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Design of bamboo ladder as traditional construction equipment based on static loading analysis

Novie Susanto*, Ratna Purwaningsih, Dinar Anggita Restuti
Department of Industrial Engineering, Diponegoro University, Prof. Soedarto SH-Tembalang, Semarang 50275, Indonesia

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The bamboo ladder is a traditional construction equipment that still survives on the market and is in demand, especially in rural communities such as Kedalingan village. However, bamboo stairs still do not consider the standard of stairs design. In addition, there are concerns that users of the ladder may experience injury due to falls because the ladder cannot withstand the load (unbalanced). This study aims to obtain the maximum load that can be held by bamboo ladders and the angle of the position of the safe ladder by considering the Indonesian people's anthropometric weight. Calculation results based on the principle of equilibrium show that with a maximum user weight of 89.25 kg, the ladder must be positioned with a minimum slope of 53,26º but less than 65.43º. In addition, a static loading simulation was carried out using SolidWorks 2019 on a bamboo ladder frame structure that was made referring to SNI 19 - 1956 – 1990. Simulation results show that the design of a bamboo ladder can withstand a maximum body weight of 89.25 kg with the maximum load value of bamboo holding is 98.93 kg.

*Corresponding Author

Novie Susanto
E-mail:
novie.susanto@ft.undip.ac.id

1. INTRODUCTION

The ladder is a construction tool used to reach a taller building and can be moved around [1]. Ladders are used not only during construction projects but also to perform specific needs such as changing lights, painting walls, etc. Ladders are made of wood, bamboo, or aluminium based on the material. The amboo is lighter than wood and aluminium because it has the smallest specific gravity value but has a reasonably high strength ratio [2]. It is not surprising that people, especially in rural areas, still use bamboo because it is considered strong and more economical.

The bamboo ladder is one of the few traditional construction equipment that still survives the competition with aluminium work ladders. Bamboo is also traditionally used as a structural member in low-rise houses, bridges, roofs, and construction slabs in countries with abundant bamboo resources. In addition, bamboo structures are environmentally friendly and aligned with the goal of green and sustainable development with reasonably good mechanical properties [3]. This ladder is still often used, especially by rural communities, one of which is in Kedalingan Village, Tambakromo District, Pati. The use of bamboo ladders was chosen because it is considered more economical than the price of aluminium ladders on the market. Often the villagers make their ladders that will be used because they are easy to make and the bamboo material is easy to find. Specifically, the bamboo type suitable for making household appliances and light construction is apus bamboo (*Gigantochloa apus)* [4]. Several studies related to the use of bamboo were carried out by Chung and Yu [3], which examined variations in the compressive strength of various physical properties along the bamboo stem for the two species of bamboo used as scaffolding materials used in construction projects. In addition, Simeonov et al. [5] discussed improving the optimal angular position for the extension ladder. At the same time, Hung [1] evaluated the effect of a designed “walk-through” extension ladder based on the kinetic behaviour and externally induced destabilizing forces on the ladder during the transition to elevation. Fall accidents still become the primary issue of ladder use due to structural safety features [6], loss of lateral stability [7], [8], suboptimal ladder inclination [9], [10], and lack of training and instruction system [11], [12]. Some biomechanical analyses result in an ergonomic hazard during ladder climbing tasks [13]–[17]. Besides, the traditional ladder has higher bio-mechanical and psychophysical exposure associ-ated with the development of musculoskeletal disorders while performing ladder loading and unloading tasks [18], [19]. Some human body exposures should also be considered [20], [21].

In practice, the ladder design used by the Kedalingan village community does not meet the existing ladder case design standards [22], due to a lack of knowledge about safe ladder case design standards. In addition, from the results of a preliminary study conducted on twenty workers, it is known that users of bamboo ladders experience several difficulties (Table 1).

Table 1. Difficulties using bamboo ladders

Difficulty type	Amount
Positioning the ladders to balance	37%
Position the ladder, so it doesn't slip	18%
Falling because the ladders are not comfortable to use	18%
Don't know the maximum load the ladder can withstand	27%

It shows that bamboo ladders must withstand loads that vary depending on the user's weight. Load analysis on bamboo material needs to be done to determine whether the bamboo frame used is strong enough to withstand variations in the user's load so it is safe to use. In addition, to get the optimal ladder position angle seen from the user's weight. In identifying the forces involved, including the reaction force caused by the support and weight, a diagrammatic sketch of the Free Body Diagram is taken into account. Furthermore, because a stable object such as a bamboo ladder will remain in balance, the forces acting on it will satisfy the static equilibrium equation. In contrast, the analysis of the bamboo ladder frame is carried out using SolidWorks software because it can be used to analyze the static load on the frame.

Based on this background, it is necessary to research the design of bamboo ladders as traditional construction equipment to result in safe and reliable tools. Based on the Free Body Diagram, this study aims to calculate the compression force that occurs in the body segments of workers who use bamboo ladders *and to* get the optimal ladder position angle based on body weight. And to determine the critical point on the bamboo ladder frame when loading based on the worker's weight using SolidWorks software simulation.

