3D FINITE ELEMENT ANALYSIS OF A WOOD DOWEL IN BENDING PERPENDICULAR TO THE GRAIN

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Abstract

This paper simulated the bending behavior of a wood dowel in a three-point bending test using the Finite Element Method (FEM) in ANSYS Workbench. Most researchers performed a three-point bending test to measure the flexural strength parallel to the wood grain. In this paper, the analysis is carried out perpendicular to the grain direction. The three-point bending test provides the mechanical properties of the wood, such as the modulus of elasticity and the modulus of rupture. These properties are important to define orthotropic wood material in finite element modeling. The aim is to determine the modulus of elasticity of the wood dowel perpendicular to the grain. The process overview of modeling wood elements in ANSYS is also presented. The results from the FEM were then compared with the experimental results from laboratory tests. In this work a good agreement between FEM and experimental results was obtained. The modulus of elasticity obtained was relatively very small in the perpendicular direction compared to the value in the parallel direction.

Keyword: 3D, FEM, three-point bending, wood dowel, ANSYS

Introduction

Emerging technology in the wood industry nowadays increases the demand for wood and wood-based products as building materials. The advantages of wood structures are low weight/strength ratio, environmental-friendly and renewable materials. (Marjanović, 2020) The strength of wood structures is largely determined by how well is the connection between the members. In the direction parallel to the grain, wood shows outstanding strength and stiffness. (Naderer, 2016). In contrast, tension perpendicular to grain becomes the weakest point of the jointing system resulting in brittle failures under small loading. (Oudjene, 2009; Franke, 2011). Mechanical fasteners are used to increase the load carrying capacity of a connection. Wood dowel is one of the most common types of fasteners in wood joints. To estimate the load-carrying capacity of the connection, it is important to understand the mechanical behavior of wood dowels.

Many studies focused on determining the flexural strength of structural wood and wood-based materials in a direction parallel to the grain. (Hassan, 2011; Yasin, 2020). Most of them were using their local wood species. Sun et.al., (2021), on the other hand, performed compression and tensile tests to determine the modulus of elasticity of wood-based materials in parallel to grain and perpendicular to grain directions. However, bending tests in the direction perpendicular to grain and tangential to grain are difficult to conduct because of the low strength of wood dowel in these two directions.

Finite element model (FEM) is another method for simulating the behavior of wood under bending, compression and tensile force. The mechanical properties of wood in three orthotropic directions must be clearly defined in FEM to get better simulation.

Wood is an anisotropic and nonhomogeneous material with different characteristics in each of its orthotropic planes. **Figure 1** shows the wood grain directions and the orthotropic plane considered in testing. The direction along wood grain is referred to as longitudinal axes (L), while the direction perpendicular to the grains is referred to radial axes (R) and tangential axes (T) referred to the axis tangent to the annual growth ring. As the wood behaves differently in its orthotopic planes, the mechanical properties in these three directions must be studied.

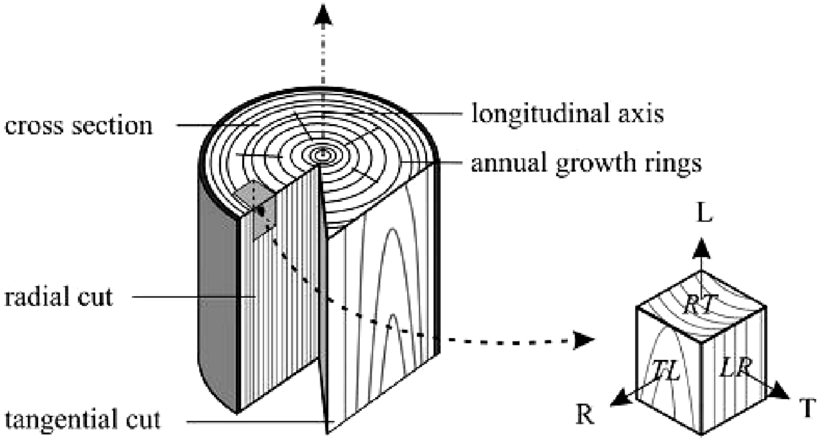


Figure 1 Wood orthotropic axes and sampling method (Franke, 2011)

Flexural behavior of wood can be determined using three-point bending test (Li, 2020). This test is much more suitable for brittle material like wood. Modulus of elasticity (MOE) and modulus of ruptures (MOR) are the properties that can be obtained from the bending test. MOE represents the deformation of the material that is produced by low stress and is recoverable after the load is removed. For orthotropic material the elastic moduli in the three principal axes are denoted by E_L, E_R, and E_T which are the moduli in longitudinal, radial and tangential axes. These three moduli are important properties in FEM in order for the modelling to be truly presenting the behavior of the wood under testing.

