16th World Congress in Computational Mechanics (WCCM)
21-26 July 2024, Vancouver, Canada
A. Korobenko, M. Laforet, S. Prudhomme, R. Vaziri (Eds)

DETERMINATION OF ORTHOTROPIC ELASTIC MODULUS OF WOOD BY INDENTATION WITH NONE-AXISYMMETRIC INDENTER AND FEM SIMULATION

TOMOAKI TSUJI[1], KOUHEI SAITO[2]

[1]Chuo University
1-13-27, Kasuga, Bunkyou-ku, Tokyo, JAPAN
tomtsuji.34b@g.chuo-u.ac.jp and https://c-research.chuo-u.ac.jp/html/100003184_en.html

[2] Chuo University
1-13-27, Kasuga, Bunkyou-ku, Tokyo, JAPAN
a18.cwyc@g.chuo-u.ac.jp

Key words: Wood, Indentation, None-Axisymmetric Indenter, FEM, Orthotropic.

Abstract. *The purpose of this study is to estimate the material constants of woods as an anisotropic material, by indentation tests using an ellipsoid indenter. Firstly, uniaxial compression tests are performed to investigate anisotropic modulus. Secondary, indentation tests are conducted to get load-displacement curve by rotating the non-axisymmetric indenter along the indentation axis. Finally, the orthotropic elastic parameters are estimated by comparing the indentation test results and finite element analysis results. The modulus along longitudinal direction, which is given by the present indentation method, are in good agreement with the measured modulus by the compression test. Therefore, it is confirmed that the longitudinal modulus can be measured by using the present method with the non-axisymmetric indenter.*

1 INTRODUCTION

Wood has long been used as a structural material, and Japanese forests are expected to be a source of structural materials. The trees planted after World War II are now at the optimum age for harvesting. In addition, the use of carbon-neutral wood as a structural material is expected to reduce carbon dioxide emissions. As a biomaterial, wood has a complex structure, as typified by the annual rings found in coniferous trees. In order to expand its use as a structural material, it is important to clarify its mechanical properties. It is known that wood can be approximately regarded as an orthotropic material with different mechanical properties in the longitudinal, radial, and tangential directions. On the other hand, the indentation test is a quasi non-destructive testing method that can read the local mechanical properties of a specimen from the relationship between the load applied to the indenter and the indentation displacement obtained by pressing the indenter into the specimen surface.

The theoretical model has been developed to the contact problem by the ellipsoidal indenter on the anisotropic half space [1]. Overview of the indentation to anisotropic material has been given [2]. Klímek et. al. has been proceeded nano indentation test to the cell of the wood [3]. However, the further study on the evaluation of elastic constants of wood by micro-order indentation tests are required. Moreover, it is required to get the orthotropic mechanical properties of wood by easy method and non-destruction method as indentation test.

Therefore, in this study, we use the non-axisymmetric indenter to the wood as anisotropic material. By rotating the non-axisymmetric indenter along the indentation axis, the different load-depth curves can be given. Using finite element simulations and these load-depth curves, orthotropic mechanical properties can be obtained.

2 MEASURE THE ORTHTOROPIC MODULUS BY COMPRESSON TEST

Tests specimens are commercially available agatis wood (Agathis square timber planar finish, Hattori Shoten Co., Ltd.). Uniaxial compression tests are proceeded along the fiber direction or longitudinal direction (L), radial direction (R), and tangential direction (T), and the compressive modulus of elasticity are determined along each directions. As shown in Fig. 1, the specimens are 30-mm-high rectangles with a 15-mm × 15-mm base, and are cut from the base material using a 3-axis modeling machine (MODELA PRO II MDX-540, Roland DG Corporation. Ltd.). Uniaxial compression tests are performed using a universal testing machine (AGS-J, Shimadzu Corporation) at a displacement rate of 0.5 mm/min.

The nominal stress-nominal strain curves in each direction obtained from the compression test are shown in Fig. 2. The compression longitudinal modulus of elasticity E in each direction for the agatis material are given by using a linear least-squares approximation. The obtained longitudinal modules are listed in Table 1.