2. RESEARCH METHODS

The study was conducted on ladder users in Kedalingan Village, Tambakromo District, Pati Regency, with a sample of twenty people. The respondents are divided into ten respondents as construction workers and ten who use ladders only for household purposes. The data in this study are specifications of bamboo ladders, the respondent's height, weight, and the angle of inclination of the body segment to the horizontal plane. In addition, interview methods and distributing questionnaires to find out the difficulties experienced by ladder users, especially construction workers, were also carried out. The bamboo ladder specification data were obtained through direct measurements in the field. The equipment used during the data collec-tion process includes:

1. A three-meter-high bamboo ladder.
2. The hammer to see the ladder user's posture when carrying equipment in one hand.
3. The meter measures the height of the respondent.
4. Weight scales to calculate the weight of respondents.
5. The goniometer measures the angle of the respondent's body when he is on the ladders.

The making of a work ladder model is based on the results of measuring ladder specifications carried out in the field and based on existing ladder design standards. The standards refer to ANSI A14.1-1990: Ladders Wood-Safety Requirements and SNI 19-1956-1990: Occupational Safety in

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the Manufacture and Use of Work Ladders. This standard is a proposed configuration for improving villagers' ladder case design. Some of the limitations used in the design of the ladders are:

1. The type of bamboo material used is apus bamboo with a diameter of 60 to 80 mm, and the age of bamboo when it is cut is about 3-5 years
2. the bamboo's diameter and thickness are adjusted in the bamboo type used and the age at which it is cut
3. The bamboo's shape, which is close to round with holes, has non-uniform dimensions, both outside diameter, wall thickness and the distance between books.
4. The conceptual design of the ladders refers to the American National Standards Institute (ANSI A14.1-1990): Ladders Wood-Safety Requirements and the Indonesian National Standard (SNI 19-1956-1990): Occupational Safety in the Manufacture and Use of Work Ladders

The standards used in the design of work ladders are declared safe and suitable for use, including [22]:

1. All steps of ladders must be given the same distance and a minimum of 22 cm or more by 27 cm.
2. The width of the bannisters between one another should not be less than 27 cm or not more than 36 cm.
3. The length and width of the ladders shall not be less than the details (Table 2).

Table 2. Single ladder size [22]

Ladder length (m)	Smallest size bannister
4 to 0 (the smallest)	6,50 cm x 3,50 cm
4 to 7 meters	7,20 cm x 3,50 cm
7 to 10 meters	9,50 cm x 4,50 cm

According to ANSI A14.1-1990: Ladders Wood-Safety Requirements, ladder case design requirements include [23]:

1. The single ladder, as determined further, consists of three types, namely type IA and type I not more than 30 ft, type II not more than 20 ft and type III not more than 14 ft.
2. The width between the side rails at the base must be at least $11 - \frac{1}{2}1$ inch for all ladders up to 10 ft long. The minimum width must be increased by at least 1/4 inch for each additional 2 feet of ladder length.
3. The minimum dimensions of single ladder side rails are not less than those specified in American National Standards Institute [23]

In making this ladder model, SolidWorks 2019 software was used. After the ladder model was created, the next step was to perform a simulation to analyze the model framework. The specifications for the improvement of the ladder case design based on the standards used include the following:

1. Configuration 1 with a ladder height of 4 meters, a footing length of 6.5 cm, a distance between steps of 27 cm, a ladder diameter of 80 mm, and a footing diameter of 40 mm.
2. Configuration 2 with a ladder height of 4 meters, a footing length of 4.5 cm, a distance between steps of 28 cm, a ladder diameter of 80 mm and a footing diameter of 40 mm.

The result of the Solidworks simulation includes the following:

a. Displacement is a movement that occurs due to the load on the ladder frame. The high and low value of the movement depends on the high and low *Force Load* applied to each part of the ladder frame.
b. Von mises stress is the surface of an object due to applying a load on the ladder frame.
c. The safety factor is used to evaluate a structure's safety.

Manual calculations are carried out by making a Free Body Diagram describing the forces in the worker's body segments when climbing ladders. From the FBD calculation, the force and moment values of each body segment will be obtained. Then, for the calculation of the angle of the ladder position using the equilibrium equation between the load force borne by the ladder and the friction force generated between the ladder and the surface.

