Determination of Modulus of Dynamic Elasticity of Wood Using Ultrasonic Pulse Velocity Testing

Darmono, F Ma’arif, S Widodo, and M S Nugroho

Department of Civil Engineering and Planning, Yogyakarta State University, Yogyakarta - Indonesia

Corresponding author: darmono@uny.ac.id

Abstract. In the present times, Non Destructive Tests have been applied in many quality evaluations of existing wood structures. One of the Non Destructive Tests (NDT) is based on Ultrasonic Pulse Velocity (UPV). The use of UPV method among others are to estimate the strength of wood, the grade of wood based on Specific Gravity as well as elastic properties of wood. This research will apply the NDT technique. This research used 15 wood test samples in five groups, which were reference Teak (code JT), Yellow Ballau (BK), Camphor (KP), Coconut (KL), and Breadfruit (SK). Those samples were of 100 mm in width, 60 mm in depth, and 500 mm in length. The Ultrasonic Pulse Velocity(UPV) test was conducted with indirect test method. The test result showed that the objects test of Teak, Yellow Ballau, Camphor, Coconut, and Breadfruit are 5,65 km/s, 6,34 km/s, 6,12 km/s, 4, 72 km/s, and 4,94 km/s. Result also showed that Dynamic Modulus of Elasticity (MOEd) for the objects test are 144683 kg/cm², 314101 kg/cm², 173973 kg/cm², 160094,64 kg/cm², dan 73157,74 kg/cm².

Keywords: Dynamic Modulus of Elasticity (MOEd), Ultrasonic Pulse Velocity

1. Introduction

The use of wood as construction material in Indonesia remains the main choice because it is more profitable compared with other materials. Wood is easy to work with despite with simple tool, it is easy to be spliced, it is relatively strong though it is lighter, it lasts long enough, and it has high aesthetic value. The various kinds and dimensions of wood are as results of the nature of its physical, mechanical and diverse congenital defect. Of all the excellence, wood is often chosen as the construction materials in many regions.

For example, Yogyakarta, which is known as a tourism area, is also designated as an area with the most cultural heritage, namely 127 buildings designated as cultural heritage. Of the many cultural heritage buildings, the use of wood construction is often found in historic buildings in Yogyakarta. For example, the Keraton building and Kauman the Great Mosque of Yogyakarta, buildings that are hundreds of years old with woods as the main construction material.

In general, cultural heritage buildings need to be specifically reviewed to determine whether the construction in the building needs to be repaired, or reinforced structures. Specific review mentioned earlier is by doing non-destructive test (NDT) in the heritage buildings. However, a laboratory-scale NDT also needs to be done to indirectly see the impact of the test on the material’s quality.
One of the NDTs that has been widely used is the ultrasonic wave method. Non-destructive test of ultrasonic wave method is an activity to identify the physical and mechanical properties of a material without disturbing the final product so that the right information on the nature and condition of the material are obtained before for determining the final decision of its use [1]. Non-destructive testing of ultrasonic methods to suppose the wood quality, to review the cultural heritage buildings, and to prepare the grading of the wood. The grading is in principle to reduce the variations that arise and to classify wood into several quality classes, where the sorting activities of construction wood are directed to Non-Destructive Test.

The basic theory of the ultrasonic wave method is that there is a relationship between the speed of ultrasonic waves that passes through the materials with the dynamic modulus of elasticity (MOEd) and material Specific Gravity. The parameters measured in this method are the ultrasonic wave propagation time, which is then used to calculate the propagation speed. When the wave velocity is known, it can be used to determine the dynamic modulus of elasticity of the material.

2. Material and Method

2.1. Tools and Materials

The method used in this research is laboratory experimental methods. In this study, the specimens used were variations in the types of Teak, Yellow Ballau, Camphor, Coconut and Breadfruit with dimension b x h x l of 100 mm x 60 mm x 500 mm. The specimens are 15 pieces of 5 predetermined variations. Other tests that are carried out in this study were wood’s moisture content testing and wood specific gravity or Specific Gravity testing. The tools that are used in this study were calipers, surfaces, split saws, cut saws, drilling machines, scales, ovens, and ultrasonic pulse velocity test equipment, Portable Ultrasonic Non-destructive Digital Indicating Tester.

