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EFFECT OF BOX BEAM WALL THICKNESS ON THE STIFFNESS OF THE CAMPHOR WOOD TIMBER BRIDGE TRUSS

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Bridges are vital for community development, and wood is a primary material due to its environmental benefits. However, wood's moisture absorption can cause swelling and shrinkage, and low-density wood tends to have lower strength. The moment of inertia of a box beam is related to wall thickness and stiffness. Insufficient wall thickness can lead to plastic retention before peak load, reducing structural integrity. Thin walls can cause buckling under compressive loads, leading to failure. Truss bridge failures can also result from design errors. This study aims to analyze the effect of box beam wall thickness on the stiffness of camphor wood timber bridge trusses. Camphor wood with a cross-sectional area of 1,600 mm^2 was used, with box beams of dimensions 45×45 mm (12 mm wall), 50×50 mm (10 mm wall), 58×58 mm (8 mm wall), and a solid beam of 40×40 mm (20 mm wall). Physical tests showed the wood's specific gravity at 0.506 g/cm^3 and moisture content at 12.47 %. The highest peak load was 19.613 kN for the BB.58.58.8 variation, which also had the greatest stiffness at 3.502 kN/mm. The BB.58.58.5 variation had the largest moment of inertia at 683,733 mm^4 compared to the solid beam SB.40.40.20 at 213,333 mm^4. The BB.45.45.12 sample had a t/D ratio 1.93 times larger than BB.58.58.8, indicating a more flexible structure with lower stiffness. This is confirmed by experimental results, showing that BB.45.45.12 had a stiffness 1.73 times lower than BB.58.58.8. Theoretical calculations also showed that BB.45.45.12 had a stiffness 2.03 times smaller than BB.58.58.8. Thus, the t/D ratio is inversely proportional to stiffness. This research contributes valuable insights for developing engineered wood products in construction and bridge design, particularly for village bridges in Indonesia.

Keywords: wooden truss bridge, box beam, peak load, stiffness

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1. Introduction

Bridges as a means of transportation are essential in efforts to develop community life [1]. Bridges act as a means of transportation that is very important for traffic movement, and can have an impact in several fields such as social, economic, defense and security [2]. In Indonesia, the need for bridges in villages is very high. The country has 12,484 moderately damaged bridges, 2,287 severely damaged bridges, 261 bridges in critical condition, and 122 bridges collapsed or broke [3].

Wood as the main material for bridges has actually been used in ancient times to connect rivers. This was chosen because wood is a potential material and has been known by humans for a long time. Bridge structures that use solid wood have shortcomings, including control over the quality of the wood material itself, including the physicality of wood such as defects in the wood, the wood production process during cutting that is prone to errors, and the scarcity of wood in large sizes, which will result in deforestation that has an impact on natural disasters, triggering global warming and climate change [4]. To overcome this, it is necessary to use engineered wood in the form of box beams on the bridge. Engineered wood is made from selected wood so that it avoids wood defects by cutting layers of wood from smaller wood pieces.

The choice of wood as the main material in the bridge is because wood is the most environmentally friendly material. At present, structural design requirements must meet not only strength and durability but also environmental and energy-saving requirements [5]. Camphor wood (*Dryobalanops Camphora*) is an endemic Indonesian wood with its durability quality including class II–III, and has class I–II strength [6].

Box beams are engineered processed wood products composed of several box-section profiles with a hole in the middle [7]. Box beams have advantages in material properties and structural capabilities when compared to wood in general [8]. The hollow cross-section (box beam) will increase the inertia greater than that of solid wood with the same cross-sectional area. This is proven by the calculation of the moment of inertia with the same cross-sectional area. From these studies, it is evident that box beam engineered timber has a much better advantage over conventional timber [9–11].

Wood absorbs moisture from the environment, which can cause swelling, and releases moisture, which can cause shrinkage. These dimensional changes can cause distortion, cracks, or loose connections in the bridge structure. High humidity can reduce the mechanical strength of wood, including tensile, compressive and bending strength. Wet wood is more susceptible to deformation and failure. Low-density wood tends to have lower strength, which can result in a smaller load capacity and greater potential for structural failure [12].

The problem of box beam thickness and peak load includes various technical aspects that can affect structural performance.

If the wall thickness is inadequate, the box beam can experience plastic retention before reaching its peak load, reducing the structure's ability to return to its original shape after the load is removed. The greater the moment of inertia, the greater the peak load. But this does not happen to the beam with a b/h ratio of 1.75, which has the largest moment of inertia. The 1.75 b/h ratio beam has a peak load of 2,095 kg. This decreases by 3.4 % when compared to a 1.50 b/h beam with a peak load of 2,167 kg [10].

Wood frame bridges, although they have many advantages, also face a number of problems in society regarding the stiffness and thickness of the box beam walls. Too small wall thickness can cause buckling of the box beam web or flange under compressive loads, which can result in structural failure. In theory, the greater the moment of inertia, the stiffer it is. It can be seen that the greater the inertia, the greater the load that can be supported by the beam, but for the highest moment of inertia, the beam's ability to accept the load decreases, namely a beam with a b/h ratio of 1.75 or a decrease of 0.52 % compared to a b/h ratio of 1.5. There may be a decrease in the beam strength, the emergence of lateral torsional buckling effects or local buckling in the side walls of the beam. Lateral torsional buckling effects can occur in beams with higher b/h ratios. For solid beams, the effect of lateral torsional buckling occurs if the b/h ratio becomes greater than or equal to two, whereas for box-section beams, there has been no research regarding the effect [10].

