http://dx.doi.org/10.21172/ijiet.193.01

Flexural and Fatigue Properties on Hot-Pressed Wood

Toshinobu Toyohiro
Department of Mechanical Engineering
National Institute of Technology (KOSEN), Miyakonojo College, Miyakonojo, Miyazaki 885-8567, Japan

Akihiro Takahashi
Department of Mechanical Engineering
National Institute of Technology (KOSEN), Miyakonojo College, Miyakonojo, Miyazaki 885-8567, Japan

Naoyuki Yamamoto
Technical Support Center
National Institute of Technology (KOSEN), Miyakonojo College, Miyakonojo, Miyazaki 885-8567, Japan

Abstract-Flexural and fatigue tests on hot-pressed wood were examined to investigate fatigue failure behavior related microstructural modification by hot-pressing. The hot-pressed wood (*Fraxinus Mandshurica var. Japonica*) was manufactured under the several conditions. As a result, the optimum hot-pressed condition without any manufactured defects for flexural testing specimen was 483 K (210 °C) × 11.2 MPa, and that for fatigue testing specimen was 473 K (200 °C) × 12.5 MPa in this study. Flexural strength and fatigue strength increased by hot-pressing treatment. The fatigue limit of the hot-pressed specimen at cycle number of 10^7 was 33 % higher than that of without hot-pressed.It was observed that the vessel and tracheid in wood structure were crushed and flatted by hot-pressing. SEM observation results was described in this study, and discussed fatigue crack propagation mechanismin particularearlywood region based on microstructural change between hot-pressed and without hot-pressed specimen.

Keywords –flexural test, fatigue property, wood, hot-press, microstructure, fatigue crack propagation

I. INTORODUCTION

Climate change is a significant global issue. Environmental issues on carbon dioxide (CO_2) gas (i.e. greenhouse gas)emissionshave been came to surface in global [1]. Carbon emission research expands over various research field which include environmental science, engineering, economics, energy and so on [2]. Utilization of biomass resources as a kind of renewable sources due to carbon neutralis widely promoted in the countries of the world [3-6]. The increasing demand for materials made from renewable materials with small environmental load has been risen in recent year. It happens due to the action of various driving forces, such as shortage of natural resources, evolution of consumer's profile that makes much account of the social environmental problems and proposal from the SDGs [7]. As well known, wood isa kind of plant-based natural product and has a benefit feature of absorbing CO_2 gas for own photosynthesis, and the CO_2 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 CO_2 gas than that of industrial metals and plastics. Also woods have several advantages, for example woods could be cheaper, lighter, and easier to produce and so on. Recently, wood applications have been discussed to be developed to the new productions which woods have not been applied on. Therefore the demand of woods is expected to increase, however it is not say that research on fatigue property which is always significant for mechanical structure has been satisfied enough, in particular plane bending fatigue test is hardly performed yet. In our previous study, the microstructural, flexural and fatigue characteristics on hot-pressed wood in a number of coniferous tree *(Cryptomeria japonica*)of Japanese cedar was examined to investigate mechanical property related microstructural change by hot-pressing [8]. Thereby, the flexural strength increased three times than original wood could be achieved under a certain hot-pressing condition of soaking time for 7 minutes and compressive ratio of 50 % at die temperature of 513 K (240 °C). The plane bending fatigue strength overcome three times than original wood could be achievedon the sample fabricated underthe same hot-pressing condition. In this study, flexural and fatigue tests were carried out to investigate on wood in kind of deciduous tree(*Fraxinus mandshurica var. Japonica*).Density and stiffness of this tree is higher than those of Japanese cedar. The one of this study's aim is to prove the hot-pressingeffect on mechanical and fatigue property with regards to both woods.Thus, manufacture on hot-pressing condition, flexural, fatigue, other examinationsand estimation of them wereconducted with reference to our previous study [8].

II.EXPERIMENTAL PROCEDURE

2.1. Material–

Wood of a series of a broadleaf tree(*Fraxinus mandshurica var. Japonica*) called TAMO in Japanese was used in this study. This wood piece wastaken from tree log in an even-aged 100-years old forest stand from Russia.Specific gravity of TAMO was 0.46 [9].