Wood is a complex material that shows nonlinearity behavior under loading. Recent work focusing on modeling failure behavior of wood material such as splitting and cracking under nonlinear analysis. Many two-dimensional (2D) or three-dimensional (3D) (FEM) models have been presented in recent years to simulate the behavior of structural woods and wood-based engineered material such as glulam and cross-laminated timber structures. (Guo, 2016; Li, 2020; Navaratnam, 2020; Marjanović, 2020; Zahedi, 2021). The behavior of wood joints and structural beams were the most reported studies based on the literature. However, the FEM model of wood dowel under bending is still lacking. The common FEM applications used by the researchers were ANSYS and ABAQUS. In this study, ANSYS Workbench was adopted to simulate three-point bending test.

This paper presents, first, a numerical modeling of 3 points bending test of a wood dowel in parallel and perpendicular to grain direction. The description of the FE model, load-displacement curve obtained and the MOE results are the purpose of the later discussions.

Materials and Methods

The schematic of the three-point bending test configuration studied is shown in **Figure 2**. The FEM modeling follows the same configuration to the experimental test conducted by Hassan (2011). In this study, a 20 mm diameter wood dowel with a length of 230 mm was used. The wood dowel was made of Kempas species.

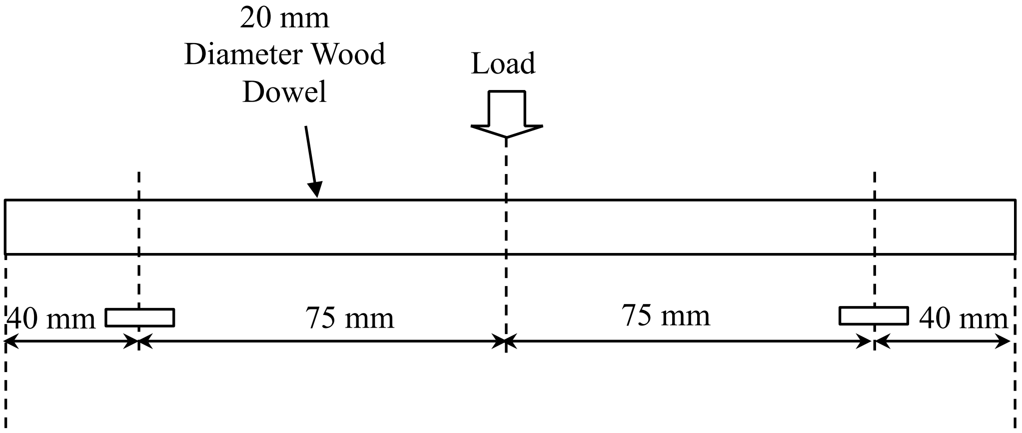


Figure 2 Schematic diagram of three-point bending test

Flexural strength properties are calculated using bending stress theory. Analytical analysis of stress and strain in the three points bending test follows equation in (1) and (2), respectively. These formulas are simplified formulas for circular cross-section.

$$\sigma_f = \frac{8PL}{\pi d^3} \tag{1}$$

$$\varepsilon_f = \frac{6d\delta}{L^2} \tag{2}$$

Definition: *P = Applied load (N)*
L = Span between support (mm)
d = Diameter of wood dowel (mm)
δ = Deformation at the mid-span (mm)

FEM Model Geometry

ANSYS Workbench 2021 R1 (Academic version) was used to create two 3D models of a three-point bending test. Each model consists of a wood dowel, two roller supports and an impactor for the load application. The SOLID85 element was used to represent all the solid elements in the ANSYS application. Elastic orthotropic analysis was selected to model the wood behavior. The axes used in the modeling are shown in **Figure 3**. The longitudinal, radial and tangential axes are represented by the global axis x, y and z, respectively. The wood dowel sample in the direction parallel to grain was cut in the LR plane and the wood dowel sample perpendicular to grain was cut in RT plane.