Truss bridge failure can occur for various reasons. Design errors, construction errors, hydraulics, impacts and overload are the 5 main causes of bridge failure, which cause more than 70 % of bridge failures. The causes of bridge failure are closely related to the type of structure, type of use, type of material, and service life [13].

The results of these studies provide a strong description of the scientific basis for engineers and building construction practitioners to design bridges by adopting box beam wood engineering innovations. This is expected to overcome the use of wood with large dimensions. Because engineered wood basically only uses wood that has been sorted to avoid wood defects. In addition, the use of box beam engineered wood in bridges has economic value and local wisdom because the main wood material can be found in most parts of Indonesia. This explains the relevance of this scientific topic.

2. Literature review and problem statement

Basically, wooden bridges are more environmentally friendly than steel or concrete ones. In Australia, an innovative construction system using cross-laminated timber (CLT) was applied to improve the design and provision of urban residential buildings. The application of wood as the main material in building construction offers the opportunity to turn building construction into a carbon sink [14]. Applying timber construction to bridges in Indonesia, which is mostly forested, can make a positive contribution to the environment. However, the use of engineered wood in bridge construction to date is still minimal. In Indonesia, steel and concrete materials tend to be chosen for bridge construction.

Engineered wood box beam is a highly efficient structural component, can be produced by joining wood board products through gluing, and is one of the processed wood products composed of several profiles with a hollow box section in the center [7]. The use of box beam engineered wood shows efficiency in the use of wood and reduces cost estimates. This is because the wood used is selected wood, not solid wood. Parameters that influence the strength and stiffness of box beams are wall thickness and dimensions. The thickness of engineered wood has been regulated in SNI 7973-2013 [15]. The research generally examines glulam type wood engineering. Meanwhile, the novelty in this research is the focus on developing a model for box beam wall thickness regarding stiffness, peak load and failure mode. The development of the application technique for the box beam method is to assemble the box beam elements into a single structural unit that forms a wooden frame bridge. Wood frame structures are influenced by the quality of the wood. In SNI 7973-2013, wood strength classes are divided into 4 categories. Strength class I has a bending stress of 150 kg/cm^2, strength class II – 100 kg/cm^2, strength class III – 75 kg/cm^2, strength class IV – 50 kg/cm^2. The mechanism for making box beams to achieve high strength was identified, including:

1. Wood must be air dry with a standard of 12–18 %.
2. The size of the wooden knot does not exceed 1/6 of the beam width and must also be no more than 3.5 cm.
3. The beam must not contain wanvlak greater than 1/10 of the beam height.
4. Cracks in the radial direction must not exceed 1/4 of the wood thickness and cracks along the growth circle must not exceed 1/5 of the wood thickness.

Camphor wood is categorized in strength class II. This means camphor wood has excellent mechanical strength.

The mechanism for making box beams involves using bamboo, which is sliced and glued to form a glulam type box beam wall. The box beam walls were bonded with 268 g/m^2 urea formaldehyde adhesive and clamped with a pressure of 2 MPa for 4 hours. The load-bearing capability of engineered box beams using Asian bamboo material increases proportionally with an increase in the moment of inertia for the same amount of material. However, the capability of engineered box beams made of bamboo material increases only until the ratio between the height and width of the beam reaches 1.50, beyond which the beam capability decreases [10].

Another study mentioned that engineered wood box beams have a higher torsional constant than solid wood beams with the same cross-sectional area [16]. Box beams have a higher compressive strength than solid wood and are recommended as a type of short-span bridge structure [17]. The existence of positive results on the torsional constant and compressive strength of the box beam, makes researchers interested in continuing research using camphor wood material applied to frame bridges. Research on truss bridges was chosen, because truss bridges depend on the tensile strength and compressive strength of the trunk. In terms of compressive strength, a very important component is the moment of inertia. The higher the moment of inertia, the higher the compressive strength capacity of the bars.

The use of box beams with bamboo material shows that the inner shear stress values range from 4.39 MPa to 10.13 MPa with an average of 6.50 MPa and shear modulus in the range of 690.68 MPa to 1072.28 MPa with an average of 902.10 MPa [10]. The adhesive strength value in the wet and dry adhesion firmness tests in the presence of 37 % formaldehyde additive exceeds the minimum firmness limit referring to SNI 6/6049/1999 [18].

In the application of a wooden truss bridge, the choice of bridge frame type greatly influences the bridge strength. The K-Truss type bridge has the smallest ratio of strength and material utilization of 41.40 compared to other truss types (Howe, Pratt, Baltimore, Warren), and the K-Truss Hollow Section Truss (HST) innovation can save materials by 13 % for compressive bars and 14.90 % for tensile bars [11]. The research shows that box beams from bamboo and wood materials both have positive strength. However, the strength of wood material gives better results than bamboo. This is indicated by the size of the engineered box beam from bamboo receiving loads that tend to be small. Meanwhile, wood material tends to have material efficiency, which is shown by the deflection of the tensile rod and the small tensile rod.

Apart from the type of frame, wooden truss bridges are also influenced by the specific gravity and moisture content of the wood material. Density and humidity are two important factors that influence the mechanical properties and performance of wood frame bridges. Wood density is positively correlated with mechanical strength. Wood with a higher density tends to have higher tensile, compressive and flexural strengths. The elastic modulus (E) and shear modulus (G) are also higher in wood with greater density, so it is stiffer and better able to resist deformation [19]. Wood absorbs and releases moisture from the environment, which causes dimensional changes (expanding and contracting). This may cause distortion, cracking, or deformation. High humidity tends to reduce the strength of wood. Wood that is too wet becomes weaker and more susceptible to deformation [20]. Apart from the moisture content and specific gravity of the wood, the strength and stiffness of the box beam depend on its wall thickness.