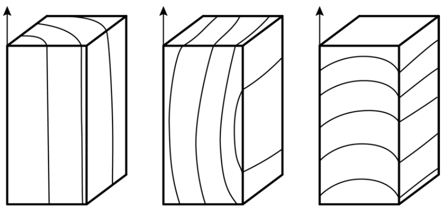
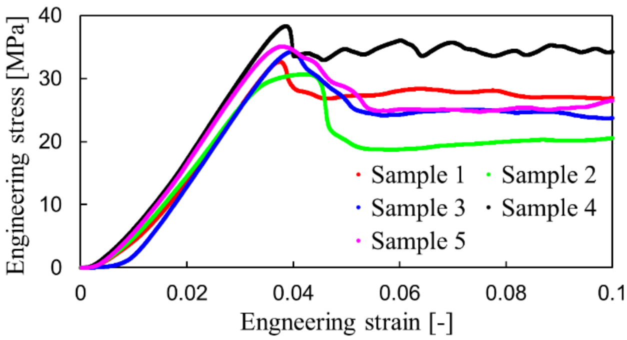
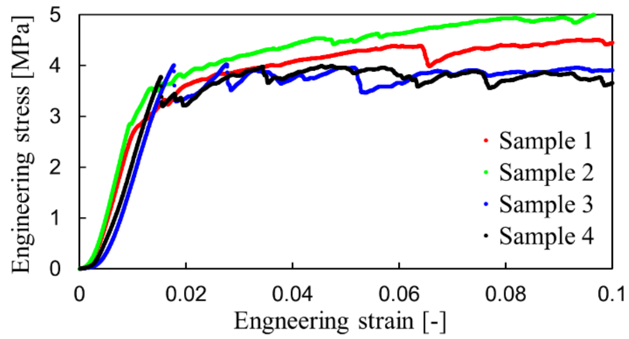


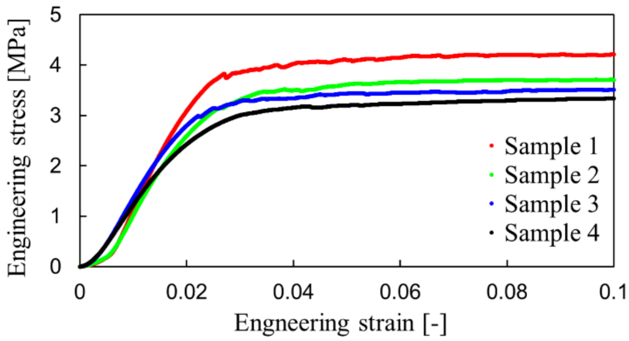
Figure 1: Three orthotropic directions of the compression specimen



(a) Longitudinal axis L (N. of test is 5)



(b) Radial axis R (N. of test is 4)



(c) Tangential axis T (N. of test is 4)

Figure 2: Stress-strain curve of the Agathis

Table 1: Orthotropic Young's modulus *E* of Agathis

Direction	N. of test	*E* Avg [MPa]	*E* SD [MPa]
L	5	1169	68
R	4	356	39
T	4	186	31

3 INDENTATION TEST OF ANISOTROPIC MATERIALS

Shape of commonly used indenters are spheres or pyramids. But it is difficult to consider the longitudinal elastic modulus in three directions with a single load-displacement curve obtained from such indenters. In this study, the different load-displacement curves can be given by rotating an ellipsoidal indenter around an axis in the indentation direction, as shown in Fig. 3.

The configuration of the indenter tip is an ellipse with a major axis of 10 mm and a minor axis of 2 mm as shown if Fig.4. The indenter is machined from an aluminum alloy A5056 bar using a 3-axis modeling machine.

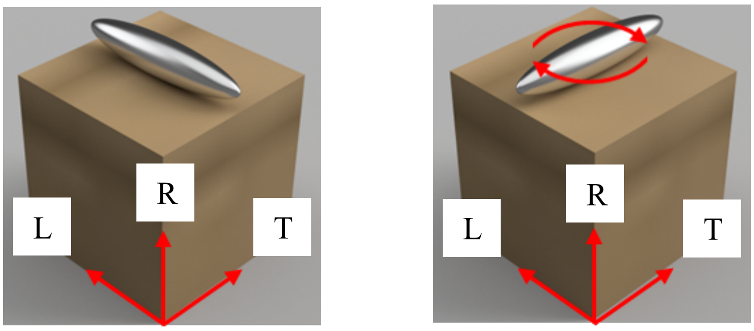
The shape of specimen are rectangular and heights are more than 10mm. The surface of the specimen are TL surface, so that indentation direction is R direction.

Figure 5 shows the indenter testing machine. The speed of the indenter is 1000 µm/min.