The research was conducted by calculating each body segment's force and moment values based on the Free Body Diagram (FBD) diagram. To get the compression value in the L5-S1 (back) bone. A free Body Diagram (FBD) is a sketch that depicts and measures the forces and moments acting on a person's body as an indicator of potential injury. The equation to calculate the forces and moments in each body segment is based on the FBD sketch [24].

$$W_H = weight\ segment\ value\ for\ each\ body\ x\ W_{body} \quad (1)$$

$$W_o = m_{object}\ x\ g \quad (2)$$

$$F_{yw} = \frac{W_0}{2} + W_H \quad (3)$$

$$M_w = F_{yw} x\ SL_1 x\ cos\ \theta \quad (4)$$

After getting the value of the force of each body segment, the value of the compression force or compression force can be calculated with the equation:

$$F_C = \left|W_{tot}\ x \cos\theta_H - F_A + F_M\right| \quad (5)$$

$$W_{tot} = W_o + 2W_H + 2W_{LA} + 2W_{UA} + W_T \quad (6)$$

$$F_M = \frac{M_{L5/S1} - (F_A\ x\ D)}{E} \quad (7)$$

$$F_A = PA\ x\ AA \quad (8)$$

$$P_A = \frac{10^{-4}|43-0,36(\theta_H+\theta_T)|\left|M_{L5/S1}\right|^{1,8}}{0,0075} \quad (9)$$

Equilibrium is a characteristic of a state with a balance of force and torque (moment of force) on the human body. Three conditions must be met to achieve static equilibrium conditions, namely:

$$\Sigma F_x = 0 \quad (10)$$

$$\Sigma F_y = 0 \quad (11)$$

$$\Sigma M = 0 \quad (12)$$

Safety Factor is a factor used to evaluate the safety of a structure [25]. The calculation of the safety factor is formulated as follows:

$$SF = \frac{S_y}{\sigma_e} \quad (13)$$

Information:

P_A	:	abdominal pressure (N/m^2)
F_A	:	abdominal force (N)
θ_H	:	angle of abdominal inclination
θ_T	:	angle of inclination of the thigh
AA	:	diaphragm area (465 cm^2)
F_M	:	muscle force on *spinal erector* (N) *spinal erector* muscle moment from L5/S1 (5 cm)
D	:	distance from abdominal force to L5/S1 (11 cm)
F_C	:	compression force L5-S1 (N/m^2)
W_{tot}	:	total weight (N)
SF	:	safety factor
S_y	:	yield strength (N/m^2)
σ_e	:	maximum Von Mises voltage (N/m^2)

3. RESULTS AND DISCUSSION

The profiles of the respondents in this work simulation are as follows:

1. Gender is male
2. Age 27-50 years ($\bar{X}$=43 $\pm$7.17 years old)
3. At least 3 years of experience as a construction worker
4. Respondents as research objects are in good physical and psychological health.
5. The average height was X=164.5$\pm$ 5.07 cm.
6. The average body weight was X 61.45$\pm$2.11 kg.

3.1. Configure Ladder Design Improvement

Based on the survey, the ladder case design commonly used by construction workers does not meet the design standards, so they ignore the safety of their users. Fig. 1 shows an illustration of a ladder commonly used by construction workers.

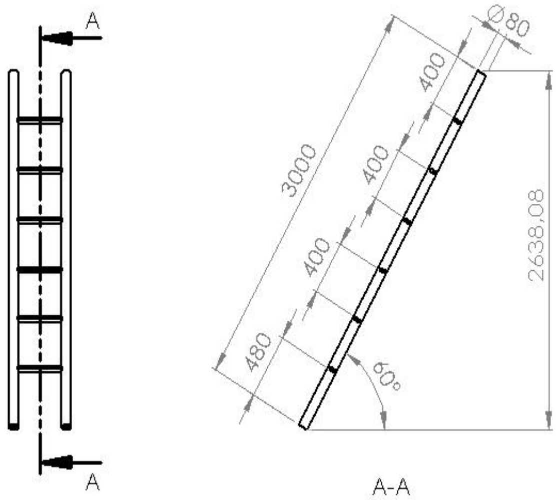

Fig. 1. Actual bamboo ladder design

For the actual ladder case design, construction workers used bamboo to make the ladders and wood to make the steps for the ladders. The actual ladder specifications commonly used by construction workers are as follows :

Ladder length	: 3 meters
Footing width	: 2 cm
Footing length	: 5 cm
Distance between steps	: 40 cm
Ladder diameter	: 70 mm

Repair ladders are needed to overcome the deficiencies in the actual ladder design. Fig. 2. shows the ladder case design that follows the SNI 19-1956-1990 standard [22].

Ladder length	: 4 meters
Ladder diameter	: 80 mm
Footing length	: 6.5 cm
Footing diameter	: 40 mm
Distance between steps	: 27 cm

Next, Fig. 3. shows the ladder case design that follows ANSI A14.1-1990: Ladders Wood-Safety Requirements [23].