The wall thickness of the box beam and the moment of inertia are two crucial factors that influence the peak load capacity of the box beam. Wall thickness and moment of inertia work together to determine the strength and stability of a box beam. A larger wall thickness directly increases the moment of inertia, which in turn increases the peak load capacity. Thicker walls increase the box beam's stability against bending moments and lateral cooling, which is important for maintaining structural integrity under load [21]. The wall thickness of the box beam also affects its stiffness. The weakness of engineered wood such as box beams or I-Joists is that cross-sectional stability is greatly influenced by stiffness.

The stiffness of a box beam refers to the structure's ability to resist deformation under load. A box beam consists of two flanges and two webs forming a closed cross-section. The closed cross-section of the box beam provides a high moment of inertia, which directly contributes to its stiffness. The moment of inertia is a measure of the tendency of a cross-section to resist bending, and a higher value results in lower deformation under load. By having the top and bottom flanges connected by two webs, box beams distribute the load more evenly throughout the structure. This reduces stress concentrations in certain areas, minimizing the chance of local deformation [22].

The thickness of the box beam walls on wooden truss bridges is an important factor that influences the overall strength and stiffness of the structural elements. A box beam is a structural element that has a square or rectangular cross-section with an empty space in the middle, which provides high strength with a relatively light weight. Wall thickness affects the distribution of normal stresses along the beam. In a box beam, the largest normal stress usually occurs at the outer wall (flange), which bears the bending moment [23].

The moment of inertia of the cross section is greatly influenced by the wall thickness, because the moment of inertia is a function of the material distribution about the neutral axis of the cross section. For box beams, the moment of inertia is determined by the outer dimensions and wall thickness. To ensure optimal stiffness, the ratio between the outer dimensions of the beam and the wall thickness must be observed. Too small wall thickness can cause buckling and structural failure. The wall thickness is usually chosen so that it is sufficient to withstand the load without experiencing excessive deformation, but remains light for material efficiency. Adequate wall thickness helps prevent local buckling in the web or flange walls. Buckling analysis is required to determine a safe minimum thickness [24].

The results of the peak load experiment on the box beam include an analysis of how the box beam reacts to the load until it reaches the point of failure. In the context of the experiment, peak load is the maximum load that can be supported by a box beam before significant damage or structural failure occurs [25].

Failure in wooden box beams can occur due to various mechanisms that are influenced by material properties, structural design, type of load, and environmental conditions. Bending failure occurs when the bending moment acting on the box beam exceeds the bending strength of the wood material. This usually causes cracks or breaks in the wood fibers at the flange (top or bottom) of the box beam. Shear failure occurs when the shear stress in the box beam web exceeds the shear strength of the wood. This may cause tearing or shearing of the wood material. Buckling failure occurs when thin, long structural elements (such as webs) experience instability and buckle under compressive loads. This is especially the case in elements with a high length to thickness ratio [26].

In its implementation, researchers will continue to study variations in box beam wall thickness that will be applied to truss bridges. The connection between the box beam walls used is adhesive. This needs to be done considering Indonesia's geographical conditions, which is located in the tropics and only has two seasons (dry and rainy). This condition can cause the joint to experience extreme conditions, leading to fracture. Indonesia needs wooden truss bridges because wood is a building material that is abundantly available in many regions of Indonesia. Using wood as the main material for bridge frames can be more economical and environmentally friendly compared to other materials such as steel or concrete. Apart from that, wooden frame bridges can also be a symbol of sustainable natural resource management in Indonesia.

3. The aim and objectives of the study

The aim of this study is to identify regularities of the effect of box beam wall thickness on the stiffness of the camphor wood timber bridge truss. This will make it possible to pay attention to density, moisture content, the effect of wall thickness on the peak load and stiffness of wooden frame bridges, as well as failure modes to enrich information that can be used by bridge planners and the government as a regulator of village bridges in Indonesia.

To achieve this aim, the following objectives are accomplished:

– to make moisture content and density test;

– to identify the relationship between box beam wall thickness (t) and the peak load (P) of the wooden truss bridge;

– to identify the relationship between box beam wall thickness (t) and the stiffness (k) of the wooden truss bridge;

– to identify the failure mode of the box beam of the wooden truss bridge.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study is a box beam truss bridge made of camphor wood with a fixed variable, namely the length between supports of 1,000 mm and a changing variable, namely the ratio of wall thickness and box beam dimensions, namely t/D: 0.138; t/D: 0.200; t/D: 0.285; t/D: 0.5.

The hypothesis of the study is that the BB.58.58.8 size has greater stiffness compared to BB50.50.10, BB.45.45.12, and SB.40.40.20. This is because BB.58.58.8 has the largest moment of inertia compared to other variations. To test this research hypothesis, the experimental method given below was used.

The assumptions of this research are that the type of wood used is homogeneous camphor wood, the length of the bridge span is 1,000 mm, and the adhesive used is urea formaldehyde.

In this study, several simplifications were adopted to facilitate the analysis of the camphor wood timber bridge truss. First, the material properties of camphor wood were assumed to be homogeneous and isotropic. Second, the bridge geometry was modeled in two dimensions to reduce complexity.