2.2. Flexural and fatigue tests–

Flexural test was examined to use universal material testing machine (AG-I, Autograph, capacity of 250kN, SHIMADZU Corp.) at initial loading speed of 1 mm/min under the atmospheric pressure. The flat oriented specimen for flexural test was only machine-cut from hot-pressed sample. That is to say that the longitudinal direction of flexural specimen is corresponding to the flat orientation of the wood. The dimensions of flexural specimen was longitudinal, L=150 mm, breath, b=30 mm and thickness, h=10 mm, respectively. The support span length was S=125 mm. Flexural strength$\sigma_{b,u}$ is given as follows:

(1)

whereP_{max} means maximum load in flexural load-displacement curve.

Fatigue test was carried out to use plane bending fatigue testing machine (PBF-30B, TOKYO KOUKI Corp.) as shown in Fig.1. Cyclic rate was at 1500 cpm (count per minutes). The flat and edge oriented specimens for fatigue test specimen were cut from hot-pressed sample. Fig. 2 shows configuration and dimensions of the plane bending fatigue testing specimen. Applied stress$\sigma_{app}$to the fatigue specimen was set up with range from 35 MPa to 70 MPa. Cyclic number to failure $N_f$was measured to use counter in fatigue testingmachine.In general, fatigue life is the number of cycle to failure at a specified stress level, while the fatigue strength (i.e. endurance limit) is the stress below which failure does not occur. In this study, failure behavior was not observed even cycle number of 10^7at all fatigue specimen.The cyclic number crossed over 10^7 cycles, and then the fatigue test was stopped. Furthermore, to assuming failure of specimen, fatigue test was closed as half a measured σ_{app}.

Figure1.Plane bending fatigue testing machine

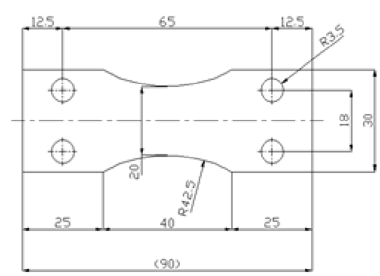

Figure 2.Fatigue testspecimen

2.3. Hot-pressing experiment–

Fig.3 shows experimental flow until each mechanical tests.The two kinds of sampling orientations: (a) edge grain direction and (b) flat grain directionfrom thelog was adopted in this study. The moisture content (MC) was 14 % after sun drying into Hot-pressing treatment was conducted to make flexural and fatigue tests at each oriented samples. Fig. 4 shows hot-pressing apparatus. Hot-pressing was performed at die temperature range from 473 K (200 °C) to 483 K (210 °C) and with compressive pressure range of 8.5 to 14.5 MPa, with reference to pre-experiment. The soaking time was 5 minutes at all hot-pressing. A strange expansion on surface of specimen as shown in Fig.5 was often confirmed during/after hot-pressing. It was found by pre-experiment that an important fault was caused by high MC in wood, and the fault could be reduced by decreasing until MC of 6 to 8% from the original wood sample. Therefore, the microwave oven was used for one minute before hot-pressing treatment.

As results, the optimum hot-pressed condition(i.e. no manufacturing defect) for flexural testing specimenwas 483K(210°C)×11.2MPa, and that for fatigue testing specimen was 473K(200°C)×12.5MPa in this study. Fig.6 showsmicrostructure of the without hot-pressed(a) and hot-pressedspecimen (b) at the die temperature of 473K at the pressure of 12.5MPa. Up and down in the axis of the Fig. 6 indicates pressing axis. Vessel and tracheid were clearly observed in the microstructureof the without hot-pressedspecimen in Fig. 6(a). On the other hand, the vessel and tracheid were flatted and crushed by hot-pressing in Fig. 6 (b). Hot-pressed microstructure looked like a single solid, resulting in the increase of material densityin comparisonto the without hot-pressed.