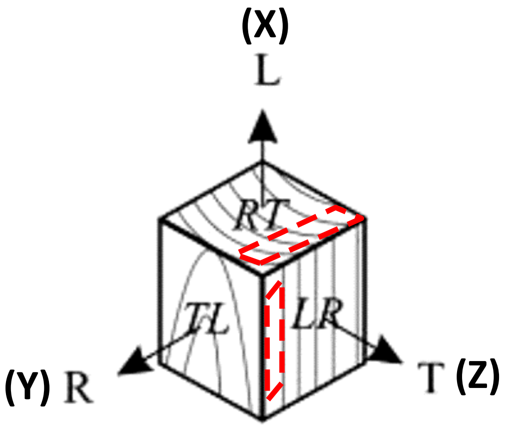


Figure 3 Global axis in ANSYS Modeling and sampling method

The first 3D model was developed to simulate a bending test parallel to grains direction. The wood dowel was drawn along the x axis with the load applied in the y axis direction. On the other hand, the second model was created to simulate flexural behavior perpendicular to the grain. In this model, the wood dowel was drawn along the y axis while the load applied along the x axis. The geometry sketches were created in Ansys Design Modeler. Surface split tool was used to split the surfaces to specify the contact region between the impactor and the supports with the wood dowel.

Material Properties

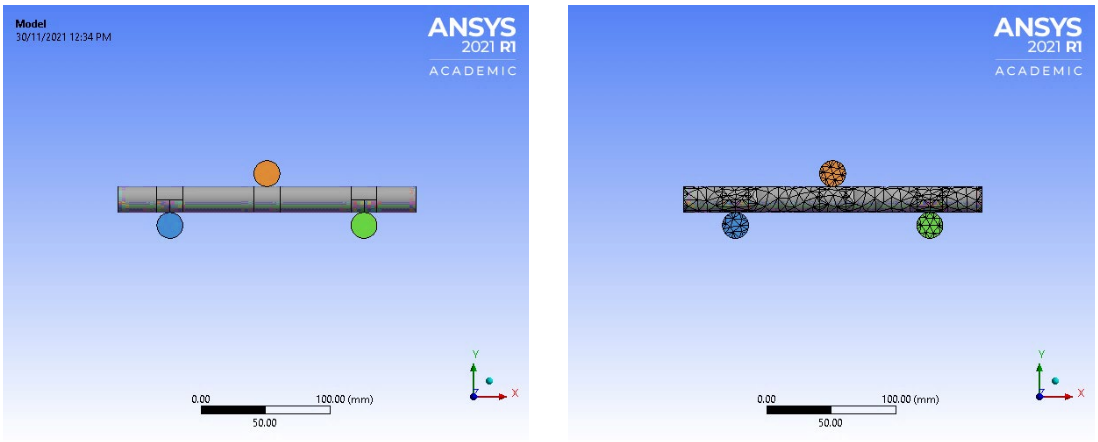
In FEM modeling, wood density and another nine material properties must be defined in the engineering data library to represent orthotropic behavior of a wood dowel. These properties can be obtained from laboratory tests. However, no experimental tests were performed in this work, thus the values were selected based on previous studies. The adopted Kempas properties are given in **Table 1** as reported by Amaruddin (2013).

Table 1 Material properties of Kempas wood dowel (Amaruddin, 2013)

Density	Modulus of elasticity (MPa)			Shear modulus (MPa)			Poisson ratio		
(kg/m^3)	$E_L=E_X$	$E_R=E_Y$	$E_T=E_Z$	$G_{LR}=G_{XY}$	$G_{LT}=G_{XZ}$	$G_{RT}=G_{YZ}$	$U_{LR}=U_{XY}$	$U_{LT}=U_{XZ}$	$U_{RT}=U_{YZ}$
930	17700	2885	1274	1522	1431	152	0.369	0.618	0.428

FEM Modeling

Static structural FE Analysis was conducted in ANSYS Mechanical. When ANSYS mechanical was loaded, the contact region between solid bodies would be automatically defined by the program. The contact was then set to frictionless with all other elements left as program controlled. Meshing was applied to the model with default sizing controlled by the program. Fine meshing can be defined by using sizing tools to get more accurate simulation. ANSYS academic version has a limited number of nodes for the analysis. Due to the software limitation fine meshing was not possible.



