Mechanical Property and Fatigue Crack in Consolidated Wood by Hot-Pressing

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Abstract- We investigated the microstructural and fatigue characteristics on consolidated Japanese cedar called "Obi-Sugi (Cryptomeria japonicain)" fabricated by hot-pressing. Hot-press treatment was conducted at various conditions. Three point bending test, hardness test and plane bending fatigue test of consolidated wood were carried out to investigate mechanical properties. Flexural strength of consolidated wood specimen was higher than that of unconsolidated specimen. Hot-press treatment improved the surface hardness on consolidated wood. Fatigue property of crack propagation strongly depended on microstructure in wood, resulting from plane bending fatigue test. It has been suggested that the improvement of the fatigue crack propagation resistance of consolidated wood is due to "crack arrest mechanism".

Keywords – Consolidated Wood, Microstructure, Mechanical Property, Fatigue Crack

I. Introduction

Recently, the serious matter of global warming has been issued by increasing carbon dioxide. Too much fossil fuel, such as oil, coal and so on is consumed and it leads to increase of carbon dioxide of the world. Wood plant has a benefit feature of absorbing carbon dioxide for own photosynthesis, and the carbon dioxide stays inside of woods even if it's after they are harvested or burnt up. Woods could be an eternal resource by planting trees where the growth up and harvest is continually alternated. Moreover, the producing process of woods has much less emission of carbon dioxide than that of industrial metals and plastics. Also woods have several advantages, for example woods could be cheaper, lighter, and easier to produce.

Mechanical product is mostly composed of metals and plastics called "a mature industry". If woods can partially replace them, it will lead to inhibit the carbon dioxide emission. Woods have been considered to be developed to the new productions which woods have not been applied on. Although the demand of woods is expected to increase, it's not been researched about fatigue strength which is really significant for mechanical structure.

We have decided to consider the effect of wood microstructure in terms of fatigue behavior by plane bending fatigue test of hot-pressed Japanese cedar (Cryptomeria japonicain) called "Obi-Sugi" specimen which strengthen by pressing under various treatment conditions [1]. Miyazaki pref. is an area with much quantity production of an Obi-Sugi in Japan. For expansion of market, the mechanical characteristics of an Obi-Sugi are requested from local industry. However, fatigue property of wood has not been clarified. This paper is report that the microstructural and mechanical characteristics on consolidated wood fabricated by hot-pressing were investigated with mechanical and fatigue test methods.

II. EXPERIMENTAL PROCEDURE

A. Material –

Japanese wood called "Obi-Sugi" in Nichinan Miyazaki pref. from Japan was used in the present study. The wood was over 40 years old, specific gravity of 0.37 and moisture content of 18.3 %. Figure 1 shows cross section of an Obi-Sugi log and position and orientation of collected specimen. The consolidated wood plate was prepared by hot-pressing machine (Thermal-pressing machine) as shown in Figure 2. Hot-pressing treatment was performed at pressing temperature range from 453 K (180 °C) to 533 K (260 °C) and a constant consolidating pressure of 4.5 MPa and the soak time for 7 minutes determined by pre-experiment.

A strange expansion on surface of specimen as shown in Figure 3 was often observed after hot-pressing treatment. This is an important fault caused by moisture in wood and leads to dimension instability and decreasing mechanical property. Therefore, the moisture content of wood in this study was decreased until 12.5% using the microwave oven. As the result, the expansion fault little occurred after hot-pressing treatment.