4. 2. Materials

Wood has been used as a storage material since long ago as it is a natural product easy to process [27]. In China, camphor wood was a common material traditionally applied to making furniture and is still widely used today [28]. The advantages of wood compared to other construction materials are relatively light weight, low transportation costs, can be done with simple tools [29]. Bridges made of wood are very profitable if the work location is remote and wood is an aesthetic material when designed properly. The material used for the manufacture of this innovative wooden bridge is camphor wood. The tree species for camphor wood belong to the lime group, especially dryobalanops aromatica, dryobalanops fusca, dryobalanops lanceolata, dryobalanops beccarii, dryobalanops rappa. The chemical components of camphor wood consist of 60 % cellulose, 26.9 % lignin, 15.7 % pentosan, 0.8 % ash, and 0.6 % silica [30]. The mechanical properties are shown in Table 1.

Adhesives are an essential part of all engineered wood, except engineered wood that uses fasteners [5]. Adhesives function to transmit stress between wood fibers, strands (long pieces of wood with small dimensions), veneers (thin sheets obtained by peeling tree trunks in a circular manner), logs, or wooden boards.

Joint strength between upright joints and oblique joints is provided using urea formaldehyde adhesive on sengon wood [33]. A camphor wood laminate gluing formula was developed, namely UA-104 powder, NH_4Cl and wheat flour with a weight composition of 150:0.5:25 [31].

The adhesive used in this study is the urea formaldehyde type. Urea formaldehyde resin is well known for its use in various fields. By using certain mixed materials, urea resin will provide formulations with high impact strength, good insulator and heat resistance. The uses of this resin include adhesive, molding compound, textile finishing, surface coating, and wood preservative [34]. Formaldehyde-based adhesives such as PRF or MUF usually have a high crosslinking density after curing, which results in high modulus but rather brittle bond lines [35].

Table 1

Physical and mechanical properties of camphor wood

Physical properties		Mechanical properties					
Moisture content (w)	Density (Specific gravity)	Fiber parallel compression ($\sigma_{tk\parallel}$)	Press perpendicular to fiber ($\sigma_{tk\perp}$)	Tensile parallel to fiber ($\sigma_{tr\parallel}$)	Shear parallel to fiber ($\tau_{\parallel}$)	Flexure (MOR)	Modulus of elasticity (MOE) or (E)
(%)	(g/cm^3)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)
12	0.599	51.538	4.936	126.913	10.913	89.989	12395.00
13.79	0.785	32.55	13.90	36.56	5.30	44.69	14783.58

Source: [31, 32]

Urea formaldehyde (UF) resin is commonly used in the manufacture of wood panels. This UF resin has the advantage of strong adhesion, and a relatively cheaper price compared to other adhesives. UF resin has different characteristics during storage until the resin is separated, this can be influenced by pH, specific gravity, and viscosity [36]. The reactions to form this UF resin are the methylation reaction and the condensation reaction [37].

Camphor wood for this research was taken from Malang City, East Java, Indonesia. Camphor wood beams are formed into rectangular slices with varying thicknesses, namely 8 mm, 10 mm and 12 mm and a length of 1,100 mm.

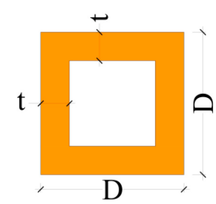

Fig. 1. Cross-sectional dimensions of camphor wood

Specimens (Fig. 1) were made in 4 variations of beam wall thickness (t), namely 8 mm, 10 mm, and 12 and 20 mm. Meanwhile, the cross-sectional dimensions are made in 4 variations (D), namely 58 mm, 50 mm, 45 mm and 40 mm. The beam span is set at 1,100 mm. There is an additional 2×50 mm to support the beam during testing. Cross-sectional dimensions for all truss bridges are shown in Table 2.

Table 2

Cross-sectional dimensions of camphor wood

Specimen	Dimension (mm)		t/D	A (mm^2)	I (mm^4)	Span length (mm)	Total length (mm)
	D	t					
SB.40.40.20	40	20	0.500	1,600	213,333.33	1,000	1,100
BB.45.45.12	45	12	0.267	1,600	336,554.43	1,000	1,100
BB.50.50.10	50	10	0.200	1,600	453,333.33	1,000	1,100
BB.58.58.8	58	8	0.138	1,600	683,733.33	1,000	1,100

Note: SB – solid beam; BB – box beam

4. 3. Methods

The research design in this study uses quantitative with experimental research [38, 39]. This research is an experimental research by modeling a real structure with a 1:8 scale model. The research stages can be seen in the flow chart shown in Fig. 2.

In the material preparation stage, after the wood has reached a standard moisture content, it is continued to cut the wood into slats according to the thickness of the box beam wall of each variation and assemble into a box beam element.

After the box beam elements have been formed, they are then joined together to form a camphor wooden truss bridge with adhesive. The adhesive used is urea formaldehyde (UF). UF has excellent strength and hardness after drying. The formula for gluing camphor wood laminates is UF, powder, NH_4Cl and wheat flour with a weight composition of 150:0.5:25 [40]. After the box beam bridge truss is formed, the gusset connection of 4 mm multiplex is installed at each joint meeting between the rods.

Testing the camphor wooden truss bridge box beam innovation is the final stage after the preparation of tools and materials. After passing this stage, the test results will be known and continued with the data analysis stage. In testing and verifying wooden frame bridge models, the use of concentrated loads at 1 node makes it easier to test and measure the forces and deflections that occur. This makes the model easier to test and verify in laboratory conditions [41]. The use of concentrated loads on a single node makes structural analysis simpler and more direct [42]. An overview of the testing procedure is shown in Fig. 3 below.