Without hot-pressed specimen was also prepared, and both tests were carried out under the same procedures of them. Flexural fracture surface, fatigue crack initiation and propagation regions were observed to use optical image scope and scanning electron microscope (SEM).

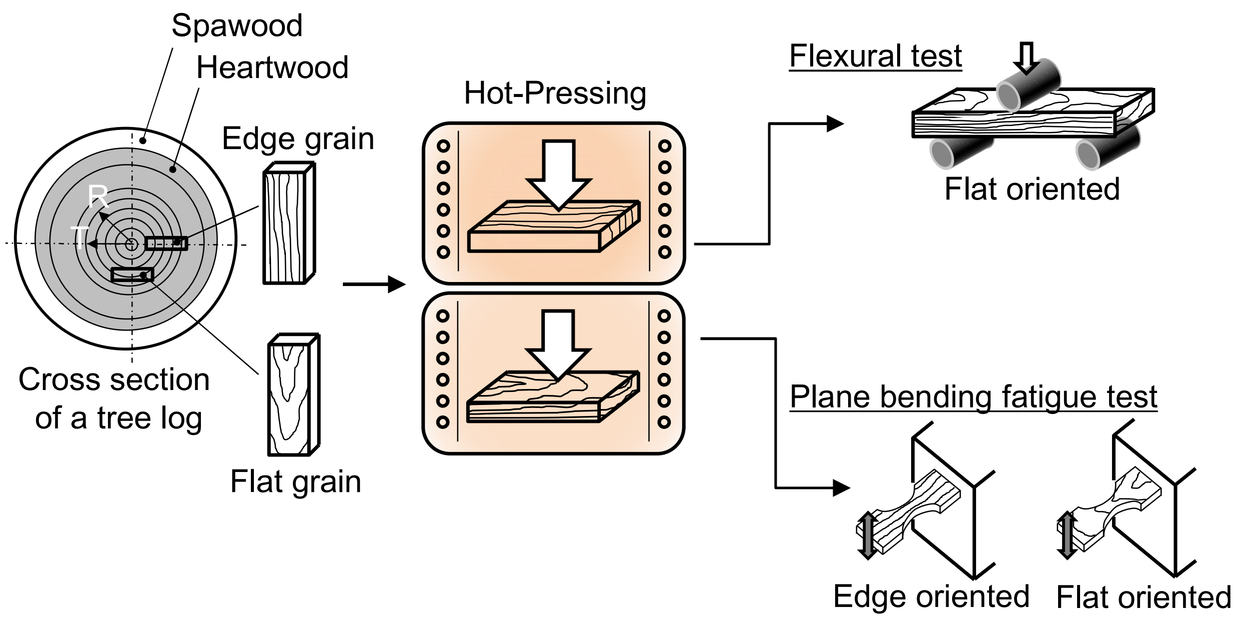

Figure3.Schematic illustration of the experimental flow from the sampling orientation to both tests at each sample

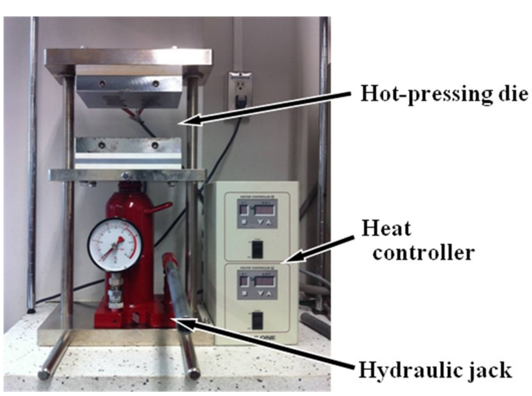

Figure 4.Hot-pressing apparatus used in this studyFigure5.Strange expansion fault

