at first and then deteriorate with continued heat treatment. This is because of the crystallization and the disintegration of crystallites in the wood caused by heat. Those phenomena depended on the heating temperature and heating duration (Hirai *et al.*, 1972; Bhuiyan *et al.*, 2000). Many investigators have studied the influence of heat treatment on the physical and mechanical properties of woods. For instance: the reduction in weight, hygroscopicity (Hirai *et al.*, 1972), dielectricity (Lin, 1969), elasticity (Kadita *et al.*, 1961) and the deflection and rupture behavior (Kubojima *et al.*, 2000).

The increasing use of various woods and composite materials in structural applications requires better detection methods for complex damage (minute fracture) development under loads has created a need for efficient and reliable testing techniques. Acoustic Emission (AE) techniques have been considered the prime candidate for monitoring the structural health and damage in loaded structures. The AE techniques offer the user a number of inherent advantages, including continuous sensitive monitoring capabilities and the possibility of examining the whole volume of a structure (Miller *et al.*, 1978; Surgeon *et al.*, 2000). The AE techniques that can be used during the service life of these materials clearly have the potential to serve as a damage detection technique for woods and wood-based materials. They are one of the most effective methods for determining the relationships between mechanical properties and changes in the internal structure (Noguchi, 1991; Huang, 1994; Hwang, 1996; Fujii, 1997; Lin, 2002).

Minute fractures in woods are gradually generated until failure when the woods undergo deformation. Elastic waves are generated because of the release of strain energy stored in the wood. The aims of this study were to apply AE monitoring techniques during static bending tests to evaluate the bending strength of heat-treated wood and to examine the characteristics of AE monitoring. Air-dried clear spruce specimens were heat-treated under various temperature and time conditions and examined. The load, deflection and AE characteristics were investigated using static bending tests with the aid of an AE monitoring system. The fundamental information obtained from the bending strength mechanisms and AE behavior of heat-treated wood, was expressed by the relationships between the modulus of rupture, static Young's modulus, deflection and AE events.

II. MATERIALS AND METHODS

(I) *Specimen preparation and heat treatment*

In these experiments spruce (*Picea sitchensis*) lumber was air-dried and specimens with dimensions 12 x 12 x 240 (R x T x L) mm were prepared. All specimens were conditioned to equilibrium at 20℃ with 65% RH for about four weeks. The average moisture content was 11.7% and the density at this moisture content was 0.40 ± 0.02 g/cm^3.

Before dividing the specimens into each experimental group, 265 defect free specimens were chosen and their static Young's modulus (E) was individually measured. The distribution of E is shown in Fig. 1. The results obtained indicated that the spruce specimens exhibited E values

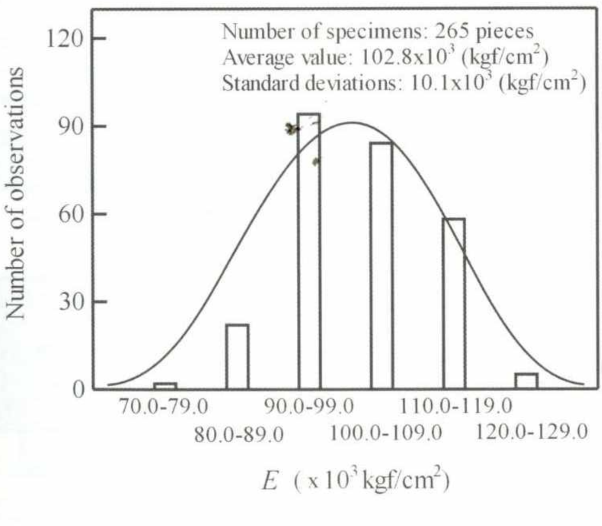

Fig. 1. Distribution of E for all experimental (untreated) speciments.