Ladder length	: 4 meters
Ladder diameter	: 80 mm

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Footing length : 4.5 cm
Footing diameter : 40 mm
Distance between steps : 28 cm

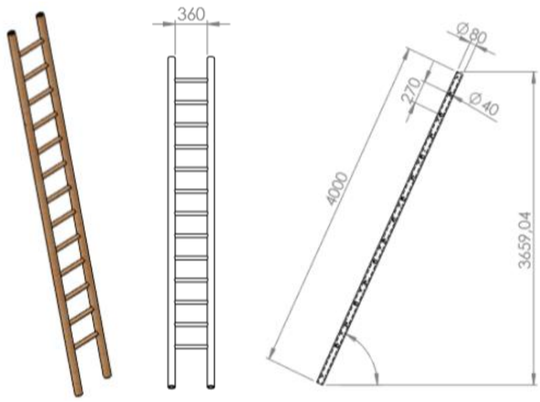

Fig. 2. Design improvements 1

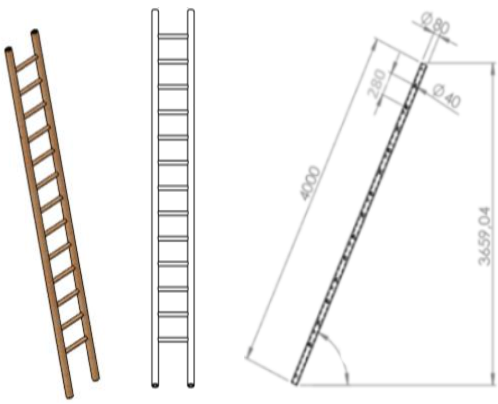

Fig. 3. Design improvements 2

The difference in the specifications for improving the ladder case design is in the length and distance of the step between the steps, where the footing length for SNI is wider than for ANSI. The body posture of each respondent when climbing the ladders varies. The working posture to be studied is shown in Fig. 4. The respondent carried out this work posture when standing in the middle of the ladders with both feet on the same step. The respondent stands straight with his right hand raised. The footing was chosen in the middle because respondents often use it, and the angle of inclination of the body to the horizontal plane can be measured. From this working posture, a Free Body Diagram sketch is made for each body segment, and the force's magnitude and moment are calculated. Tayyari & Smith [26] explains the value of the length and weight of body segments and the angle formed in each body segment (Appendix 1).

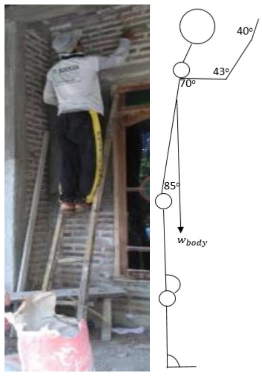

Fig. 4. Work attitude on the ladders

The following is a description of the calculation assuming the user's weight is 89.25 kg and height is 183 cm [27], namely:

The mass of the ladder = 2 kg

$w_o = m\ x\ g = 2\ x\ 9{,}81 = 19{,}62\ N$

Body mass = 89.25 kg

$w_{badan} = m\ x\ g = 89{,}25\ x\ 9{,}81 = 875{,}5\ N$

Free Body Diagram sketch of each body segment, including palm, forearm, upper arm, back, thigh, calf and foot [24] as seen in Appendix 2. Furthermore, here is a description of the calculation of the compression force on L5-S1 results:

a. Abdominal inclination angle = 98.5 °
b. Thigh inclination angle = 86.5 °
c. The value of the moment of force at $M_{L5/S1}$ = 40.07 Nm

Then, to calculate the abdominal force (F_A) (equation (8)), it is necessary to find the abdominal pressure (P_A) with equation (9). The value of PA is $241{,}5\ N/m^2$and F_A = 11.23N. Next, the value of the muscle force on the *spinal erector* with the equation (7) obtained F_M = 776.69N. Then, calculate the total weight with equation (6).

$W_{tot} = 546.65\ N$

Furthermore, the compression force at L5/S1 can be calculated by equation (5).

$F_C = 868.72\ N$

Then, calculations were made with body weight and height variations to include the lower and average percentiles. Table 3 shows the calculations for the 5th percentile with a weight of 50 kg and height of 162 cm, the 50th percentile with a weight of 63 kg and height of 172 cm and the 95th percentile [28].

It can be seen that the total weight of the force increases depending on the body mass and height. The total value of this force is to calculate the value of the compression force or compressive force that occurs in L5-S1 produced by the body when climbing ladders because it is the most crucial part of the bone that supports body weight when doing activities such as standing. Thus, from the calculation of the compression force, it can be seen whether the respondent's weight is 89.25 kg and the body position, as shown in Fig. 4. can still be held by the ladders. From the calculation results, the value of the compression force held by the ladders is 868.72N. This value is included in the safe category because it is still below the calculation of the maximum test load that bamboo can hold, which is 970.56 N. In addition, the respondent's body posture tends to be perpendicular to the horizontal plane and forms an angle of 90^{o,} producing a force that is not large enough and can still be held by the bamboo ladder.

In calculating the angular position of the ladder, it is necessary to describe the force between the ladder and the surface. Fig. 5 shows an illustration of the forces acting on the equilibrium ladder. From the figure, calculations can be made with the following assumptions:

a. The weight of the ladder is 19.62 N
b. Weight centered on the feet is 684.11 N
c. Normal force exerted by the wall (to the right)
d. The normal force exerted by the surface (upwards)
e. There is no friction between the ladder and the wall because the wall is assumed to be slippery, so that the ladder can slip easily
f. There is a frictional force between the ladders and the surface, with a coefficient of friction of 0.373.
g. The direction of friction in the calculation is assumed to be to the left. If the result is positive, then the direction is correct. Meanwhile, if the results obtained are negative, the direction of the frictional force should be to the right.

