The effect of joints model to the vibration characteristics of wood

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Abstract. The One piece of the wooden beam has different vibration characteristics compared to the two pieces of wood with a joint. One of the parameters measured is the dynamic stiffness of wood. The method used is a technique in which the vibration excitation test using a hammer with a rubber head. The wood used in this study is Gofasa (Vitex cofassus). The Properties of wood was using the data from previous studies. Vibration characteristic of a piece of wood was used for comparison purposes. Two pieces of wood have joined and secured by bolts. Cantilever beam model has used with the knock in a perpendicular direction to the wood fibres. The joints model used to excitation test is the plain scarf, hooked scarf, half lap splice, and tabled splice. All of these models were tested to determine the characteristics of vibration. The results showed the different vibration characteristics for each model. The results are used as a recommendation of the best models in distributing the vibration from the vibration source.

1. Introduction

The mechanical properties of wood can be known through experimental test both destructive or non-destructive. The Non-destructive test is known as technical methods of vibration or modal analysis as performed by [1, 2, 3], while the approach to the finite element carried by [4]. The destructive test is often used only to verify the results of the non-destructive test, such as a deflection test to ensure that the value and method used was valid.

Analysis of damage to wooden ship structures has also been carried out by [5, 6, 7]. Research on the vibration characteristics of various types of material has been done, but not so much who research the vibration characteristics of wood. Wood has classified as an orthotropic material with different mechanical properties in three axis directions.

Fibre orientation is characteristic of wood. So, it is necessary to compare with an anisotropic material such as is done by [8] where the value of Poisson's ratio of spruce wood is most easily obtained through mechanical tests. Numerical variation of the Poisson's ratio of tropical timber has done by [9] with consideration of corner of the wood fibre through experiments. Vibration characteristics can be detected through vibration technique on the cantilever beam model, measuring the first natural frequency and amplitude in different cycles of materials such as done by [3] for verification of deflection test conducted on three materials.

The method in this research is the non-destructive method with the use of vibration technique on a cantilever beam to obtain the value of vibration parameters. Data of elasticity of the material and the Poisson's ratio has obtained through the deflection test and compression test.
2. Materials and Method

2.1. Material
The material used is wood Gofasa (*vitex cofassus*) with a specific gravity $\rho$ is 1.04 g cm$^{-3}$. Model and dimensions of joining as shown in Figure 1.

![Diagram of joint models](image)

**Figure 1.** Joints model (geometry and dimension) in mm

2.2. Elasticity of wood
The modulus of elasticity of wood differs from the modulus of elasticity in steel because the wood elasticity limits are not very clear, only the $\sigma/\varepsilon$ diagrams obtained in the straight section before bending and this meeting point are proportional limits which are finally regarded as elasticity limits (Figure 2). The proportional stress limit for wood is 75% of the broken stress.
Wood elasticity value is not ideal at the time of deformation because wood is different on all three sides. Similarly, the values of stiffness and Poisson's ratio as well as elasticity values also vary depending on the type, humidity and specific gravity. In modulus elasticity wood is usually written EL, ER and ET where each represents the value of elasticity in the longitudinal, radial and tangential direction. In this study, the stiffness value (k) was obtained with the help of polynomial regression.

Wood has three different fibre directions, namely radial, tangential and longitudinal fibre direction. Each has a different elasticity value or is usually written into ER, ET and EL. This elasticity value can be searched by using bending test following the direction of fibre to be reviewed. In the isotropic material the modulus of elasticity can be obtained from the stress-strain diagrams in the linear region but not in the orthotropic material.