After making a sequence of test procedures illustrated in Fig. 3, testing tools and materials were prepared. The preparation of tools and materials is shown in Fig. 4 below.

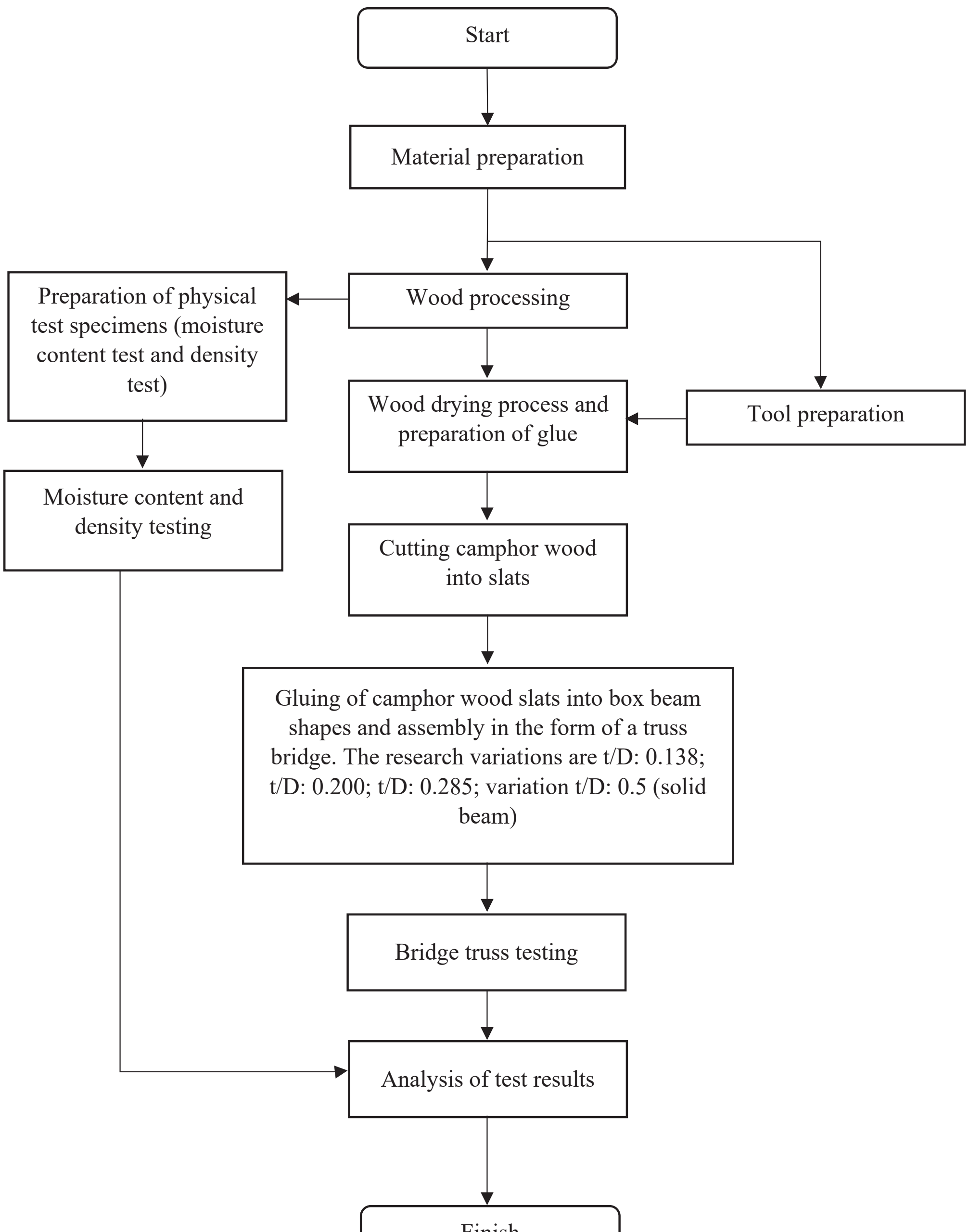

Fig. 2. Research flow chart

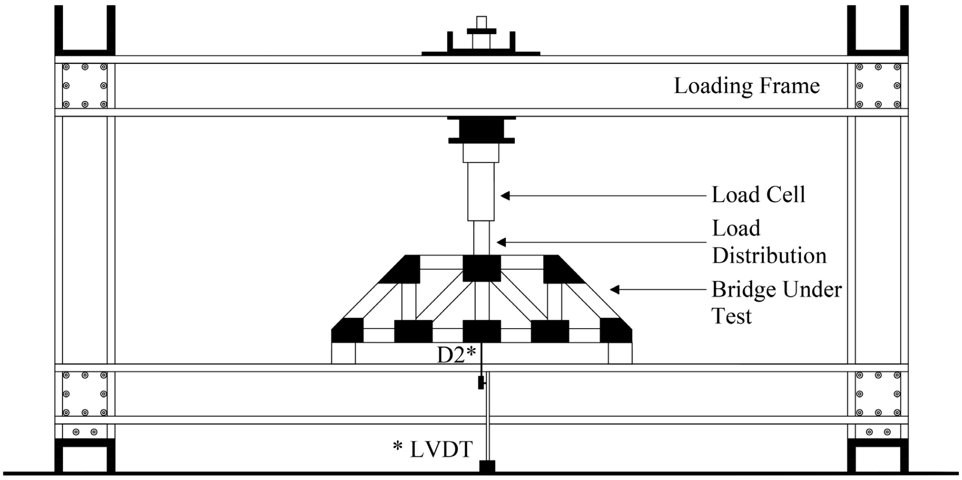

Fig. 3. Testing procedure for a wooden truss bridge with box beam section

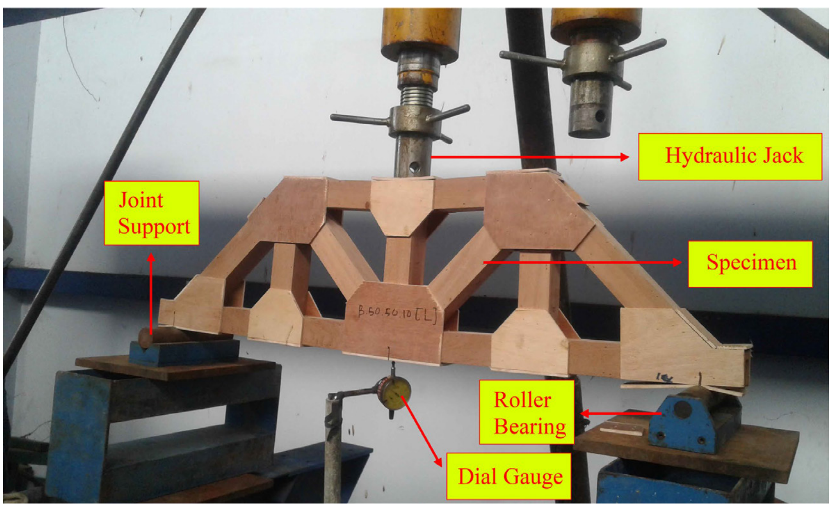

Fig. 4. Set up of testing equipment for a wooden truss bridge with a box beam section innovation

The testing procedure of the truss bridge can be seen in Fig. 4 with the following procedures. The main test equipment uses a loading frame with a capacity of 10 tons, hydraulic jack, load cell for load measurement and LVDT for deflection measurement. Bridge specimens are placed on joint and roll supports. Beam loading is carried out with a centralized load (P) of 3 pieces imposed on the gusset point (joint) of the upper bridge. The stage of giving load is carried out per 100 kg until finding the maximum load (Pu). During the loading stage, deflections were controlled and recorded until the bridge collapsed.

5. Results of studying the effect of box beam wall thickness on the stiffness of the camphor wood timber bridge truss

5. 1. Moisture content and density test

Moisture content and density play an important role in determining the physical and mechanical properties of wooden beams used in bridge construction. The moisture content is obtained when the water content has disappeared from the wood (at least the last 2 weighing the weight of the test object remains). From testing the moisture content of camphor wood, the results are as shown in Table 3.

From the data above, the lowest moisture content was obtained for sample A at 12.47 %, while the highest moisture content was for sample E at 12.79 %. Table 3 shows the moisture content values of camphor wood according to [31] at 12 % and [32] at 13.79 %.

Wood density is the ratio of mass and volume at a certain moisture content. Density testing is carried out to provide an overview of the state of a material to withstand mechanical loads and is a physical property of a building material. The results of the camphor wood density test can be seen in Table 3.

This table shows that the five camphor wood samples have an average density value of 0.506 g/cm^3. Meanwhile, the specific gravity value according to [31] is 0.599 g/cm^3 and [32] – 0.785 g/cm^3.