The axis of rotation takes the point where the ladder meets the surface because there is the most unknown force value at that point.

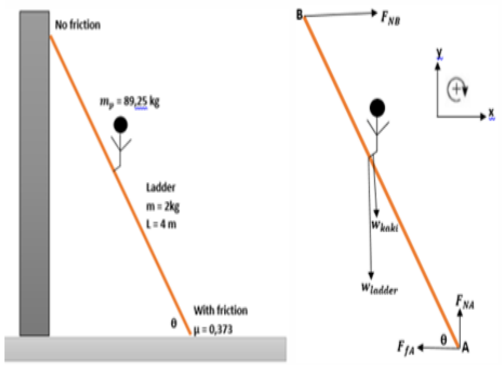

Fig. 5. Stylistic decomposition illustration

Table 3. Recapitulation of FBD calculations by percentile

Body Segment	5th percentile Style (N)	5th percentile Moment Style (Nm)	50th percentile Style (N)	50th percentile Moment Style (Nm)	95th percentile Style (N)	95th percentile Moment Style (Nm)
Palm	12.75	1.94	13.52	2.06	15.06	2.29
Forearm	21.09	4.76	24.03	5.37	29.94	6.48
Upper arm	34.82	7.53	41.33	8.8	54.45	11.18
Back	314.89	24.21	391.68	29.61	546.65	40.07
Thigh	363.94	12.11	453.48	14.81	634.2	20.04
Calf	385.03	12.11	480.06	14.81	671.85	20.04
Foot	391.9	109.32	488.71	143.53	684.11	211.82
Total weight value of each segment	314.89		391.68		546.65	
Compression style	510.56		631.89		868,72	

Table 4. Force moment calculation

Forces	F_x	F_y	τ
Weight of the ladder	0	- 19.62 N	-39.24 Nm x sin (90° – θ)
Tension	0	- 684.11 N	-1368.22 Nm x sin (90° – θ)
Normal force wall	F_{NB}	0	F_{NB} x 4 mx sin (θ)
Normal force ground	0	F_{NA}	0 Nm
Friction force ground	$-F_{fA}$	0	0 Nm

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For the axis of rotation, take the meeting point between the ladder and the surface because there is the greatest unknown force value at that point. Torque calculation assuming the user's weight is 89.25 kg is shown in Table 4.

Then we can follow the equilibrium equation (10), (11) and (12) and find

$F_{N1}.\tan\ \theta = 351{,}865\ N$

To find the value of the angle (θ), the value F_{N1} first. Based on the sum of the forces from the x-axis component, the value of the normal force is F_{N1} equal to the value of the frictional force. So, the equation becomes:

$F_f.\tan\ \theta = 351{,}865\ N$

Static friction has a maximum value equal to $\mu.F_{N2}$, so the equation becomes:

$F_f.\tan\ \theta\ \leq\ \mu.F_{N2}\tan\ \theta$

So, it can be calculated as follows:

$$351{,}865\ \leq\ \mu.F_{N2}\tan\ \theta$$
$$351{,}865\ \leq 0{,}373\ x\ 703{,}73N.\tan\theta$$
$$\tan\theta\ \geq 1.34$$
$$\theta \geq 53.26\ ^{o}$$

Based on these calculation steps, the minimum value of the ladders' slope angle is obtained, so there is no slip. Furthermore, interpolation is carried out to obtain the maximum angle of inclination of the ladders to keep them safe. By using weight based on the anthropometry of the Indonesian people, the calculation of the angle of inclination can be described as follows:

$$\frac{63-50}{89{,}25-50} = \frac{\theta - 53{,}26^o}{90^o - 53{,}26^o}$$
$$\frac{13}{39{,}25} = \frac{\theta - 53{,}26^o}{36{,}74^o}$$
$$\theta - 53{,}26^o = 12{,}17^o$$
$$\theta = 65{,}43^o$$

So, the calculation of the angle of the ladder position using the equilibrium equation shows that assuming the weight of the ladder user is 89.25 kg and the height is 183 cm, the slope angle of the ladder is between 53.26º to 65.43º. This calculation considers the user's body weight by assuming the coefficient of friction between the ladders and the surface is 0.373 [27]. The body weight selection is based on the Indonesian people anthropometry with the 95th percentile, 89.25 kg and a height of 183 cm. The highest body weight and height of respondents in Kedalingan village is below the anthropometric. It is expected that the results of this angle calculation can be applied.

Based on these calculations, to prevent a falling ladder when used, the ladder must be positioned with a minimum slope of 53.26º. However, interpolation calculations are conducted to get a maximum of the most optimal angle. Assuming that the maximum angle of inclination of the ladder until it falls is 90o, it gets the safest angle of inclination in positioning the ladder with the respondent's body mass of 89.25 kg is 65.43º.