The elastic modulus of wood as the orthotropic material can be searched by using a vertical load test just in the middle of the wood where maximum deflection occurs. The elasticity value can be searched by using Hooke's law equation that is:

\[ \sigma = E \varepsilon \text{ or } E = \frac{\sigma}{\varepsilon} \]  
(1)

Test bending on wood using equation:

\[ \Delta = \frac{P L^3}{4 B E I} \]  
(2)

where P is the given weight of a load, L is the length of material, E is modulus elasticity of the material, and I is the moment of inertia of the central axis cross-section.

\[ E = \frac{P L^3}{4 B I \Delta} \]  
(3)

By increasing the load P, the block will be deflected. The ratio between load P and deflection \( \Delta \) in the load-deflection graph in the linear region is the stiffness value k (equation 4).

\[ k = \frac{P}{\Delta} = \frac{4 B E I}{L^3} \]  
(4)

With the equation above, the elasticity modulus value can be obtained as follows:

\[ E = \frac{k L^3}{4 B E I} \]  
(5)

2.3. Shear modulus

There are three shear modulus of wood, is written with symbol G_{LR}, G_{LT} and G_{RT} respectively on longitudinal radial, tangential and tangential longitudinal radial fields. These three values are known as modulus of rigidity.
2.4. Poisson’s ratio

Poisson's Ratio is a measure of changes in the geometry of a comparison between a lateral strain deformation with axial strain caused by certain axial pressure, which can turn into a form that is not limited. Poisson's Ratio can be expressed by the following equation:

\[
\mu = \frac{\text{lateral strain}}{\text{axial strain}} = \frac{\varepsilon_{\text{Lateral}}}{\varepsilon_{\text{Axial}}}
\]

In the wood known there are six values of Poisson ratio are: \(\mu_{LR}, \mu_{LT}, \mu_{RL}, \mu_{RT}, \mu_{TL}\) and \(\mu_{TR}\). The first index shows the working force and the second index indicates the direction of the lateral strain. The general equation of the elasticity value for isotropic material conditions [10] is:

\[
\mu_{ij} = \frac{E_{i}}{G_{ij}}
\]

The elasticity of wood material can be approached with attention to the direction of the fibre. The elasticity of the wood material can be approximated by using three E modulus elasticity values, three rigidity G values and six Poisson's ratio \(\mu\) values.

For an orthotropic state this relationship can be expressed by the equation:

\[
\frac{\mu_{ij}}{E_{i}} = \frac{\mu_{ji}}{E_{j}}, \quad i \neq j, \quad j = L, R, T
\]

The orthotropic model can be expressed in matrix form with finite element model by Carne & Stationas (2008) as follows:

\[
\left\{\begin{array}{c}
\varepsilon_{RR} \\
\varepsilon_{LL} \\
\varepsilon_{TT} \\
\gamma_{RL} \\
\gamma_{LT} \\
\gamma_{TR}
\end{array}\right\} = \frac{1}{G_{RL}} \begin{bmatrix}
\varepsilon_{LL} & -\nu_{LR} & -\nu_{TR} \\
-\nu_{RL} & E_{RR} & E_{TT} \\
-\nu_{TR} & E_{RR} & E_{TT} \\
\gamma_{RL} & -\nu_{LT} & E_{RR} \\
\gamma_{LT} & E_{LL} & E_{TT} \\
\gamma_{TR} & -\nu_{TR} & E_{LL}
\end{bmatrix} \begin{bmatrix}
\sigma_{RR} \\
\sigma_{LL} \\
\sigma_{TT} \\
\sigma_{RL} \\
\sigma_{LT} \\
\sigma_{TR}
\end{bmatrix}
\]

Where: the notation index shows the field of fibre direction. The modulus of elasticity value in three directions of fibre is longitudinal, the radial direction and tangential direction, i.e. \(E_{L}, E_{R}\) and \(E_{T}\); Poisson's ratio values \(\nu_{LR}, \nu_{RL}, \nu_{LT}, \nu_{TL}, \nu_{RT}\) and \(\nu_{TR}\). The first letter shows the direction of stress while the second letter indicates the direction of lateral deformation.

The value of modulus of elasticity for radial fibre direction (ER) which obtained from the mechanical test is 12411.231 Mpa.