Figure 6 shows the relationship between the indentation depth and the indentation load. Two indentation curves are produced when the long axis of the ellipsoidal indenter is oriented in the L (Fig.3(a)) and T (Fig.3 (b)) directions, respectively. All tests are performed on the same plane of the same specimen. The average values are show by solid lines. There is difference between L direction curve and T direction cure. Thus, the different modulus can be given by rotating the ellipsoidal indenter.

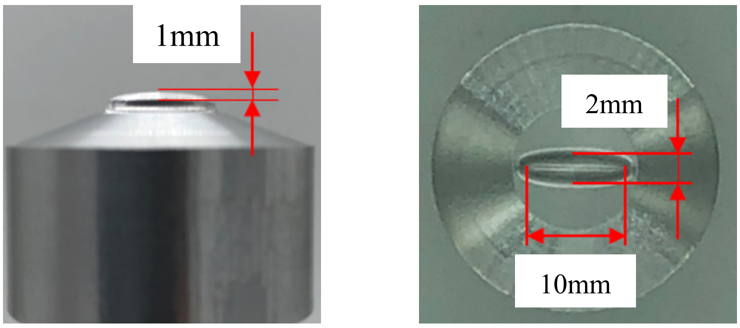
These lines are fitted to the quadratic equation as follows and the results are listed in Table 2.

$$F = ah^2 + bh \tag{1}$$



(a) Step.1 (Major axis L) (b) Step.2 (Major axis T)

Figure 3: Rotating the ellipsoidal indenter.



(a) Front view (b) Top view

Figure 4: Ellipsoidal indenter

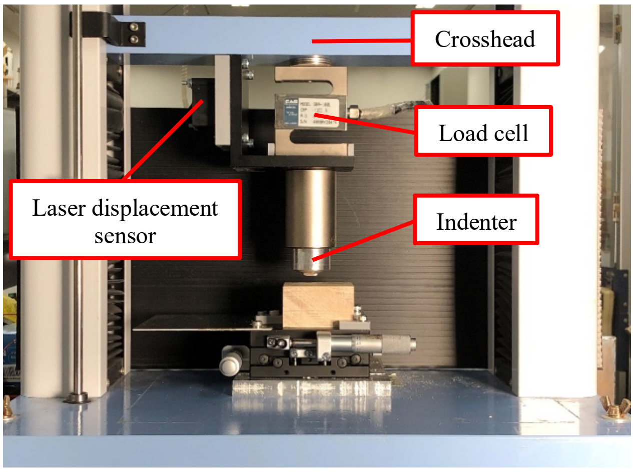


Figure 5: Experimental setup of the indentation

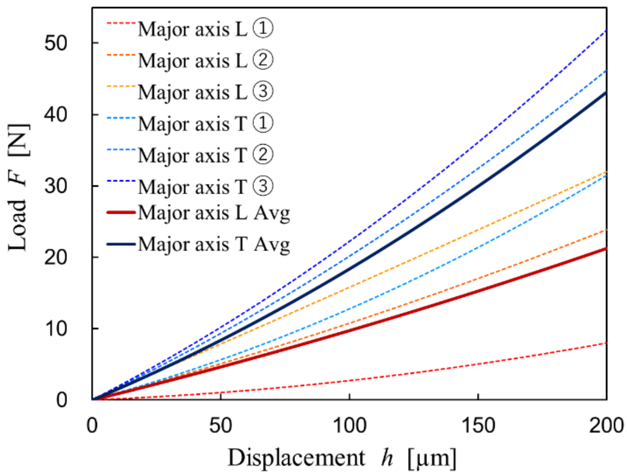


Figure 6: Load-displacement curves to LT surface. (Major directions of the ellipsoidal indenter are L and T) surface of the Agathis

Table 2: Indentation test result of Agathis

Major axis	a [N/μm^2]	b [N/μm]	Load Max.[N]	R^2
L Average	89.5×10^{-6}	88.5×10^{-3}	21.3	0.796
T Average	321.4×10^{-6}	151.6×10^{-3}	43.2	0.958

4 INDENTATION SIMULATION BY FEM

Finite element simulation are performed using Ansys 2022 R1 (Cybernet Systems, Inc.). As shown in Fig. 7, the simulation model is a cylinder with a specimen size of 20 mm in diameter and 5 mm in height, and the dimensions of the indenter are the same as those of the indenter used in the previous chapter. Poisson's ratios ν are set to ν_{LR}=0.4, ν_{LT}=0.5, and ν_{RT}=0.6 using the rough evaluation value for softwoods [4]. The transverse modulus of elasticity, *G*, are calculated from eq. (2), referring to the relationship between *E*, *G*, and ν for isotropic materials as an approximate value, since there is no clear way to calculate it.