(a) (b)

Figure 4 Three-point bending test model. (a) Geometry model (b) Element meshing

Boundary conditions were applied to the model. The bottom surface of the roller supports was set as fixed support. At the contact surface between roller and wood dowel, displacement was restricted in the x, y and z axis. The loading was applied using a displacement-controlled method. A linear analysis was conducted in this study. According to Hassan, 2011, kempas wood dowel behaves nonlinearly after very small displacements. Nonlinear analysis is recommended to fully investigate the flexural strength of wood dowel. Nevertheless, nonlinear analysis requires more parameters to be identified in FEM and a longer time to solve. In this study, a 10 mm displacement was applied at the top of the impactor to simulate the linear state behavior of the kempas wood dowel. The analysis was conducted using sub steps where the displacement was increased linearly with time until each reached 10 mm. The displacement and stress diagrams were evaluated for the results and discussions. Load-displacement curve and stress-strain curve were plotted to determine the bending behavior of the wood dowel.

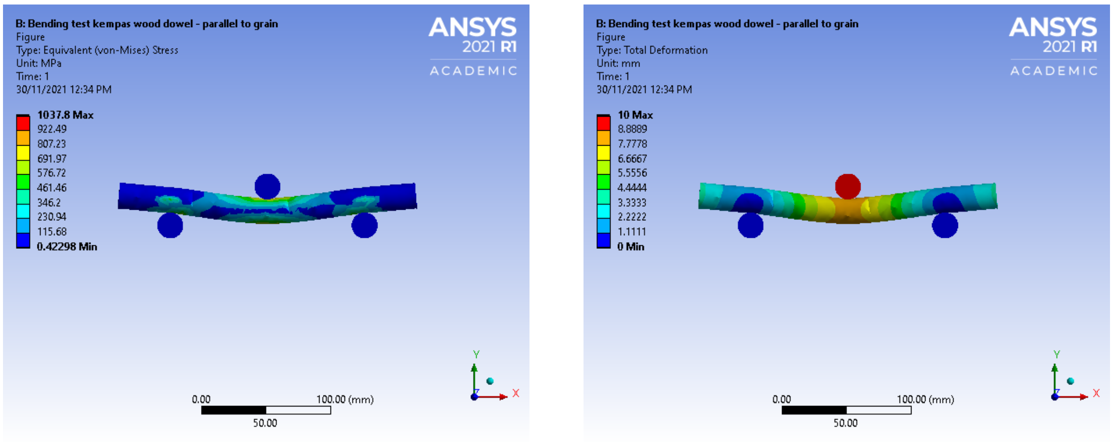
Result and Discussion

Simulated Bending Behavior Parallel to Grain

The stress diagram and total deflection diagram after the completion of the ANSYS mechanical analysis of a wood dowel loaded perpendicular to grains are shown in **Figure 5(a)** and **5(b)**, respectively. A higher stress value is seen at the dowel's mid span at top and bottom surface based on the contour color grading. Maximum bending moment occurred at the mid span, where the compression stress and tensile stress are higher. The stress probe value at the mid span is 690 MPa. At 10 mm displacement, the corresponding force applied is 24.1 kN.

Simulated Bending Behavior Perpendicular to Grain

Bending test of a wood dowel perpendicular to the grain was established. In this simulation, the applied displacement was reduced to 5 mm downward to avoid large displacement occurring thus leading to linear analysis failing to achieve convergence. The stress distribution shows the stress distribution similar to the results from parallel to grains bending.



(a) (b)

Figure 5 (a) Stress diagram (b) Total deformation diagram

Load-displacement Curve

Figure 6 shows the load-displacement curve of a wood dowel parallel to grain. FEM results were superimposed on experimental results from Hassan (2011). From the graph plotted, a good agreement between FEM and the experimental results in the elastic region was obtained. Since, FEM modeling only consider the elastic region, the ultimate load capacity cannot be evaluated.