Previously, there was research on the angle of the ladder position with the extension ladder type [5] using four methods, one of which was the anthropometric method. Based on this method, the value of the angle of the ladder position is generated with an interval of 64.6º – 79.2º. These results were obtained with a 95% confidence level. The results are the user's weight is considered valid because they fall within the range of the angle of the ladder position, and the calculation results are both based on the anthropometry of the user.

The selected bamboo apus is 80 mm in diameter with a thickness of 20 mm and has a compressive stress value of 60.66 kg/cm^2 [29]. From this value it can be calculated the maximum test load that can be held by bamboo, namely:

$$\sigma_{tk} = \frac{P_{maks}}{b\ x\ h}$$
$$P_{maks} = \sigma_{tk}\ x\ b\ x\ h$$
$$P_{maks} = 60{,}66\ x\ 2\ x\ 8 =\ 970{,}56\ N$$
$$m = \frac{P_{maks}}{9{,}81} = \frac{970{,}56}{9{,}81} =\ 98{,}93\ kg$$

The value of the load that the apus bamboo material can withstand is 970.56 N or 98.93 kg. Thus, the value of the compression force generated is 868.72. Newton is still safe to be held by the ladders with the posture as shown in Fig. 4. Compressive strength is the ability of objects to withstand external forces that are given in parallel directions, which tend to shorten or compress parts of objects together [30]. The compressive strength for apus bamboo material can be calculated by providing a distributed test load on the bamboo truss structure. The force is accepted by the cross-sectional area of the cylindrical test object so that stress will occur. From the calculations, the bamboo apus can withstand a maximum test load of 970.56 N; when converted in mass, it becomes 98.93 kg.

Previously there was research on the effect of the arrangement and size of the blades on bamboo apus [30]. This study showed that the average maximum load on bamboo was 14,123.30 N, which could be converted to 1439.68 kg. There is a significant difference because the apus bamboo used by the researcher is bamboo without prior preservation. In contrast, the apus bamboo used in the study by Manik et al. [30] is laminated, namely bamboo that has been laminated with adhesive using *Polyvinyl Acetate (PVAc)*, and it has higher strength.

3.2. Static Loading Simulation Results Using SolidWorks 2019

Strength analysis is done by calculating the stress based on static simulation. The materials used are apus bamboo. In the Solidworks simulation, material properties regarding apus bamboo are not yet available. It is necessary to input data regarding the mechanical properties of apus bamboo, including elastic modulus, poison's ratio, shear modulus, mass density, tensile strength, compressive strength, and yield strength [31]. The external loading inputted in the simulation is on all ladder steps. The load given on the steps of the ladders is 89.25 kg or 875.5 Newtons, where the force exerted is directed downwards, and the gravitational force is 9.81 m/s^2. The meshing process uses a size of 9 mm with many elements of 286,378 elements.

Static loading simulations were carried out using the SolidWorks 2019 software. Loading was carried out using the 95th percentile approach, using a body weight of 89.25 kg. To get the force unit, the weight value is multiplied by the acceleration due to gravity of 9.81 m/s^2. Each loading point is assumed to receive a force of 875.5 Newtons, and the angle of the ladder position is 65°. From the simulation results, three outputs are obtained, namely *von Mises stress* and *displacement*. In the failure criteria, three theories are often used: the theory of maximum everyday stress, the theory of maximum shear stress and the theory of von Mises stress. Of the three types of theory, it was shown that the von Mises theory predicted failure with the highest accuracy. In addition, it is recommended to use this theory for design analysis because it is easier than the others.

The highest stress value is 5.097 x 10^6 N/m^2, the lowest stress value is 1.721 x 10^2 N/m^2, and the yield strength value is 3.206 x 10^7 N/m ^{2} (Fig. 6). Maximum stress indicates that at that position, the ladder experiences maximum strain or experiences more excellent thinning or thickness reduction. The possibility of fracture usually starts from the area experiencing the maximum stress. The simulation results show that the value of the resulting von Mises stress is still below the yield strength value of apus bamboo material. It means that with the ladder position in the middle of the ladder and the ladder footing holding the given load, the ladder structure will only experience elastic deformation where the ladder shape will return to its original shape when the load is released. The structure is still able to withstand the given load.

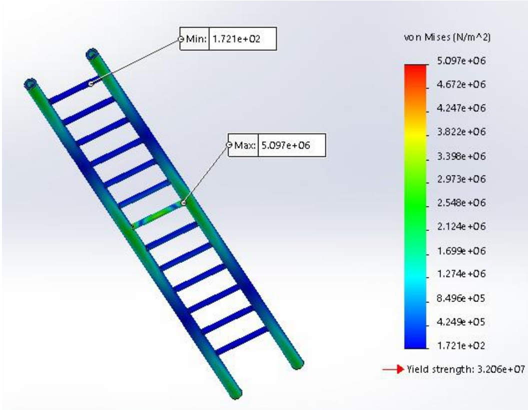

Fig. 6. Von Mises voltage results

Displacement value to see which frame works best to support the weight of the load, as shown in Fig. 7. The maximum displacement value is 5.841 mm. From the simulation results, it is known that the ladder structure can support the given load.