$$G_{xy} = \frac{E_x}{2(1+\nu_{xy})} \quad (E_x \geq E_y) \tag{2}$$

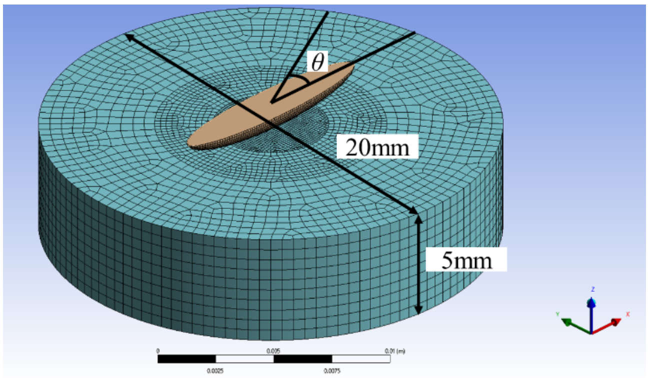


Figure 7: Finite element model

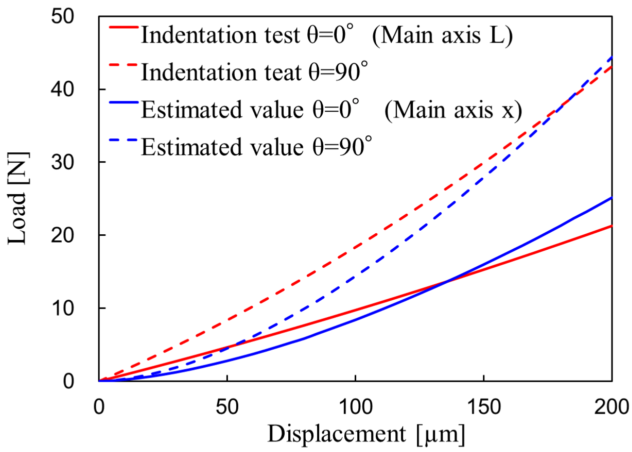


Figure 8: Load-displacement curves with the estimated parameters.

5 PARAMETER ESTIMATION FOR ANISOTROPIC MATERIALS

To easy estimation, the value of E_T is fixed as 55MPa. The values of E_L and E_R are given by using the optimization method with E_T = 55MPa. The finite element simulations are proceeded by changing values of E_R and E_L in order to minimize the error between the measured load displacement curves and simulated ones. The obtained optimized values are E_L = 1500MPa and E_R = 10MPa. Figure 8 shows load-displacement curves with different orientation and

E_L=1500MPa and E_R = 10MP. The measured curves are almost in agreement with simulated curves.

The modulus E_L = 1500MPa along L direction, which is hardest direction, is in good agreement with the compression test results listed in Table 1. But the other modulus E_R and E_T are littler to the compression test results listed in Table 1. The direction of the wood pole are along fiber direction, that is L direction. Thus, the indentation test along T or R direction is easy and the hardest modulus E_L is most important. By the present method, the value of E_L can be given.

6 CONCLUSION

In this study, we conduct indentation tests using an ellipsoid indenter on an anisotropic material, wood, and used finite element analysis to estimate the elastic modulus along the different directions. The estimated modulus are comparing to the measured modulus by the uniaxial compression test. The modulus along longitudinal direction, which is given by the present indentation method, are in good agreement with the measured modulus by the compression test. Therefore, it is confirmed that the longitudinal modulus can be measured by using the present indentation method with the non-axisymmetric indenter.

REFERENCES

[1] Shi, D., Lin, Y., Ovaert, T. C., *Indentation of an Orthotropic Half-Space by a Rigid Ellipsoidal Indenter*, Journal of Tribology, (2003), Vol.125, Issue 2, pp.223-231.

[2] Lamuta, C., *Elastic constants determination of anisotropic materials by depth-sensing indentation*, SN Applied Sciences (2019), 1:Article number: 1263.

[3] Klímek, P., Sebera, V., Tytko, D., Brabec, M., Lukeš, J., *Micromechanical properties of beech cell wall measured by micropillar compression test and nanoindentation mapping*, Holzforschung, Vol.74, Issue 2, (2020), pp.899-904.

[4] Sawada, M., *Deformation behavior of wood*. Journal of the Society of Materials Science, Japan, Vol.32 No.359, (1983), pp.842.