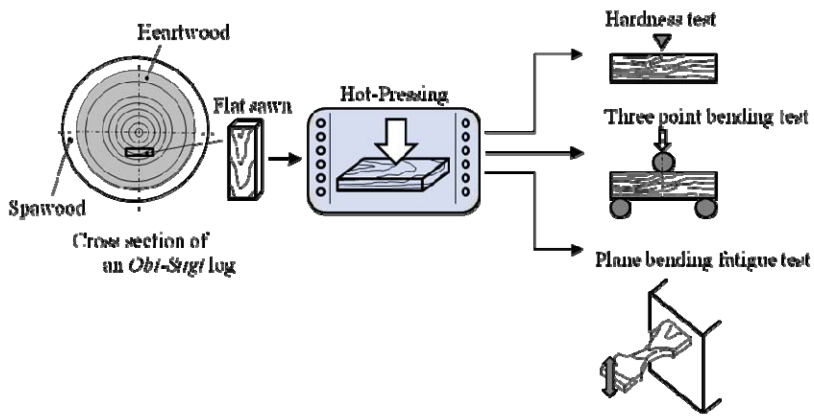


Figure 1. Schematic representation of the experimental flow in this study

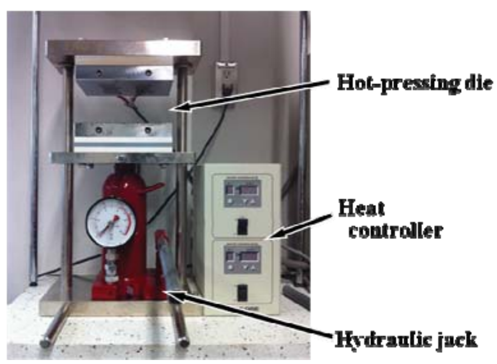


Figure 2. Hot-pressing apparatus used in this study

Figure 3. Photograph showing strange expansion on a wood surface occurred during hot-pressing treatment

B. Mechanical tests –

Rectangular specimen having configuration of $180\times30\times6$ mm was prepared for three point bending test. Bending deflection was measured using crosshead stroke displacement. The support span of specimen was set for 125 mm.

Load was applied to the specimen at loading speed of 1 mm/min. Three point bending test was concluded using applied loading control by universal material testing machine (AG-I, Autograph, capacity of 250kN, SHIMADZU Corp.).

Flexural strength, σ_b is given by equation (1):

$$\sigma_b = \frac{3P_{\max}L}{2bh^2} \qquad (1)$$

where P_{max} is peak load in load-displacement curve, b, h and L are breadth, height and length of the specimen, respectively.

Hardness measurement was conducted using universal testing machine (LSC-1, Little Senstar, Capacity of 1kN, JT-TOSHI Corp.) as shown in Figure 4, following the recommended testing procedures as described in JIS Z 2101 (in Japanese) [2]. Indenter for hardness test was spherical steel ball in diameter of 10 mm. The average indented speed was at 1 mm/min. Indent depth was approximately 0.32 mm corresponding with 1/π mm by diameter of steel ball indenter. Hardness, H in unit of MPa is expressed as:

$$H = P / 10 \qquad (2)$$

where P is the applied load (N) when indent depth leads to into 0.32 mm below the surface. Dimension of the hardness specimen was 40×40×thickness of 30 mm.

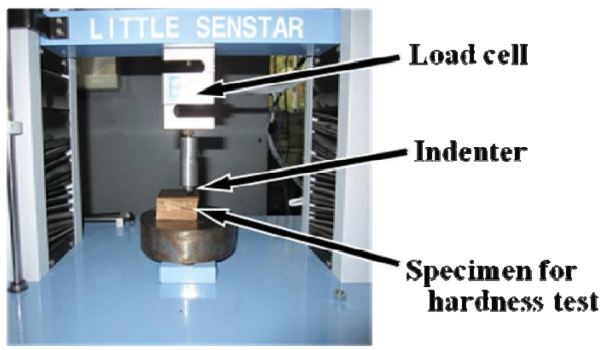


Figure 4. Photograph showing setup for hardness measurement of the consolidated wood specimen

Figure 5. Photograph showing plane bending fatigue testing apparatus

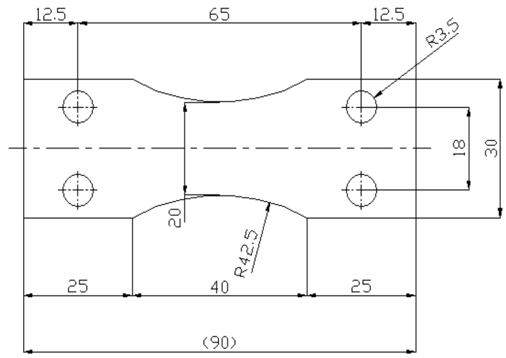


Figure 6. Configuration of the specimen on stiff orientation for plane bending fatigue test

Plane bending fatigue test was conducted on measure cyclic number to failure, N_f, corresponding applied stress, σ_{app} using fatigue testing apparatus in Figure 5 (PBF-30B, TOKYO KOUKI Corp.). The plane bending fatigue specimen was mechanically cut in stiff orientation of wood as shown in Figure 6. Specimen thickness was 10 mm for consolidated and 3 mm for untreated specimen, respectively. Fatigue test was performed at cyclic rate of 1500 (cpm; count per minutes) and at room temperature.