Note Histogram: Experimental value, Curve: Theoretical value. E : Static Young's modulus.

centralized from 90.0 to 110.0 (x 10^3 kgf/cm^2). The average E value was 102.8 ± 10.1 (x 10^3 kgf/cm^2). For this study, the specimens with distribution of the E from 90.0 to 119.0 (x 10^3 kgf/cm^2) were selected and randomly divided into 21 groups of 10 specimens each. These specimen groups were assigned to 20 different heat treatments with 1 group used as the control specimens. The heat treatment conditions involved five levels of temperature (40, 80, 120, 160 and 200°C) and four levels of heating time (8, 24, 72 and 120 h). All specimens were heat-treated using a convection oven (LC-122, Tabai Espec Corp.). After the heat treatment was completed, the specimens were left at 20°C with 65% RH for about three weeks. Specimen density was then measured. The specimens were placed into convection ovens at 105°C for over 24 h to determine the actual moisture content after static bending tests using AE measurements.

(II) *Static bending tests with AE monitoring system*

The AE monitoring apparatus and the static bending tests for examining the heat-treated specimen are illustrated in Fig. 2. The static bending tests were conducted in accordance with the central concentration loading method (JIS Z 2113, 2000). A universal-testing machine (Shimadzu Corp., AG-100 KNE) at a crosshead speed of 2 mm/min was used. An AE sensor with a fundamental resonant frequency of 140 kHz was mounted onto the tensile face of the specimen. The AE sensor location was 30 mm left side from the center of the specimen because the static bending failure types for various heat-treated woods occur within 30 mm after the static bending tests (Sumi, 1982). Wax was used to attach the AE sensors to the specimen. The AE signals detected during static bending tests were amplified to 40 dB using a preamplifier (NF

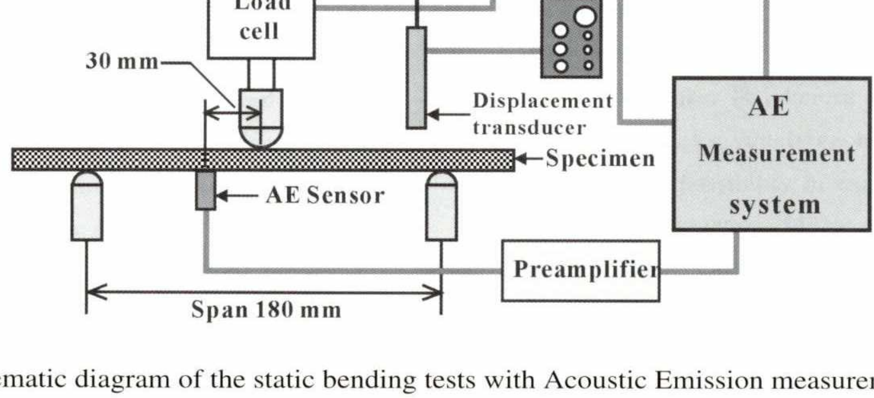

Fig. 2. Schematic diagram of the static bending tests with Acoustic Emission measurement system

Corporation, AE-912). The AE testing system (a MUSIC system, NF Corporation, 9406) was amplified 40 dB again using the main amplifier and discriminated at a threshold level of 400 mV after using a 100 kHz to 1.0 MHz band pass filter. The influence of the heat treatment on the AE generation during static bending tests was examined. The numbers of AE events were counted during the static bending tests when they were greater than the setting threshold voltage. Modulus of rupture (σ), static Young's modulus (E), deflection and AE events were obtained using a computer.

III. RESULTS AND DISCUSSION

(I) *Variations of moisture content (MC) and density (ρ)*

After the specimens were heat-treated under the experimental conditions, the heat treatment influence on changes in moisture content and density are shown in Fig. 3. To compare the changes in moisture content and the density at

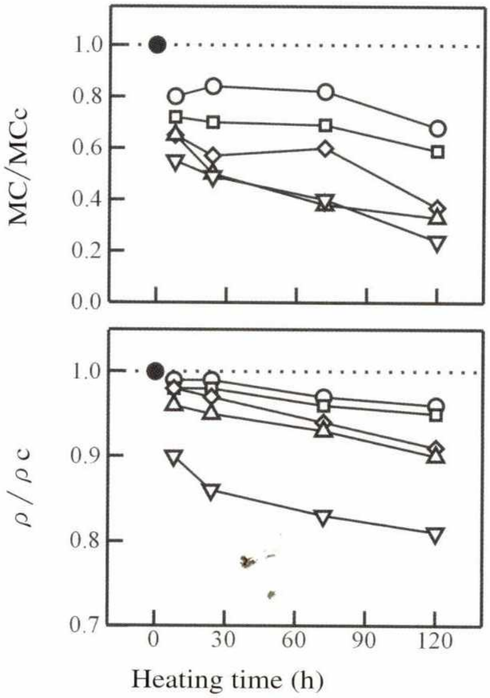

Fig. 3. Changes of moisture content and density due to heat treatment.