Table 3

Experimental results of moisture content and density testing

Component	Number of specimen					Average of number exp.	[31]	[32]
	1	2	3	4	5			
Moisture content (%)	12.47	12.54	12.63	12.58	12.79	12.602	12.00	0.599
Density (g/cm^3)	0.501	0.499	0.517	0.500	0.514	0.506	13.79	0.785

5. 2. Relationship between box beam wall thickness (t) and the peak load (P) of the wooden truss bridge

The loading process started from zero and was incrementally increased until the beam failure. The results of studying the ratio of wall thickness and cross-sectional dimensions to peak load are shown in Table 4.

Based on Table 4, as the t/D ratio decreases, the cross-sectional inertia of each variable increases. Beam B.45.45.12 (45×45 mm, 12 mm thick) has an increase in moment of inertia of 336554.43 mm^4 or an increase of 58 %. Then beam B.50.50.10 (50×50 mm, with a thickness of 10 mm) has a moment of inertia of 453333.33 mm^4 or an increase of 113 %. And beam B.58.58.8 (58×58 mm, 8 mm thick) has a moment of inertia of 683733.33 mm^4 or an increase of 221 %.

The test results show that bridges without using box beams or solid wood have the smallest peak load of 11.768 kN. This result is compared to the 45×45 mm box beam, 12 mm thick at 14.710 kN. As for the 50×50 mm box beam, 10 mm thick, the peak load is 16.671 kN. Then the largest size is the 58×58 mm box beam, 8 mm thick having a peak load of 19.613 kN.

Table 4

Experimental results for the ratio of wall thickness (t) and cross-sectional dimensions (D) to peak load

Specimen	Dimension (mm)		t/D	A (mm^2)	I (mm^4)	Peak load (kN)
	D	t				
SB.40.40.20	40	20	0.5	1,600	213,333.3	11.768
BB.45.45.12	45	12	0.267	1,600	336,554.4	14.710
BB.50.50.10	50	10	0.2	1,600	453,333.3	16.671
BB.58.58.8	58	8	0.138	1,600	683,733.3	19.613

5. 3. Relationship between box beam wall thickness (t) and the stiffness (k) of the wooden truss bridge

The primary focus of this study was how load affects the deflection at the midpoint. The relationship between load and deflection is usually linear, according to Hooke's law:

$$\delta = \frac{P}{k}. \qquad (1)$$

In equation (1), δ is deflection, P is load, k is stiffness. Stiffness is the ratio between load and deflection. In this study, stiffness was obtained when the load reached 11.768 kN. This can be seen in Table 5 below.