2.2. Scheme of the research

The [2] standard is used to test the moisture content and specific gravity or Specific Gravity of the wood. While the ultrasonic wave testing is carried out with the indirect method, at 4 points on the wood surface with reading notation (A1 to G1). The illustration can be seen as Figure 1 below:

![Figure 1. Indirect method testing scheme at point A1 and B1](image)

Note:
T = Transducer
R = Receiver

Transducer and Receiver are used to measure the speed of propagation of the ultrasonic waves. The transducer sends a signal and is received by the receiver. This method is one of the methods that is used in ultrasonic pulse velocity testing. The indirect method works on one surface of the object, where the transducer and receiver are placed in parallel. From the calculation of the ultrasonic wave speed is then used as the basis to see the characteristics of the wood.

2.3. The Testing of Moisture Content

Moisture content is the amount of water that present in wood, which is generally expressed as a percent of the dry weight of a wood oven. Below is the formula to find the value of wood moisture or water content:
Where KA is water content, BA is origin weight, and BKO is oven dry weight. The values of moisture content are shown in Table 1 below:

| Specimen      | Code Specimen | Moisture Content (%) |
|---------------|---------------|----------------------|
| Teak          | JT            | 7.22                 |
| Yellow Ballau | BK            | 7.62                 |
| Camphor       | KP            | 6.67                 |
| Coconut       | KL            | 5.02                 |
| Breadfruit    | SK            | 5.81                 |

2.4. Specific Gravity Test

Specific gravity is the weight of a particular object of a material divided by the weight of water at the same volume. The following formula can be used to find wood specific gravity or Specific Gravity:

\[ BJ = K \times \frac{BKO}{V} \]  

Where BJ is specific gravity, K is multiplier constant (1000), BKO is oven dry weight, and V is volume based on puncture diameter and the depth of the hole. The specific gravity values are shown in Table 2 as follows:

| Specimen      | Code Specimen | Specific Gravity (Oven Dry) |
|---------------|---------------|-----------------------------|
| Teak          | JT            | 0.45                        |
| Yellow Ballau | BK            | 0.76                        |
| Camphor       | KP            | 0.44                        |
| Coconut       | KL            | 0.69                        |
| Breadfruit    | SK            | 0.29                        |

2.5. UPV (Ultrasonic Pulse Velocity) Test

The method of indirect testing using Ultrasonic Pulse Velocity results the value of travel time. Then the value of travel time is used to find the velocity of the ultrasonic wave (V). The average velocity of ultrasonic waves for 5 types of wood is presented in Table 3.

| No. | Specimen      | Code of Specimen | Velocity (km/s) |
|-----|---------------|------------------|-----------------|
| 1   | Teak          | JT               | 5.65            |
| 2   | Yellow Ballau | BK               | 6.34            |
| 3   | Camphor       | KP               | 6.12            |
| 4   | Coconut       | KL               | 4.72            |
| 5   | Breadfruit    | SK               | 4.94            |
3. Result and discussion

3.1. Moisture Content
The average value of the highest wood moisture content for this test is yellow ballau wood at 7.62%.
The amount of moisture content for teak, yellow ballau, camphor, coconut, and breadfruit wood is 7.22%, 7.62%, 6.67%, 5.02%, and 5.81% respectively. The analysis results the following graph:

Figure 2. The relations between the value of moisture content with the type of wood

3.2. Specific Gravity
The highest value of wood specific gravity for this test is yellow ballau wood at 0.76. The high value of specific gravity for teak, yellow ballau, camphor, coconut and breadfruit wood is 0.45, 0.75, 0.44, 0.69, and 0.29 respectively. Specific gravity testing for all five types of wood can be classified into several classes according to their specific gravity. The strength class of wood based on specific gravity is presented in Table 4. Based on the test results obtained, the highest average specific gravity is yellow ballau wood, teak, coconut at 0.76, and included in the strength class of wood II, while the lowest specific gravity is breadfruit wood at 0.29 and included in the strength class of V.