Fracture of specimen was finally defined as half a σ_{app}. And when the cyclic number crosses over 10^7 cycles, fatigue test was finished. Subsequence observation of fatigue behavior on stiff orientated specimen in which kept on applied stress of 30 MPa was conducted. Additionally, crack initiation and propagation observed using scanning electrical microscope (VE7800, KEYENCE Corp.) and optical microscope.

III. Experiment and Result

A. Mechanical properties –

Figure 7 represents the flexural strength, σ_b obtained from three point bending test of the consolidated and untreated wood specimen. The consolidated wood improved three times as large as untreated specimen. Strengthening may occur as the result of increase of wood density by consolidating. Figure 8 shows hardness, H on surface of the wood specimens consolidated at several temperatures and the untreated wood specimen. Maximum hardness value was H=12.5 MPa, of which hot-pressing condition was at consolidated temperature of 513 K (240 °C), soak time for 7 minutes. Maximum hardness with untreated was approximately 31.2% lower than that with consolidated wood specimen. This could be because of effect on increase of wood density.

The S-N plots of the consolidated and untreated wood specimen were shown in Figure 9. Solid and open circle indicate the consolidated and untreated in stiff oriented specimen, and a right arrow means no fracture specimen in plane bending fatigue test. It was conformed that consolidated treatment would provide high fatigue strength and lifetime. Fatigue lifetime consists of fatigue crack initiation and its propagation lifetime. According to reference [3], the fatigue crack propagation lifetime covered most of the fatigue lifetime. It is predict that fatigue crack propagation of the cedar depend on microstructural condition. In addition, it is clear that fatigue strength of consolidated wood is higher than that of polycarbonate and vinyl chloride material [5] as shown in figure 9. In view of environmental merit, consolidated wood predominates over polymer material of oil origin. Therefore, consolidate wood could be expected for mechanical elements.

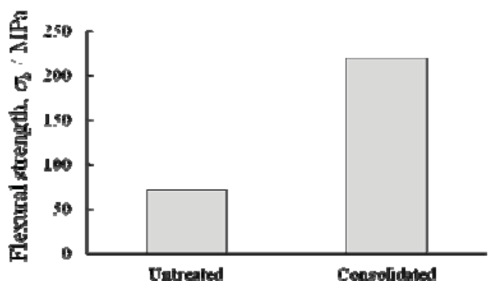


Figure 7. Comparison of the flexural strength, σ_b obtained from three point bending test

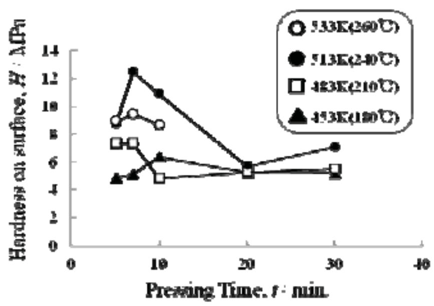


Figure 8. Relationship between the hardness and pressing time at various consolidating temperatures

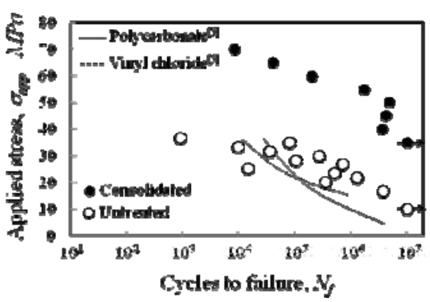
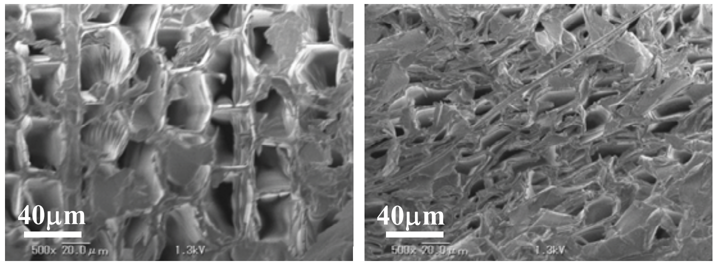