From Table 5, the load and deflection relationship is obtained, which can be seen in Fig. 5 where the greatest stiffness is obtained for BB.58.58.5. Table 5 shows that the stiffness of SB.40.40.20 is 1.444 kN/mm, BB.45.45.12 – 2.015 kN/mm, BB.50.50.10 – 2.351 kN/mm and BB.58.58.8 – 3.502 kN/mm. Normatively according to SNI 7973:2013 [15], the maximum deflection for wooden structural elements is:

$$\delta_{max} = \frac{L}{240}. \qquad (2)$$

In equation (2), L – span length (mm). So, the maximum deflection value according to SNI 7973:2013 is 4.167 mm. Theoretically, the stiffness results obtained for SB.40.40.20 are 0.151 kN/mm, BB.45.45.12 – 0.239 kN/mm, BB.50.50.10 – 0.321 kN/mm and BB.58.58.8 – 0.485 kN/mm.

Fig. 5 shows that the greater the load applied to the bridge, the greater the deflection that occurs. So, the greatest stiffness occurs for BB.58.58.8, because it has the largest moment of inertia. Fig. 5 shows an increase in the stiffness of the box beam compared to solid wood (SB.40.40.20), namely BB.45.45.12; BB.50.50.10; and BB.58.58.8 by 12 %; 15 %; and 45 %.

Table 5

Relationship between load and mid span deflection at a load of 11.768 kN

Specimen	t/D	A (mm^2)	I (mm^4)	Max. Mid span at load 11.768 kN (mm)	Stiffness experiment (kN/mm)	Stiffness theoretical (kN/mm)
SB.40.40.20	0.500	1,600	213,333.33	8.15	1.444	0.151
BB.45.45.12	0.267	1,600	336,554.43	7.30	2.015	0.239
BB.50.50.10	0.200	1,600	453,333.33	7.09	2.351	0.321
BB.58.58.8	0.138	1,600	683,733.33	5.60	3.502	0.485

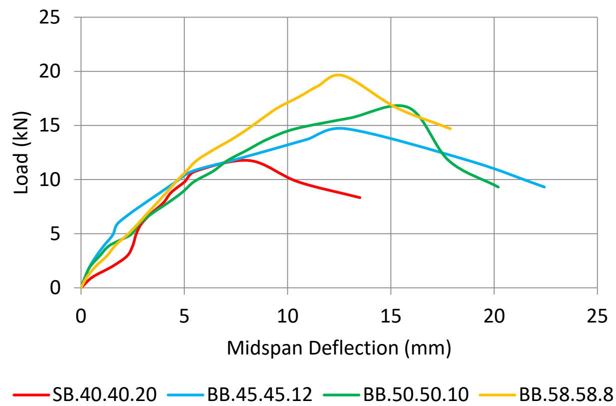

Fig. 5. Relationship between load and mid span deflection for all specimens

5. 4. Failure mode of the box beam of the wooden truss bridge

Along with adding a load to the beam, it suddenly collapsed and made a loud noise. The beam's capacity to withstand the load is also lost at that point. Beam failure mode can be seen in Fig. 6.

On the side of the beams, cracks were developing in the longitudinal axis direction. The crack was located roughly near the center of the beam's height. The direction of the cracks was in parallel to camphor grain.

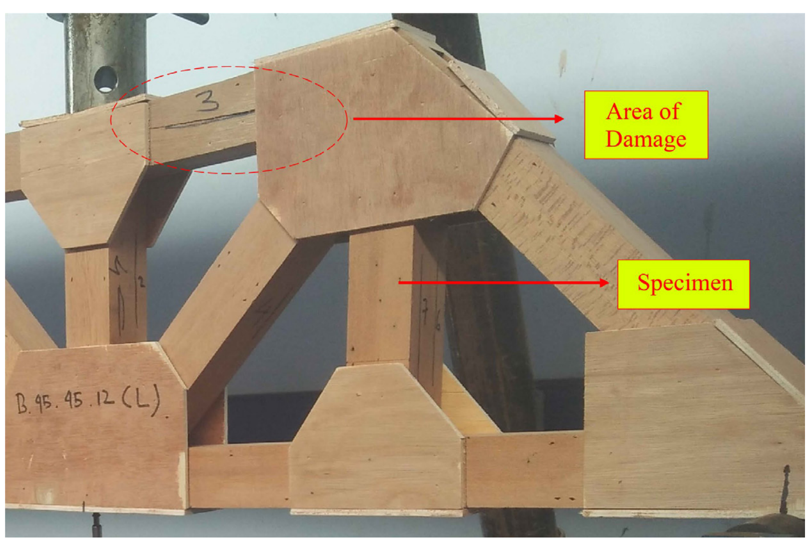

Fig. 6. Beam damage pattern

6. Discussion of the effect of box beam wall thickness on the stiffness of the camphor wood timber bridge truss

High-density wood tends to have denser fibers, so it can withstand compressive and tensile loads better. Wood with a higher density tends to have a higher modulus of elasticity, meaning it is stiffer and less likely to buckle under load. The density of camphor wood of strength class I–II and durability class III is between 0.61–1.01 g/cm^3, and the moisture content for construction materials under balanced conditions is between 12 % and 16 % [6]. The average moisture content in this test is 12.60 %, which already meets the regulatory standards for moisture content in PKKI [6]. This means that the camphor wood used is in the *Dryobalanops oocarpa* camphor wood classification, which has a wood strength class between II–III and durability class IV.