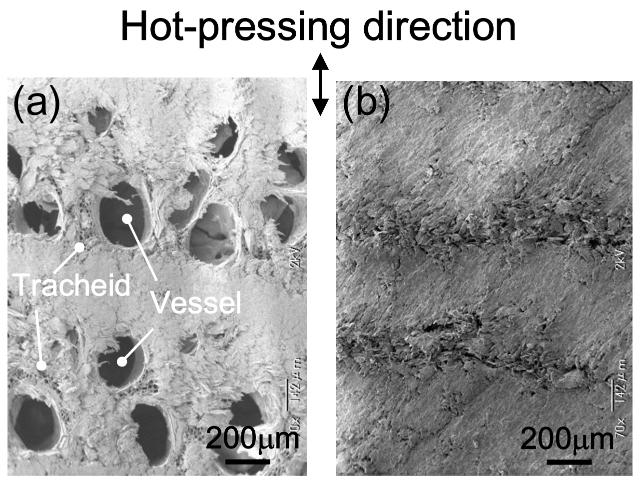

Figure6.Micrograph of the without hot-pressed, (a) and hot-pressed, (b)

III. RESALTS AND DISCUSSIONS

Fig.7 shows flexural strength, $\sigma_{b,u}$of hot-pressed and without hot-pressed specimen together with reference data [8].The flexural strength of the hot-pressed specimen was higher 1.5 times than that of the without hot-pressed. In comparison, it was interesting to note that the strength of the hot-pressed cedar is higher than that of the hot-pressed TAMO.

Fig. 8 shows the S-N plot results obtained from fatigue test at each specimen together with reference data [8] and another engineering plastics [10].A right arrow means fatigue limit that specimen unfailed until 10^7 cycles during fatigue test. It was found that hot-pressing treatment would provide high fatigue strength and lifetime to this wood. Fatigue limit of hot-pressed specimen increased 33% than that of without hot-pressed. It is interesting to note that fatigue strength at stress cycles of 10^7 was almost the same. Fatigue lifetime consists of fatigue crack initiation and its propagation lifetime. According to reference [11], the fatigue crack propagation lifetime occupies most of the fatigue lifetime. It is obvious that fatigue crack propagation of the hot-pressed specimen depends on microstructural factor of the specimen.As a result of SEM observation for crack propagation path, stationary of propagation crack was confirmed on a latewood region of hot-pressed specimen in this study. It was suggested that earlywood and latewood regions become much higher density by hot-pressing, then high crack propagation resistance takes place at both regions. However, microstructural factor analysis such as size, distribution, fraction ratio of earlywood/latewood and vessel/tracheid in each specimen are not satisfied yet.Closer experiment on this point should conduct in the future.

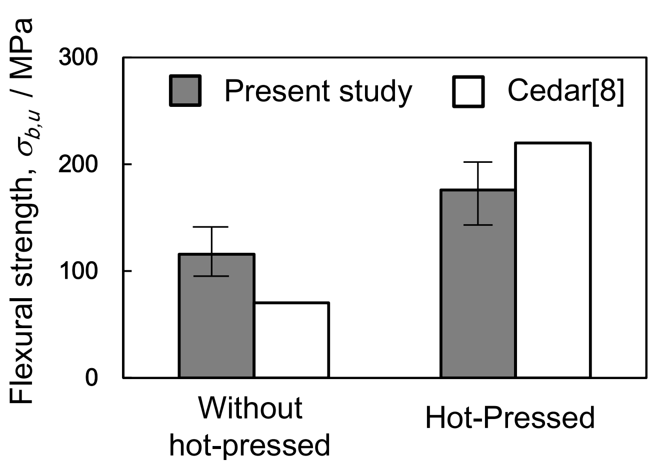

Figure7.Flexural strength $\sigma_{b,u}$of hot-pressed and without hot-pressed specimen together with reference data [8]