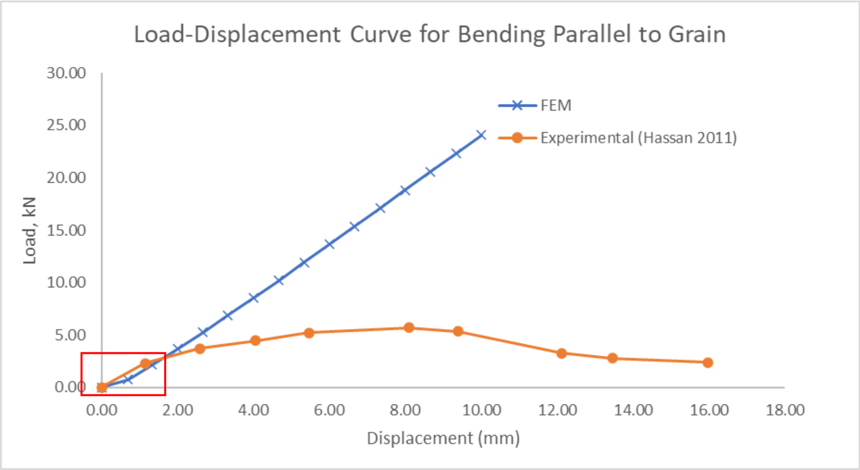


Figure 6 Load-Displacement curve comparison between FEM and experimental

Stress-Strain Diagram

Stress-strain diagram was plotted from the FEM results as shown in **Figure 7**. Based on Hooke's Law, MOE is determined by calculating the gradient of the stress strain curve. The MOE in perpendicular to grain has lower value than the MOE in parallel to the grain. The elastic modulus in longitudinal and radial are 17856 MPa and 2566 MPa, respectively. **Table 2** shows the comparison between Modulus of elastic of kempas adopted in the modeling with the FEM results. The percentage difference between adopted kempas properties and FEM results are 1 % and 12% for longitudinal modulus, E_L and radial modulus, E_R, respectively.

Table 2 Modulus of elastic (MOE) of kempas wood dowel

	Kempas Properties		FEM Results	
	E_L	E_R	E_L	E_R
Modulus of Elasticity (MPa)	17700	2885	17856	2566

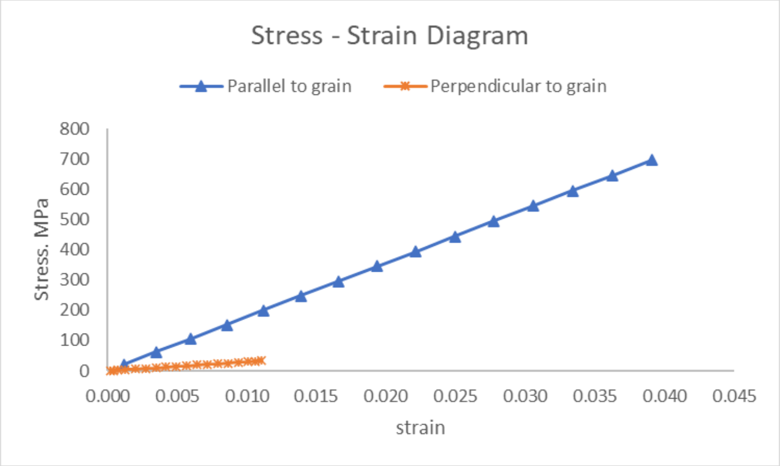


Figure 7 Stress-strain diagram for three-point bending test of a wood dowel parallel to grain and perpendicular to grain

Conclusion

Two 3D models of three-point bending test for a wood dowel loaded perpendicular to grains and parallel to grain were developed. The 3D FEM analysis using the elastic orthotropic material model was able to compute the modulus of elasticity (MOE) of the wood dowel in longitudinal and radial directions. The obtained results closely represented the material properties, with percentages differences of less than 12%. For future work, the elastic orthotropic model can be improved by incorporating strain hardening properties into nonlinear analysis to fully evaluate the behavior of a wood dowel in bending.

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Conflict of interests

The authors state that they have no conflicting interests in the publication of this research.

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