| Standard Specific Gravity* | Wood Type | Specific Gravity Test Result | Strength Wood Class* |
|---------------------------|-----------|------------------------------|----------------------|
| 0.60-0.40                 | Teak      | 0.45                         | III                  |
| 0.90-0.60                 | Yellow Ballau | 0.76                     | II                   |
| 0.60-0.40                 | Camphor   | 0.44                         | III                  |
| 0.90-0.60                 | Coconut   | 0.69                         | II                   |
| ≤ 0.30                    | Breadfruit | 0.29                        | V                    |

* based on (RSNI:2002)

3.3. Speed of Ultrasonic Wave Propagation in Various Types of Wood
The mean speed of propagation of ultrasonic waves for Teak, Yellow Ballau, Camphor, Coconut and Breadfruit wood, respectively 5.65 km / s, 6.34 km / s, 6.12 km / s, 4, 72 km / s, and 4.94 km / s. The speed will increase when the ultrasonic waves go through solid media, and vice versa, the speed will slow down as the waves propagate through the cracks and pores. Based on the analysis of UPV test data, the ultrasonic wave velocity values are presented in Figure 3 as follows:
3.4. Dynamic Modulus of Elasticity (MOEd)

Based on ultrasonic pulse velocity (indirect method) testing, ultrasonic wave velocity propagation values have been obtained. The data is used to determine the relation between the speed of propagation of ultrasonic waves that passes through materials with elastic material properties (dynamic modulus of elasticity, MOEd) can be seen with this formula:

$$ MOEd = \frac{V^2 \times \rho}{g} $$

Where MOEd is a dynamic elastic modulus, $V^2$ is the speed (m/sec), $\rho$ is specific gravity (kg/m$^3$), and $g$ is a gravitational constant (9.81 m/sec$^2$). The relation between the speed of propagation of ultrasonic waves and the elastic modulus of elasticity (MOEd) and material Specific Gravity will be presented in Table 5 below:

| Wood Type    | MOEd (kg/cm$^2$) | Specific Gravity | V (km/s) |
|--------------|------------------|------------------|----------|
| Teak         | 144683.34        | 0.45             | 5.65     |
| Yellow Ballau| 314100.87        | 0.76             | 6.34     |
| Camphor      | 173973.38        | 0.44             | 6.12     |
| Coconut      | 160094.65        | 0.69             | 4.72     |
| Breadfruit   | 73157.74         | 0.29             | 4.94     |

The table above shows that the dynamic modulus of elasticity (MOEd) for Teak, Yellow Ballau, Camphor, Coconut and Breadfruit wood, respectively is 144683 kg/cm$^2$, 314101 kg/cm$^2$, 173973 kg/cm$^2$, 160094.64 kg/cm$^2$, and 73157.74 kg/cm$^2$. Each type of wood tested produces almost the same propagation speed and dynamic elasticity modulus (MOEd). This indicates that the sample of the object being tested represents the same area, so their characteristics are almost the same. There is significant difference in camphor and coconut wood, it is indicated by the tested samples that are obtained from
different stems and tree ages that make different characteristics, as presented in Figure 4 & Figure 5.

**Figure 4.** The value of the relation between wave propagation speed and the modulus of elasticity

**Figure 5.** The value of the relation between wave propagation speed and wood Specific Gravity

Figure 4 and Figure 5 show that the five types of wood that are tested have different Specific Gravity levels, where the Specific Gravity value of a type of wood has an influence on the wave propagation velocity value. This means that the decreasing of the wave velocity and increasing wood specific gravity will affect the results of the dynamic elastic modulus of wood (MOEd). The difference in value (MOEd) of camphor wood for specimens 1, 2, and 3 with a value of 143087 kg/cm², 106505 kg/cm², 272328 kg/cm²; and for the type of coconut wood specimens 1, 2, and 3 with values 109641.56 kg/cm², 215891.40 kg/cm², 154750.96 kg/cm², also affected by the wood Specific Gravity. In between types and one type of wood there is an influence of the wood Specific Gravity on the speed of propagation of ultrasonic waves.