Legend ● : 20℃(Control; Untreated specimen),

-○- : 40℃, -□- :80℃, -◇-:120℃

-△- : 160℃, -▽- :200℃.

Note MCc : Moisture content of control specimen,

MC : Moisture content of heat-treated specimen,

ρc : Density of control specimen,

ρ : Density of heat-treated specimen.

each heat treatment, the experimental results were expressed using MC/MCc and $\rho / \rho c$.

MC/MCc was defined as the ratio of moisture content for the heat-treated specimens to the control. Results showed that the longer the heating time, the lower the moisture content, especially for a higher temperature. The MC/MCc values for the heat-treated specimens were little changed with increased heating time when the spruce specimens were heated at temperatures of 40 and 80℃. With the other treatments (120 to 200℃) the moisture content was significantly decreased.

$\rho / \rho c$ was defined as the density ratio of the heat-treated specimen to the control. Results obtained in the case of 200℃ treatments exhibited greater density reductions compared with those treated at 40 to 160℃. Lin (1969), Hirai *et al.* (1972) and Kubojima *et al.* (1998) reported that the density influence of the heat-treated specimen was remarkably due to the decrease in dimension and weight, essentially at a higher temperature. Therefore, these experimental results showed that the $\rho / \rho c$ of the heat-treated specimen at 200℃ treatments was changed significantly while there was little decrease at 40 to 160℃.

(II) *Variations of modulus of rupture (σ) and static Young's modulus (E)*

The modulus of rupture and static Young's modulus for various heat-treated spruce specimens are shown in the top of Fig. 4. These values are expressed by $\sigma / \sigma c$ (ratio of the σ of heat-treated specimen to σ of control one) and *E/Ec* (ratio of the *E* of heat-treated specimen to *E* of control one).

The $\sigma / \sigma c$ value increased little from heating-treatments in the 40 to 120℃ range with a heating duration less than 72 h. However, this value decreased with an increase in heating time over 8 h at temperatures above 160℃. In other words, the higher the temperature (above 160℃) with increase heating duration significantly influenced the σ of the wood. This indicated that the rupture process during the bending tests was related to the brittleness of the heat-treated wood (Kitahara. *et al.*, 1951; Fushitani, 1968).

The static Young's modulus for heat-treated spruce woods is also shown in the bottom of Fig. 4. The *E/Ec* value increased gradually and then became almost unchanged at heating temperatures of 40, 80 and 120℃ with increased heating time. However, this value decreased with heating temperatures above 160℃ with heating duration's over 72 h. This value decreased significantly with 200℃ treatments. In general, the heat-treatment contributed to thermal degradation of the wood constituents and changed the crystallinity in wood celluloses and thermal chemistry in wood hemicelluloses (Fushitani, 1968). Hirar (1972) reported that the changes in crystallinity importantly influenced the toughness of air-dried Hioki (Chamaecyparis obtusa) specimens at higher heating temperatures. The initial crystallization stage occurs with higher temperatures (200℃) or with longer duration heat treatment (150℃ with above 100 h). The initial stage is followed by disintegration of the crystal structure through the thermal decomposition, which includes a decrease in crystallinity, reduction in crystallite size and expansion of the interplanar distance. Bhuiyan *et al.* (2000) also cited that the crystallinity of oven-dried spruce (*Picea sitchensis*) woods increased in the initial stage and decreased in the later stage of heat treatment