Figure 9. S-N plots of the consolidated and the untreated wood specimen on stiff orientation

B. Consolidation Effect –

Figure 10 (a) and (b) are SEM microstructures of the untreated and consolidated wood specimen, respectively. The hot-pressing conditions of the consolidated specimen in Fig.10 (b) were at temperature of 513 K (240°C), soak time for 7 minutes and compressive ratio of 50 %. Up and down in the direction of Fig.10 indicates compression axis. Although the tracheid [4] was clearly observed in Fig.10 (a), the tracheid was crushed and flatted by consolidating. Especially, tracheid of the early part of wood was strongly flatted, resulting from based on SEM observation. It is interesting that hot-pressing treatment transformed the early wood into the late wood. Flatted tracheid was constructed in early wood, as a result of which the hardness and fatigue crack propagation energy were increased for crack arrest effect [6-8] as provided in Figure 11. Fig.11 (a) and (b) show the crack propagation mechanisms into untreated and consolidated specimen, respectively. A tracheid of the untreated specimen is considered as a void. Voids could initiate and grow at very low plastic strain and matrix around tracheid is very soft ligneous material. The crack propagation process involving relatively large void is usually associated with low energy fracture. In the end, a fast crack propagation mechanism issues of the untreated specimen illustrated in Fig.11 (a). On the other hand, the consolidated specimen is a high density and hardness material. A flatted tracheid of the consolidated specimen could consider as a flatted void.



(a) Untreated (b) Consolidated

Figure 10. SEM microstructures of the consolidated and the untreated wood specimen, respectively

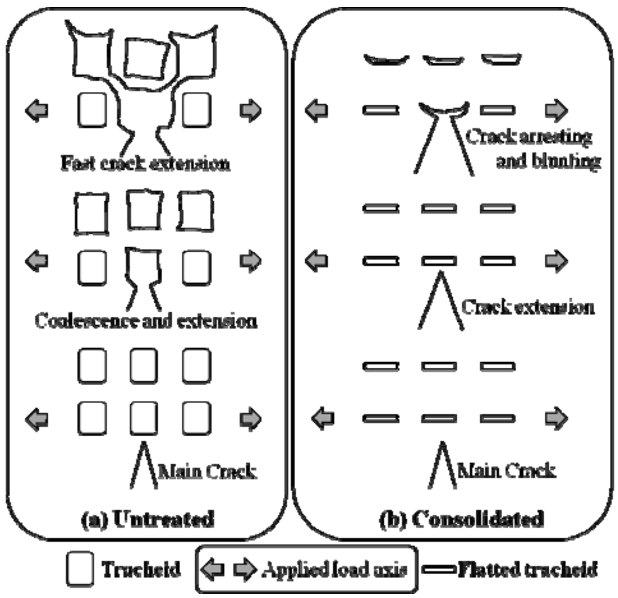


Figure 11. Crack propagation mechanism of the untreated specimen, (a), and crack arrest mechanism containing flatted tracheid of the consolidated specimen, (b). Main crack goes from bottom to upper in figure

It has been suggested that the improvement of the fatigue crack propagation resistance is due to “crack arrest mechanism [9]” in which main crack propagation is arrested by the flatted and oriented structure perpendicular to the crack propagating direction. Arrest effect ahead of crack tip reduces tensile triaxiality and reduces crack tip acuity. Both factors contribute to enhanced fracture resistance.

IV.CONCLUSION

The microstructural and fatigue characteristics on consolidated wood specimen fabricated by hot-pressing method were investigated. The results are as follows;

(1) Flexural strength, hardness and fatigue strength of the wood on stiff orientation were increased by hot-pressing method.

(2) Microstructural evaluation was conducted to the tracheids in the consolidated wood specimens were crashed and flatted, resulting in the transformation of early wood into late wood.

(3) It has been suggested that the improvement of the fatigue crack propagation resistance is due to “crack arrest mechanism” in which main crack propagation is arrested by the flatted and oriented structure perpendicular to the crack propagating direction.

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