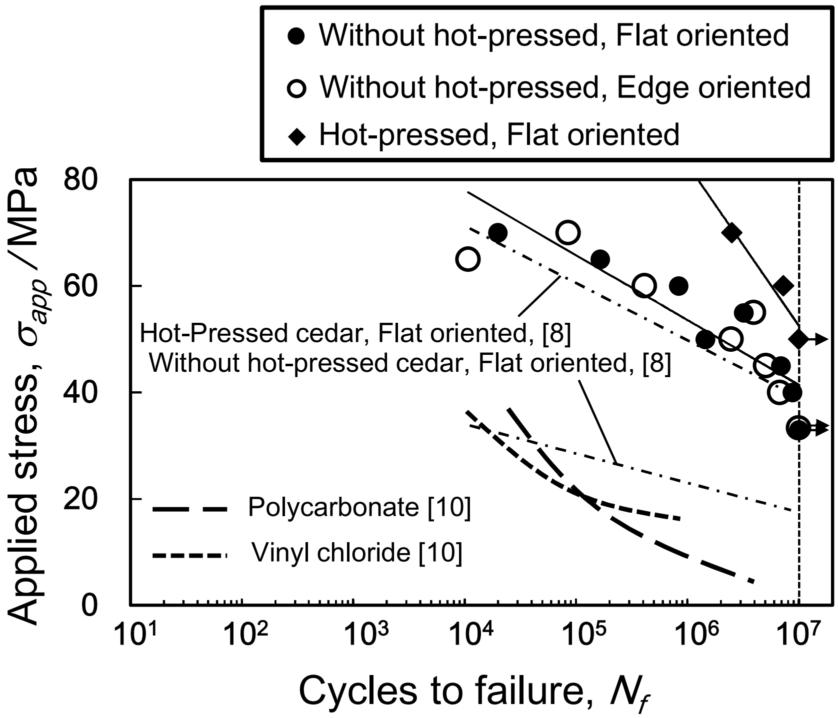

Figure8.S-N plots obtain by fatigue test at each specimen

Next, the results are discussed on the fatigue data in this study, hot-pressed cedar [8] and engineering plastics such as polycarbonate [10] and vinyl chloride [10] in Fig. 8. Solid and open circle indicate the flat oriented and edge oriented specimen withouthot-pressed, respectively. Solid rhombus shows the flat oriented specimen with hot-pressed. It wasevidenced that fatigue strength of hot-pressed wood in this study wasthe highest as compared with other materials as shown in Fig.8. In views of environmental merit and mechanical property,hot-pressed wood has a predomination over polymer material from oil origin. Therefore, hot-press wood could be expected for mechanical components.

To appreciate fatigue crack propagation mechanism, let us now results of the both microstructures in Figs. 6 (a) and (b). The hot-pressed specimen in Fig. 6 (b) wasmanufactured with condition at die temperature of 473 K (200 °C), soaking time for 5 minutes and compressive pressure of 12.5 MPa. Although the vessel and tracheid was clearly observed in Fig. 6 (a), in contrast, they were crushed and flatted by hot-pressing treatment as shown in Fig. 6 (b). It was quite possible that the vessel and tracheid in earlywood was strongly flattened. Actually, the vessel and tracheid in earlywood were severely deformed than those in latewood by SEM observation after hot-pressing. It may also be that hot-pressing transformed the earlywood into the latewood as qualitative prediction. Our findings raise the possibility that consolidated microstructure due to flatted vessel and tracheid was constructed into earlywood region, resulting in increase of the flexural strength and fatigue strength based on crack arrest mechanism [8, 12-15].Figs.9 (a) and (b) represent different crack propagation mechanisms on the earlywood region without and with hot-pressed specimen in flat oriented, respectively. Vertical direction indicates hot-pressing direction, and horizontal direction is corresponding to applied stress of fatigue testin Fig. 9.A vessel and a tracheid into earlywood of the without hot-pressed specimen are considered as equal to a large void. In addition, ligneous material around the vessel and tracheid is very soft and has not material resistance. Especially, the microcracks easily take place from vessel flange which are large voids can initiate and grow at low plastic strain. The crack extension process involving relatively large void is usually associated with low energy fracture. In the end, acoalescence and propagation of main crackforms in earlywood of the without hot-pressed specimen illustrated in Fig. 9 (a), resulting the low fatigue strength and lifetime. On the other side, as shown in Fig. 9 (b), the consolidated specimen by hot-pressing becomes a high density and hardness material, because of the flattened vessel and tracheid, and the earlywood region in consolidated specimen could consider as a low defect density material.Thus, it is expected that damage and microcracks in the hot-pressed specimen have not been occurreddue to crack arrest and blunting as fatigue progresses, consequently the high fatigue strength and lifetime compared to without hot-pressed.