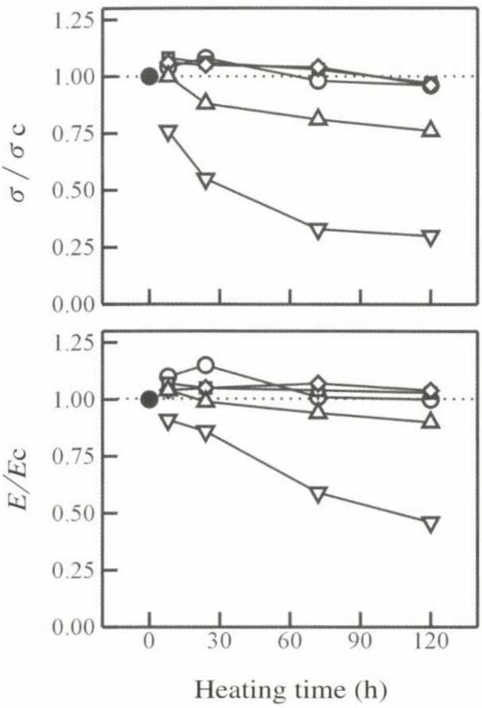

Fig. 4. Effect of heat treatment on bending strength and static Yiung's modulus.

Legend Symbols are the same as Fig. 3

Note σ : Bending strength of heat-treated specimen,

σ c : Bending strength of control specimen,

E : Static Young's of heat-treated specimen,

Ec : Static Young's of control specimen.

owing to crystallization of the quasicrystalline region and thermal degradation in both the crystalline and noncrystalline regions. In this study, the toughness of the wood was significantly decreased when the woods were heat-treated at 200℃ or above 160℃ with heating time greater than 72 h. It is suggested that thermal degradation produces brittleness in the wood and change in cellulose crystallinity resulting in reduction in the bending strength and toughness.

The differences in the dispersion analysis between the heating temperature and the duration were statistically analyzed. There were significant differences at the 1% level among temperatures for both σ and *E* for the heat-treated specimens. Insignificant differences were found among heating duration for σ at 120℃ and for *E* at 160℃. This indicated that the internal structure of wood was changed when the wood was treated using longer duration heat treatment at higher temperatures (above 160℃).

(III) *AE behavior in the static bending tests*

A typical change in AE behavior due to the heat treatment effect in the static bending tests with AE monitoring is shown in Fig. 5. The results showed that AE events were continuously accumulated from the initial minute fracture to the load at failure, even if the structural mechanics of the wood were changed as a result of the heat treatment effect. This indicated that the elastic waves were generated because of the release of strain energy stored in the materials (Miller *et al.*, 1978). Compared to the control (20℃) specimens, the cumulative counts of AE events, defined as AE events accumulated from the load at AE generation until the maximum load (the load at failure), for spruce woods heat-treated at 160 or 200℃ for 72 h showed a decrease in the maximum load and deflection. This indicated that the bending strength mechanism was closely related to AE behavior.

Fig. 6 shows normalized load and the AE events obtained from the static bending tests with AE monitoring. Comparing the load level at the initiation of AE generation, it was found that AE events for specimens heat-treated at 160℃ for 72 h were generated at the initial load nearly. However, the load level at the initiation of AE

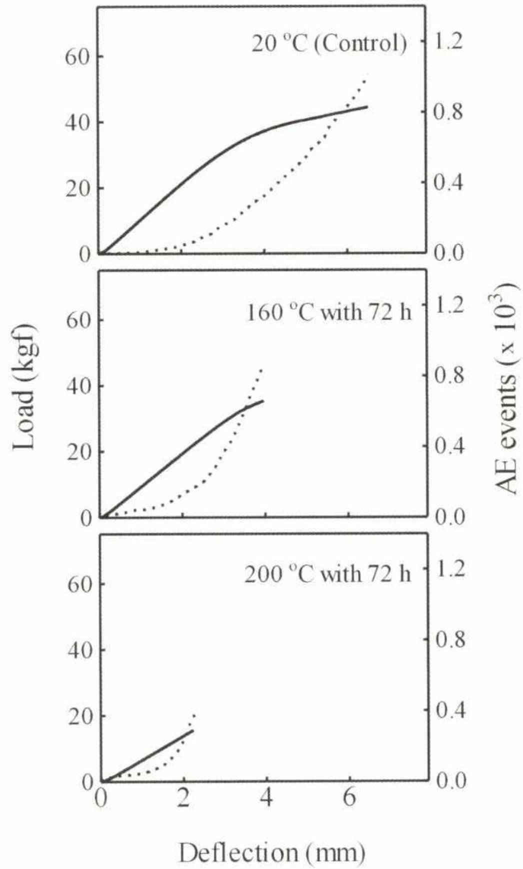

Fig. 5. Typical variation of load, deflection and AE event counts in the bending tests due to heat treatment.