Bolts are used as the connection tool. There is four testing point with a predetermined distance. This research using vibration technique method with a cantilever beam at the perpendicular direction of the wood fibres (see Figure 3). The test results are the set of Frequency Response Function (FRF).
2.5. Generalization of SDoF with Rayleigh-Ritz method

The most common method of simplifying the number of degrees of freedom (DoF) and in seeking approaches to the lowest natural period is the Rayleigh-Ritz method. This method is an addition to Rayleigh’s method by W. Ritz in 1909.

The general equation of a system with N degrees of freedom given the force p(t) = sp(t) is:

\[ m \ddot{u} + c \dot{u} + k u = sp(t) \]  \hspace{1cm} (10)

The natural or personal frequencies in radian/sec units are obtained from the equation:

\[ \omega_n = \sqrt{\frac{k}{m}} \text{ (rad/det) atau } \omega_0 = 1/t \text{ (Hz)} \]  \hspace{1cm} (11)

The transmission force can be calculated using the following general equation:

\[ F_T = kA \sqrt{1 + \left(2 \xi \frac{\omega}{\omega_0}\right)^2} \]  \hspace{1cm} (12)

As for the value of the transmission ratio (TR) is the ratio between the values of the transmission force (F_T) with the amplitude of the excitation force (F_0), namely:

\[ TR = \sqrt{\frac{1+(2 \xi \omega/\omega_0)^2}{(1-(\omega/\omega_0)^2+(2 \xi \omega/\omega_0)^2)}} \]  \hspace{1cm} (13)

The amplitude equation A

\[ A = \frac{F_0}{\sqrt{1-(\omega/\omega_0)^2+2 \xi \omega^2/\omega_0^2}}} \]  \hspace{1cm} (14)

Result from FFT analyzer is transferred with Mathcad to obtain curve fit for vibration parameters. Vibration parameter which considered are Compliance a (m/N), dynamic stiffness k (N/m), Natural frequency \( \omega_0 \) (Hz), damping ratio \( \xi \) and transmission ratio TR.

3. Results and Discussion

Analysis of the changes of vibration characteristics was done based on the value of each parameter of vibration at the graph (see Figure 4). The value of vibration parameter can be seen in Table 1.

The graph shows that the compliance value of 4 existing models is below the wood without a connection. The model I have the lowest compliance value that indicates the value of the highest
stiffness. It is supported by the chart of dynamic stiffness which is the opposite of the graph of compliance. The highest stiffness is Model I, followed by model IV. The same value of natural frequency at all points on each model. The decreased of the value of natural frequency occur on type IV. Model II has an equal value of the natural frequency of the wood without the connection. It shows that this model has a high elasticity compared to other models. The value of Transmission Ratio on wood without connection increased but otherwise, the value of damping ratio is moving down. In all four model test, the opposite condition occurs where the value of the Transmission Ratio decreased while the value of Damping Ratio increased. It shows that the force is transmitted muffled because of they are joint. In the model I and III the reduction of transmission rates quite sharply. These conditions can damage the structure of local connection. On models II and IV a reduction of transmission rates occurs slowly, which is good because it does not cause stress concentrations in the connection.

![Graph of vibration characteristic](image)

**Figure 4.** Graph of vibration characteristic
The First Maluku International Conference on Marine Science and Technology

IOP Conf. Series: Earth and Environmental Science 339 (2019) 012038
doi:10.1088/1755-1315/339/1/012038

4. Conclusion

Joints model with best dynamic rigidity is Model I, while the model with the best elasticity is models II and III. Model II is quite elastic and models IV is rigid enough and can be considered as the best connections model in transmitting vibrations from the vibrating source. No fluctuations values of vibration parameter occur in the area of connection. Placement of the right model is based on the needs and functions of such construction.

There are still many other factors that affect the vibration characteristics of the wood connection. The influence of the use of other connecting device and the location of the connection to the vibration characteristics are the concern for future research.

Acknowledgement

The research is a part of Nuffic funding; therefore the authors gratefully acknowledge the Nuffic Program, Indonesia Higher Education, Pattimura University and ITS Surabaya, especially Laboratorium of Manufacturing Process, Department of Mechanical Engineering, ITS.