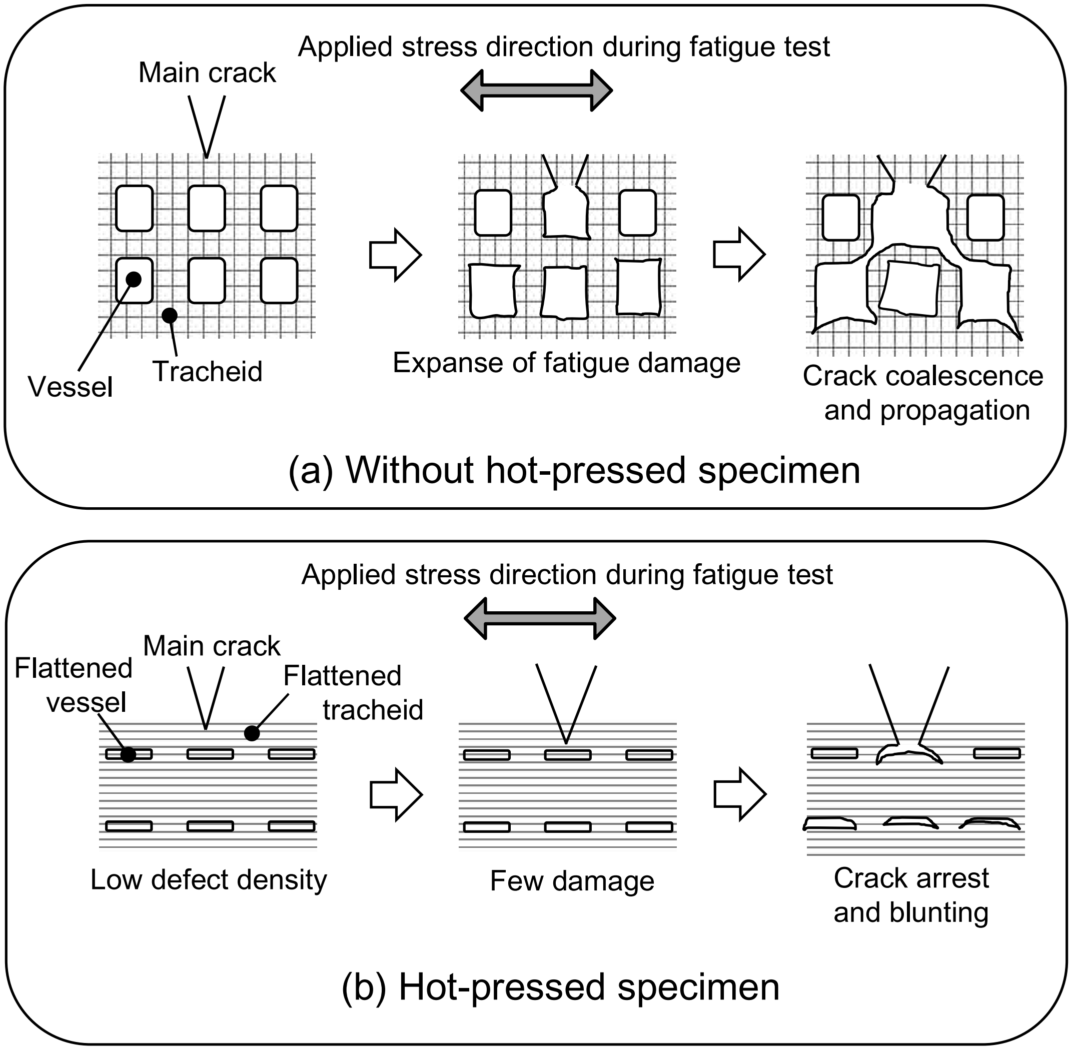

Figure9.Fatigue crack propagation mechanism of the without hot-pressed specimen, (a), and the hot-pressed specimen, (b). Main crack progresses toward to below in this figure