Legend —— : load, ---- : AE events.

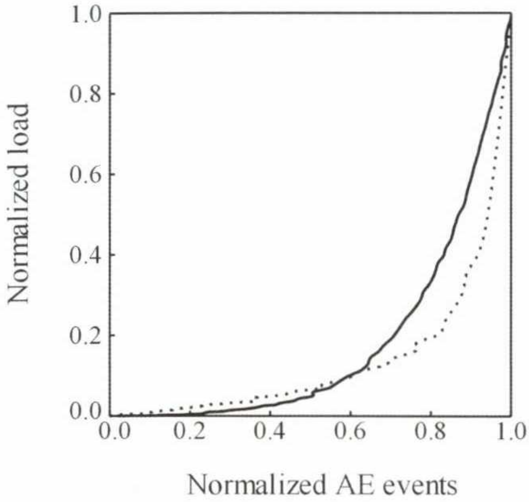

Fig. 6. Relationship between norimalized load and normalized AE events.

Legend ——: Control (20℃) specimens,

-----: Heat-treated (160℃ with 120 h) specimens.

generation was about 10 to 15% of the maximum load for the control (20℃). This suggests that minute fractures in heat-treated specimens are found at an extremely low load levels because of the brittleness effect. In other words, AE events at the fracture point were generated later for the control specimens. Minute fractures in the control and heat-treated woods tended to increase gradually until failure (maximum load). AE events for heat-treated specimens were greater than for control specimens at the same load level after the load level increased over 60% of the maximum load. This could be because the thermal degradation resulted in lower toughness. AE events increased before reaching the load level at failure.

To evaluate the load level at the initiation of AE generation for various heat treatments, the cumulative counts of AE at a deflection of 1 mm in the bending tests with AE monitoring were investigated. The results are shown in Fig. 7. Compared to the control (20℃) specimens, the cumulative counts of AE was nearly unchanged at 40, 80 and 120℃ with various heating time periods. The AE counts increased when the wood was treated a higher temperatures (above 160℃) and a longer time period (over 24 h). This indicated that the initial minute fracture behavior varied when the heat-treated woods were under loads. The value expressed by the cumulative counts of AE at a deflection of 1 mm might be an index for evaluating heat-treated wood.

The relationships between AE behavior and bending strength mechanism for spruce woods with or without heat treatment are shown in Fig. 8. The load, deflection and AE events were normalized. The results showed that the deflection for spruce woods heat-treated at 160℃ for 120 h became greater than that for the control (20℃) at the same load level for either the elastic or plastic

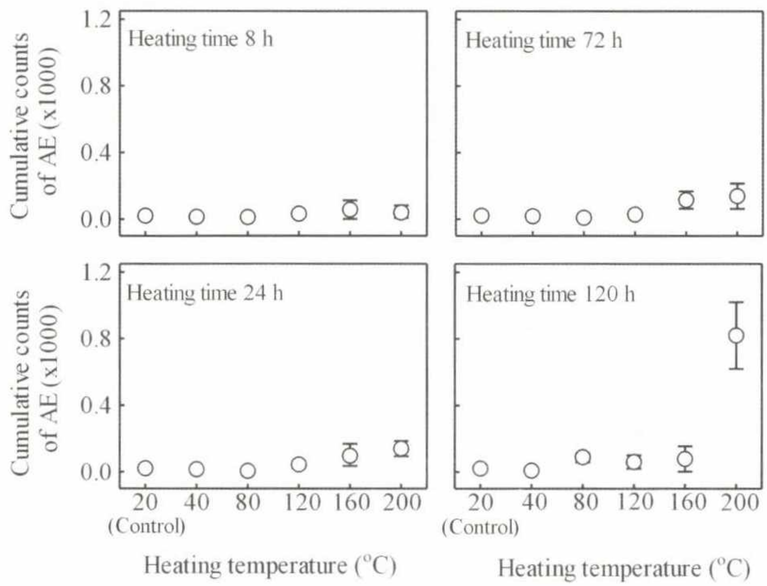

Fig. 7. Effect of heating temperature and time on the cumulative counts of AE at a deflection of 1 mm in the bending tests with AE monitoring.