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| Table 1. Parameter of vibration of Model I, II, III and IV |
|---|---|---|---|---|---|---|
| Number | Wood | F0 (N) | \(\omega_n\) (Hz) | a (m/N) | k (N/m) | \(z_0\) | \(\xi\) | FT (N) | TR |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Model I | 1 | 8,008 | 47 | 4,129E-10 | 2,422E+09 | 0,030 | 0,015 | 7,765 | 0,970 |
| | 2 | 9,597 | 47 | 1,067E-09 | 9,371E+08 | 0,025 | 0,013 | 9,355 | 0,975 |
| | 3 | 8,615 | 47 | 2,001E-09 | 4,998E+08 | 0,025 | 0,013 | 8,396 | 0,975 |
| | 4 | 9,019 | 47 | 2,366E-09 | 4,229E+08 | 0,042 | 0,021 | 8,636 | 0,958 |
| Model II | 1 | 6,695 | 57 | 2,247E-09 | 4,450E+08 | 0,022 | 0,011 | 6,550 | 0,978 |
| | 2 | 8,880 | 57 | 7,250E-09 | 1,379E+08 | 0,030 | 0,015 | 8,612 | 0,970 |
| | 3 | 8,776 | 57 | 9,459E-09 | 1,057E+08 | 0,033 | 0,017 | 8,485 | 0,967 |
| | 4 | 7,623 | 57 | 1,361E-08 | 7,346E+07 | 0,035 | 0,018 | 7,353 | 0,965 |
| Model III | 1 | 7,691 | 43 | 1,932E-09 | 5,177E+08 | 0,019 | 0,010 | 7,543 | 0,981 |
| | 2 | 8,970 | 43 | 7,078E-09 | 1,413E+08 | 0,024 | 0,012 | 8,754 | 0,976 |
| | 3 | 7,945 | 43 | 1,028E-08 | 9,723E+07 | 0,015 | 0,007 | 7,827 | 0,985 |
| | 4 | 8,444 | 43 | 1,510E-08 | 6,625E+07 | 0,034 | 0,017 | 8,154 | 0,966 |
| Model IV | 1 | 7,674 | 34 | 6,547E-10 | 1,527E+09 | 0,036 | 0,018 | 7,398 | 0,964 |
| | 2 | 10,608 | 34 | 3,047E-09 | 3,282E+08 | 0,046 | 0,023 | 10,117 | 0,954 |
| | 3 | 10,339 | 34 | 5,288E-09 | 1,891E+08 | 0,051 | 0,025 | 9,812 | 0,949 |
| | 4 | 8,405 | 34 | 1,148E-08 | 8,707E+07 | 0,052 | 0,026 | 7,965 | 0,948 |
| R | 1 | 6,024 | 57 | 2,698E-09 | 3,706E+08 | 0,025 | 0,012 | 5,876 | 0,975 |
| | 2 | 9,407 | 57 | 9,254E-09 | 1,081E+08 | 0,020 | 0,010 | 9,224 | 0,980 |
| | 3 | 8,184 | 57 | 1,272E-08 | 7,864E+07 | 0,019 | 0,009 | 8,029 | 0,981 |
| | 4 | 8,715 | 57 | 1,743E-08 | 5,738E+07 | 0,019 | 0,010 | 8,548 | 0,981 |
| T | 1 | 8,519 | 56 | 1,386E-09 | 7,217E+08 | 0,021 | 0,011 | 8,339 | 0,979 |
| | 2 | 10,548 | 56 | 6,442E-09 | 1,552E+08 | 0,019 | 0,010 | 10,344 | 0,981 |
| | 3 | 9,619 | 56 | 1,110E-08 | 9,005E+07 | 0,020 | 0,010 | 9,430 | 0,980 |
| | 4 | 8,623 | 56 | 1,623E-08 | 6,161E+07 | 0,020 | 0,010 | 8,450 | 0,980 |
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