IV.CONCLUSION

The hot-pressed wood (*Fraxinus Mandshurica var. Japonica*)was manufactured under the several conditions, and flexural and plane bending fatigue tests were carriedout toinvestigaterelationship between flexural and fatigue properties and microstructural change byhot-pressing with reference to author's previous study. The optimum hot-pressed condition(i.e. no manufactured defect) for flexural testing specimen was 483 K (210 °C) × 11.2 MPa, and that for fatigue testing specimen was 473 K (200 °C) × 12.5 MPa in this study.The findings are summarized as follows:

1. Flexuralstrength and fatigue strengthincreased by hot-pressing treatment. The fatigue limit of the hot-pressed specimen at cycle number of 10^7was33 % higher than that of without hot-pressed.
2. It was observed that the vessel and tracheid were crushed and flatted by hot-pressing, resulting in the transformation of earlywood into latewood of the wood as qualitative prediction.

3.It was suggested that effects of crack arrest and blunting in which main crack propagation was restrained due to densification in earlywood region by hot-pressing.

REFERENCES

[1] D. Liu, X. Guo and B. Xiao, "What Causes Growth of Global Greenhouse Gas Emissions? Evidence from 40 Countries", *Science of the Total Environment, vol. 661, 750-766, 2019*

[2] L. H. U. W. Abeydeera, J. W. Mesthrige and T. I. Samarasinghalage, "Global Research on Carbon Emissions: A Scientometric Review", *Sustainability, vol. 11 3972, 2019*

[3] J. G. Canadell and M. R. Raupach, "Managing forests for climate change mitigation", *Science, vol. 320, 1456-1457, 2008*

[4] S. V. Livesley, E. G. McPherson andC. D. Calfapietra,"The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale", *Journal of Environmental Quality, vol. 45, 119-124, 2016*

[5] C. B. Field and K. J. Mach, "Rightsizing carbon dioxide removal", *Science, vol. 356, 706-707, 2017*

[6] J. Tollefson,"The wooden skyscrapers that could help to cool the planet",*Nature, vol. 545, 280-282, 2017*

[7] Food and Agricalture Organization of the United Nations, "Transforming food and Agriculture to Achieve the SDGs", *Technical Reference Document, 2018*

[8] T. Toyohiro, A. Takahashi and N. Yamamoto,"Mechanical property and fatigue crack in consolidated wood by hot-pressing", *International Journal of Innovations in Engineering and Technology, Special issue – JTL AEME (Japan), 76-82, 2014*

[9] H. Urakami and M. Fukuyama"Effects of Size, Specific Gravity and Moisture Content on Energy Absorption of Wood during Impact Bending",*Journal of the Society Materials Science, Japan, vol. 34, 949-954, 1985 (in Japanese)*

[10] "Zairyo-Kyodo-Gaku",*The Society of Materials Science, Japan, 135, 1993 (in Japanese)*

[11] T. H. Courtney, "Mechanical Behavior of Materials",*McGraw-Hill International Editions, 587-589, 2000*

[12] R. W. Hertzberg, "Deformation and Fracture Mechanism of Engineering Materials",*John Wiley & Sons, 355-363, 1976*

[13] N. Yamamoto, A. Takahashi and T. Toshinobu, "Tensile Properties of Natural Bamboo Fiber at Testing Temperature up to at 473K",*International Journal of Innovations in Engineering and Technology, Special issue – JTL AEME (Japan), 37-43, 2014*

[14] T. Higashi, A. Takahashi, N. Yamamoto and T. Toyohiro, "Mechanical Properties on Consolidated Bamboo Powder Fabricated by Thermal-pressing Method",*Proceedings of the Japan-Thailand-Lao P.D.R Joint Friendship International Conference on Applied Electrical and Mechanical Engineering 2011, vol.1, 61-64, 2011*

[15] D. Broek, "Elementary Engineering Fracture Mechanics",*NOORDHOFF INTERNATIONAL PUBLISHING, 387-391, 1974*