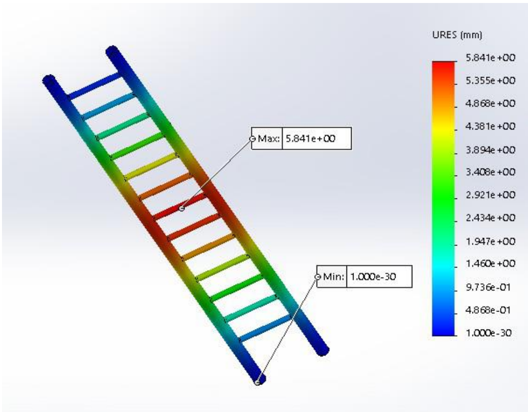

Fig. 7. Displacement Results

The bamboo used to make the ladders in this study is the Gigantochloa apus, commonly known as bamboo apus, with a cutting age of 3-5 years. This bamboo is taken from Kedalingan village, Tambakromo sub-district, Pati district, Central Java, in fresh condition and without any presservative or other chemical process. The selected apus bamboo is 80 mm in diameter with a thickness of 20 mm and has a compressive stress

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value of 60.66 kg/cm^2 [29]. So, from this value it can be calculated the maximum test load that bamboo can withstand namely:

$$\sigma_{tk} = \frac{P_{maks}}{b\ x\ h}$$

$$P_{maks} = \sigma_{tk}\ x\ b\ x\ h$$

$$P_{maks} = 60{,}66\ x\ 2\ x\ 8 = 970{,}56\ N$$

$$m = \frac{P_{maks}}{9{,}81} = \frac{970{,}56}{9{,}81} = 98{,}93\ kg$$

From the yield stress of the bamboo material and the maximum von Mises stress, the safety factor values can be calculated by equation (13). The safety factor value for the apus bamboo ladder structure is 6.28. This static load's safety factor value parameter is at least 2.0 [32]. The result of the safety factor value of 6.28 indicates that the apus bamboo ladder structure is safe to use because it falls within the recommended minimum parameter value range.

4. CONCLUSION

From the data processing and analysis results, it is obtained that the greater the weight of the ladder user, the greater the compression force held by the ladder. Based on the body posture of workers with a body weight of 89.25 kg and a height of 183 cm, the compression force value is 868.72 N. This value is still far below the maximum test load held by a bamboo apus of 970.56 Newton. The results of the calculation of the compression force can change depending on the worker's body posture and the inclination angle of each body segment. The calculation of the angle of the ladder position using the equilibrium equation shows that the optimal slope angle of the ladder is between 53.26^o to 65.43^o. The ladder's optimal angle can change depending on the interval of the user's weight value used and the assumption of the coefficient of friction between the ladder and the surface. Based on the results of the static loading simulation carried out using the SolidWorks 2019 software, it can be seen that the critical point when loading the ladder is at the step of the ladder because it withstands the greatest force. Still, there is no red color on the ladder, so the ladder is considered to be able to withstand the given load of 875.5 N. In addition, the resulting stress value is still below the yield stress of the bamboo material. Future research can focus on dynamic loading, overall loading in bamboo ladders and material or mechanical properties of other materials that may give better results.

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Appendix 1

Table A. Division of body segments angles [26]

Segmentation Body	Length Segment	Weight Segment	Center of Mass Man	Center of Mass Woman
Head and Neck	-	-	-	-
Palm	0.108	0.006	50.6%	49.4%
Forearm	0.146	0.017	43.0%	57.0%
Upper arm	0.186	0.028	43.6%	56.4%
Upper limb	-	-	60.4%	39.6%
Eye Height	0.936	-	-	-
Shoulder Height	0.818	-	-	-
Elbow Height	0.63	-	-	-
Ankle Height	0.389	-	-	-
Leg Length	0.152	-	-	-
Back	0.288	0.5	-	-
Thigh	0.245	0.1	43.3%	56.7%
Calf	0.246	0.043	43.3%	56.7%
Foot	-	0.014	42.9%	57.1%

Table B. Recapitulation of body segment angles

Body Segment	Symbol	Corner
Palm	H	40^{0}
Forearm	LA	43^{0}
Upper arm	UA	70^{0}
Back	B	85^{0}
Thigh	TH	90^{0}
Calf	S	270^{0}