The coconut wood with a specific gravity of 0.69 g/cm³ produces a speed of 4.72 km/s. The higher the specific gravity of wood, the faster the propagation speed of the waves. This is indicated as the characteristics of a type of wood both anatomy, physical properties, mechanical properties and chemical properties that influence the speed of propagation of ultrasonic waves. This is in line with [3] which states that the diversity of wood species with large wave velocities decreases with increasing wood specific gravity. In Yellow Ballau wood with a Specific Gravity of 0.76 g/cm³, it produces a speed of 6.34 km/s. The higher the specific gravity of wood, the faster the propagation speed of the waves. It
can be indicated that the higher the specific gravity of wood, the anatomy of wood, namely the cell wall thicker. This is in line with [4] which states that the thick cell walls as a medium for propagating waves where the interaction of particles in them gets stronger. Meanwhile cell walls with high porosity and permeability will slow down the speed of ultrasonic waves.

[5] stated that the specific gravity of oak was at range of 0.60-0.75 (g/cm$^3$) and the average sound speed of 4600 m / sec. Where the higher the specific gravity of the wood, the faster the sound waves propagate. Meanwhile the Spruce wood which the specific gravity ranges of 0.46-0.54 (g/cm$^3$) and an average sound wave velocity of 6000 m / sec, or the smaller the specific gravity of the wood, the more the wave speed sounds tends to increase. Based on [6], the strong class of wood can be determined using the test of ultrasonic propagation speed. The strength class of wood specimens is presented in Table 6.

| Wood Type      | MOE (kg/cm$^2$) | MOEd (kg/cm$^2$) | MOE Different in MOEd (%) | Strength Wood Class |
|----------------|-----------------|------------------|---------------------------|---------------------|
| Teak           | 80000           | 144683           | 44.7                      | III                 |
| Yellow Ballau  | 100000          | 314101           | 68.16                     | II                  |
| Camphor        | 80000           | 173973           | 54.01                     | III                 |
| Coconut        | 100000          | 160095           | 37.53                     | II                  |
| Breadfruit     | 40000           | 73158            | 45.32                     | V                   |

Based on the Table 7, it can be seen that the dynamic modulus of elasticity (MOEd) of the variation of wood species calculated based on wave propagation speed and wood specific gravity is 49.94% greater than the MOE value. This is in line with [4], [7], and [8] which shows that the average MOEd value is 20-50% higher than the MOE value.

Yellow Ballau and Camphor wood species have an average difference of above 50%, namely Yellow Ballau wood with a difference of 68.16% and Camphor wood of 54.01%. This is allegedly due to the influence of the specific gravity level on Yellow Ballau wood where the thicker the cell walls are, the better the media for propagating waves. In Camphor wood the fiber direction affects the speed of wave propagation, so that the wood stiffness increases with increasing wave propagation speed.

The different value in the modulus of elasticity is caused by the microstructural characteristics of the constituent cells of each different type of wood. Higher non-destructive testing values than the destructive testing value are due to viscoelasticity and the effect of creep effects on deflection testing [9].

4. Conclusion
After the ultrasonic wave velocity testing (UPV) by using the method and indirectly on wood specimens with a variety of woods, then the analysis of the data is done. Based on the results of data analysis that has been done, the conclusions are as follows:
- The magnitude of the propagation speed of ultrasonic waves with the indirect method on the variation of test specimens for Teak, Yellow Ballau, Camphor, Coconut and Breadfruit are 5.65 km / s, 6.34 km / s, 6.12 km / s, 4, 72 km / s, and 4.94 km / s
- The magnitude of the dynamic modulus of elasticity, MOE are based on the propagation speed of ultrasonic waves for Teak, Yellow Ballau, Camphor, Coconut and Breadfruit wood, respectively at 144683 kg/cm$^2$, 314101 kg/cm$^2$, 173973 kg/cm$^2$, 160094.64 kg/cm$^2$, and 73157.74 kg/cm$^2$

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