region. This is because the brittleness of the heat-treated wood influenced the rupture process during the static bending tests (Kitahara. *et al.*, 1951; Fushitani 1968), indicating that the internal wood structure was changed when the wood was treated using a heat treatment for a longer time at higher temperatures. This phenomenon was ascribed to the superiority of the cellulose crystallization or the degradation of the wood components during heat treatment. This is because the crystallinity index has a tendency similar to that of the Young's modulus (Hirai *et al.*, 1972; Nakao *et al.*, 1983). The bending strength of the heat-treated wood was less than that of the control specimens. Results also indicated that AE events for the control (20℃) specimens were greater than that for heat-treated specimens (160℃ with 120 h) at the same deflection level for either the elastic or plastic region. Moreover, AE events in the plastic region for heat-treated specimens were increased linearly before reaching the failure load level. This suggests that the strain energy stored in the heat-treated wood (that is, the decrease in deflection in the plastic region) was decreased.

IV. CONCLUSIONS

In this research, heat-treated woods were precisely and strictly controlled under various heating treatments. The bending strength mechanism and AE generation behavior of heat-treated woods were examined during static bending tests with AE monitoring. The values obtained from the heating temperature and duration was statistically analyzed using dispersion analysis methods. There were significant differences at the 1% level among temperatures for both σ and E for the heat-

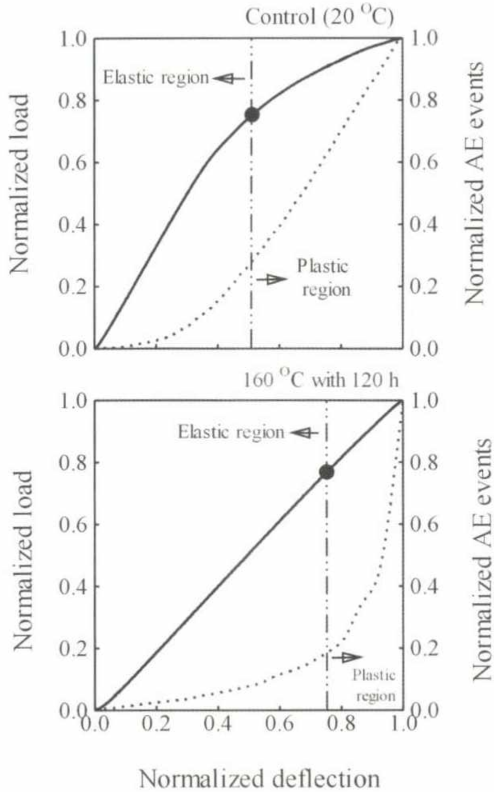

Fig. 8. Typical example of AE behavior during the bending tests for speciments with or without heat-treatment.

Legend ● : Normalized proportional loading,

---- : Relationship between normalized load and normalized deflection,

—— : Relationship between normalized AE events and normalized deflection,

treated specimens. No significant differences were found among the heating time for σ under 120℃ and E under 160℃. The internal structure of wood was changed when the wood was treated using heat treatments with longer time at higher temperatures because the wood became more brittle and the changes of crystallinity in wood cellulose influenced the rupture process. Because the thermal degradation resulted in lower toughness, AE events increased for the heat-treated specimens were before reaching the failure load level after the load level reached 60% of the maximum load. The value for the cumulative counts of AE at a deflection of 1 mm based on AE monitoring in the static bending tests increased for woods heat-treated at higher temperatures with a longer duration (above 160℃ with over 24 h). This value might be useful as an index to evaluate heat-treated woods in future research.

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