In Fig. 4, the load is distributed by hydraulic jacks. The load increases until the bridge collapses. The maximum load is recorded as peak load. The increase in moment of inertia coincides with the increase in peak load (P). The greater the moment of inertia, the higher the peak load. From the results of compressive testing, the maximum load data (peak load) is obtained, which is one of the strength parameters. The maximum load value that can be carried by each bridge variation is shown in Table 4. The results of the compressive test on the effect of wall section thickness on bridge strength concluded that box beams can be used as an alternative to solid wood for truss bridges because their strength is greater than in solid wood, namely 19.613 kN for BB.58.58.8 (with the same cross-sectional area). Based on Table 5 and Fig. 5, the compressive test results produce a positive value indicated by the greater the size of the box beam variation and the smaller the thickness, resulting in a greater inertia value. These results are in accordance with the provisions of SNI 7973 concerning design specifications for wood construction [43]. The ability of a box section beam to withstand loads increases proportionally with an increase in the moment of inertia for the same amount of material [10]. The beam's ability to carry higher loads increases with greater inertia [10]. The thicker the wall, the lower the radius of the deepest layer of the hollow part. The benefit is that it can reduce re-take, which is in accordance with the principles of engineered wood [44].

A larger moment of inertia increases the stiffness of the structural element, namely 3.502 kN/mm for BB.58.58.8. The research results show that the moment of inertia can control deformation or shape changes that occur when receiving a load. Too large deformation can reduce the structural performance of the bridge. The factors that define the amount of deflection of the beam due to a transverse load are referred to as stiffness. Therefore, the higher the flexure rigidity of the beam, the greater the inertia moment, and the lower the deflection that happened. Larger stiffness means a larger serviceability load that can be borne if serviceability is the determining factor in beam design [10]. Based on Table 5, the sample BB.45.45.12 has a t/D ratio 1.93 times greater than BB.58.58.8. It is theoretically proven that a larger t/D ratio results in a structure that is more flexible/lower in stiffness compared to a small t/D ratio. It is proven by experimental results that the stiffness of BB.45.45.12 is 1.73 times smaller than that of BB.58.58.8. Experimental stiffness testing was compared with the theoretical stiffness calculation results, which showed that the stiffness of BB.45.45.12 was 2.03 times smaller than in BB.58.58.8. So, the magnitude of the t/D ratio is inversely proportional to the magnitude of stiffness. As in Fig. 5, which shows that BB.45.45.12 is more ductile compared to BB.58.58.8. Where ductility is the ratio between the maximum plastic deformation that can be handled by the structure and its elastic deformation before it reaches failure.

Based on observations of the failure mode of the box beam truss bridge, there is a collapse from the web side of the box beam itself. Collapse occurred in the truss bridge beams and no collapse occurred in the joints or supports of the truss bridge. These results are in accordance with the study [9], which states that the adhesive used is stronger than the structural elements that are glued to withstand shear forces.

The limitation of this research is that the test was carried out by giving a point load/joint load to only one join/gusset, without loading the other two joins. The results of this study provide recommendations for the relationship between wall thickness and the strength of the box beam material used for bridges. The results of this study obtained the relationship between wall thickness and the strength of box beams applied to frame structures with adhesive joints. However, the strength of wood material and its variation in the field is a factor that can later affect the research results.

The weakness of the truss wooden bridge when applied to villages in the Indonesian region is the threat of insect attacks. This is because Indonesia is a tropical country with a variety of insects that mostly live on wood. Then for adhesive connections if the application is submerged in water (e.g. flood disaster), its strength may decrease.

The lack of support from the Indonesian government for the wood industry could hamper the future development of this research. In developed countries, the wood industry sector is a strong competitor to the concrete and steel industries. However, in Indonesia, the wood industry has not received as strong support as the steel and concrete industries.

7. Conclusions

1. From the physical experimental testing of camphor wood, the specific gravity of the wood was 0.506 g/cm^3 and the moisture content of the camphor wood was 12.47 %.

2. The largest peak load that occurs on the box beam truss bridge with the variation BB.58.58.8 is 19.613 kN.

3. The greatest stiffness of the truss bridge occurs in the BB.58.58.8 variation and is 3.502 kN/mm. The BB.58.58.8 variation has the smallest box beam wall thickness (t) compared to the other wall thickness variations, namely 8 mm. But BB.58.58.8 has the largest box beam (D) dimensions. Therefore, variation BB.58.58.5 has the largest moment of inertia, namely 683733 mm^4, compared to solid beam SB.40.40.20 of 213333 mm^4 provided that the cross-sectional area of each variation is the same. The sample BB.45.45.12 has a t/D ratio 1.93 times greater than BB.58.58.8. It is theoretically proven that a larger t/D ratio results in a structure that is more flexible/lower in stiffness compared to a small t/D ratio. It is proven by experimental results that the stiffness of BB.45.45.12 is 1.73 times smaller than that of BB.58.58.8. Experimental stiffness testing was compared with the theoretical stiffness calculation results, which showed that the stiffness of BB.45.45.12 was 2.03 times smaller than in BB.58.58.8. So, the magnitude of the t/D ratio is inversely proportional to the magnitude of stiffness.

4. The failure mode of the box beam frame bridge occurs in the box beam body and does not occur at the joints or bridge supports.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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