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Appendix 2

Table C. FBD for each body part

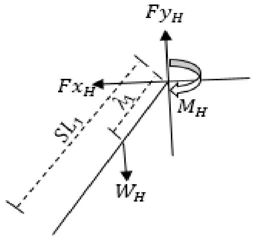
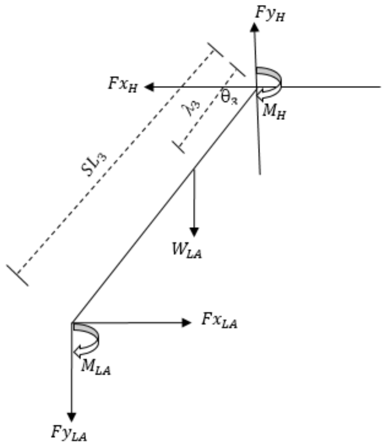
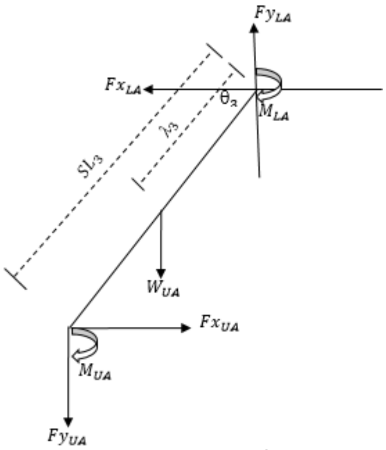
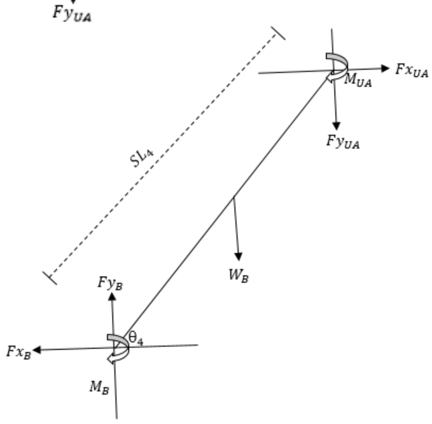
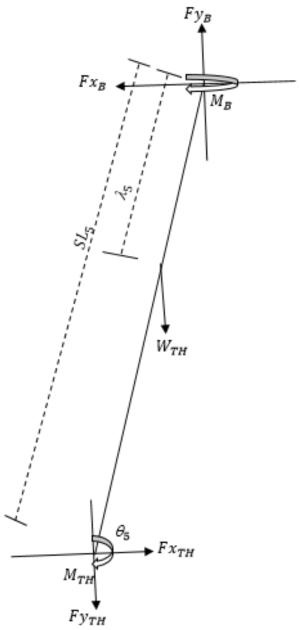
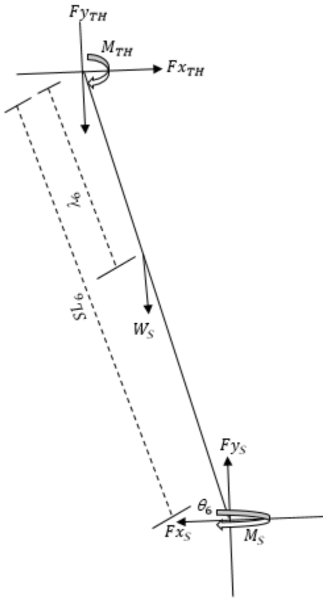
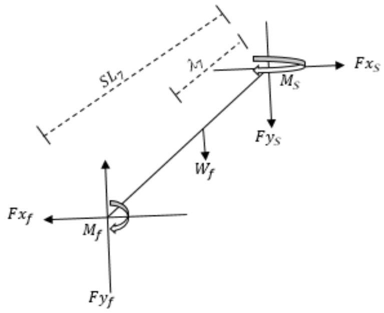
Body Part	FBD	Result
Palm		$SL_1 = 19.76\ cm = 0.1976\ m$ $\lambda_1 = 9.99\ cm$ $W_H = 5.25N$ $F_H = 15.06N$ $M_H = 2.29Nm$
Forearm		$SL_2 = 26.72\ cm = 0.2672\ m$ $\lambda_2 = 11.48\ cm$ $W_{LA} = 14.88N$ $F_{LA} = 29.94N$ $M_{LA} = 6.48\ Nm$
Upper arm		$SL_3 = 34.04\ cm = 0.3404\ m$ $\lambda_3 = 14.84\ cm$ $W_{UA} = 24.51N$ $F_{UA} = 54.45\ N$ $M_{UA} = 11.18\ Nm$
Back		$SL_4 = 52.7\ cm = 0.527\ m$ $W_B = 437.75$ $F_B = 546.65\ N$ $M_B = 4007\ Nm$

Table C. FBD for each body part (continued)

Body Part	FBD	Result
Thighs		$SL_5 = 44.84\ cm = 0.4484\ m$ $\lambda_5 = 19.42\ cm$ $W_{TH,} = 8755\ N$ $F_{TH} = 634.2\ N$ $M_{TH} = 2004\ Nm$
Calf		$SL_6 = 45{,}02\ cm = 0{,}4502\ m$ $\lambda_6 = 19{,}49\ cm$ $W_S = 37{,}65\ N$ $F_S = 671{,}85\ N$ $M_S = 20{,}04\ Nm$
Foot		$SL_7 = 27{,}82\ cm = 0{,}2782\ m$ $\lambda_7 = 19{,}42\ cm$ $W_f = 12{,}26\ N$ $F_f = 684{,}11\ N$ $M_f = 211{,}82\ Nm$

Information:

SL_n= length of each body segment

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