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The Study of Wooden Clamps for Strengthening of Connection on Bamboo Truss Structure

Astuti Masdar[a,b*], Bambang Suhendro[a], Suprapto Siswosukarto[a], Djoko Sulistyo[a]

[a]Department of Civil and Environmental Engineering, Faculty of Enginering, Gadjah Mada University, Yogyakarta, Indonesia
[b]Department of Civil Engineering, Sekolah Tinggi Teknologi Payakumbuh, Payakumbuh, Indonesia

*Corresponding author: astuti_masdar@yahoo.com

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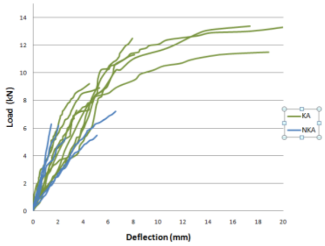
Graphical abstract



Abstract

High strength bamboo material cannot be fully utilized in construction projects due to the constraints of the connection system. The connection system element on the truss structure greatly affects the strength of the structure. Several studies have been completed to provide higher strength of the truss connections. However, the connection system is constrained by the costs of construction, availability of materials, equipment, skilled labored standardization. In this study, a connection system that possesses lightweight properties but with higher strength and lower cost while keeping the form of the bamboo being connected to remain natural has been developed. The proposed connection system consists of bolts, wooden gusset plates and special wooden clamps that have been adjusted with the shape and dimension of the bamboos being connected. A connection system without filler material on bamboo culms and wooden clamps used to increase the contribution to the shear at the connection has been proposed. The results showed an increase in the strength of the proposed connection of about 40% of the wood gusset plate system using wooden clamps than connection system without using wooden clamps, so it can be concluded that the proposed connection system possesses higher strength, yet much lower weight and has the potential for practical applications.

Keywords: Bamboo; connection system; truss; shear; wooden clamps

1.0 INTRODUCTION

Bamboo is an environmentally friendly construction material that has great potential to be used as a structural material. As a structural material, bamboo can be used in a variety of building components such as beams, columns, partitions, floors or as a truss structure. In truss structures, bamboo is commonly applied as structural members in roof construction and bridge structures.

Bamboo constructions are easy to build, resilient to wind and even earthquake forces and readily repairable in the event of damage. Viewed from the economic aspect, bamboo promotes cost saving in construction due to its cheap price, readily available at large quantity at any time possible [1]. However, there are a number of important considerations which currently limit the use of bamboo as a universally applicable construction material, i.e. durability, connection system, flammability and lack of design guidance and standardization [2].

High strength bamboo material cannot be fully utilized due to the constraints of the connection system. Splicing or coupling the whole members is usually done conventionally by using rope, nails and pins. Connection with nails or pins cause tears to the member where the fibers are aligned so that the low shear strength of bamboo easily exceeded. The connection with a rope relies on the strength of the friction of the rope with bamboo or bamboo with bamboo. The connection with a rope on bamboo truss structure is presented in Figure 1. The restraint rope shown in Figure 1 influenced the strength the connection. Due to the changes in temperature, bamboo could shrink and cause the rope to slack. This is the problem of the conventional bamboo connection that generally produces very low strength. In addition, the formula for calculating the strength of the rope connections was difficult to be formulated. Due to geometric reasons, bamboo construction often requires extension to prolong the member and connection for joining other members in a gusset or joint.

Researches to obtain a strong connection system to overcome the problem of the weakness of a connection have been widely done. Examples include the connection system with PVC joints [3], the connection system with bamboo-concrete composite [4], the connection system with gusset plate of plywood materials and devices connecting bolts [5], the connection system with gusset plate of plywood materials or hard wooden planks and devices connecting nails [6] and the connection system with gusset plate of steel and devices connecting bolts [7].

Figure 1 Connection with (a) *ijuk* rope and; (b) Rattan rope in bamboo truss structure. (*Source:* Fieldwork 2011)

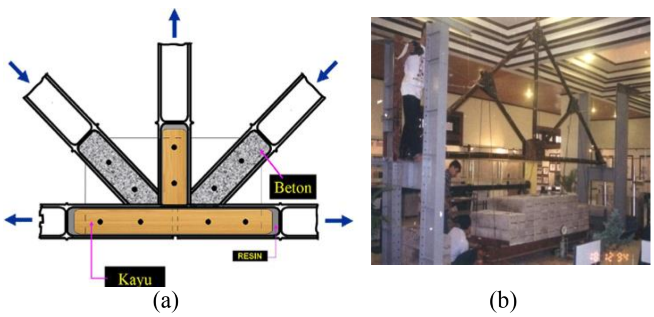


Figure 2 (a) Connection with steel gusset plate; (b) Experimental set up of testing truss structure [8]

Morisco *et al*. conducted a research to improve the strength of the connection on a bamboo truss structure [8]. The method used bolts, steel gusset plates, and cement mortar or wood filling as shown in Figure 2(a). Two common bases for determining the strength of bamboo connection are known, namely shear strength and bearing strength where shear strength is the smallest strength among others [9]. Shear strength of the weak bamboo can be increased by using the stuffing on bamboo culms as illustrated in Figure 2(a). The connection system has advantages in terms of strength, robustness and stability.

Bamboo truss structure was made to demonstrate the joint strength as shown in Figure 2(b). The loading was applied using a concrete block with a total weight of 40 kN. This jointing method has been made on the structure of the bamboo bridge with span length of 12 musing Gigantochloa atroviolacea (a tropical bamboo) with about 7 cm in diameter. The results of test show that strengths of the jointing method under investigation are quite high, and an estimated strength of the connection can be formulated [8]. Nevertheless, despite the high strength resulted from this connection, the use of steel for gusset plates and relatively heavy infill material has made this connection system to be less desirable because of the significant increase of structure weight and construction costs that make it uneconomical.

A bamboo connection system that possesses lightweight nature but higher strength and lower cost while keeping the form of the bamboo being connected remains natural has been developed by Masdar *et al*. in 2013 [10]. The proposed connection system consists of bolts, wooden gusset plates and special wooden clamps that have been adjusted with the shape and dimension of the bamboos being connected. The wooden clamps were placed between the bamboo and wooden gusset plates and tightened by the bolts as shown in Figure 3.

The wooden plates were made of Dipterocarpaceae (a tropical lowland rainforest tree) which has sufficient strength. This effort was done because the wooden gusset plate is much lighter and the price is much cheaper than that of steel. Meanwhile, the wooden clamps provide contact area that capable of mobilizing its friction capacity to transfer the applied load for stronger and reliable connection. The special wooden clamps can also make connection among various diameters of bamboo at the joint easier to construct. The details of connection system for joint with three variations of clamp developed are shown in Figure 4 which depicts three variations of wooden clamps which are distinguished by their ring angles, i.e. $\alpha = 60^0$, 90^0, and 120^0, respectively.

Figure 3 (a) Connection system on bamboo truss structure [10]

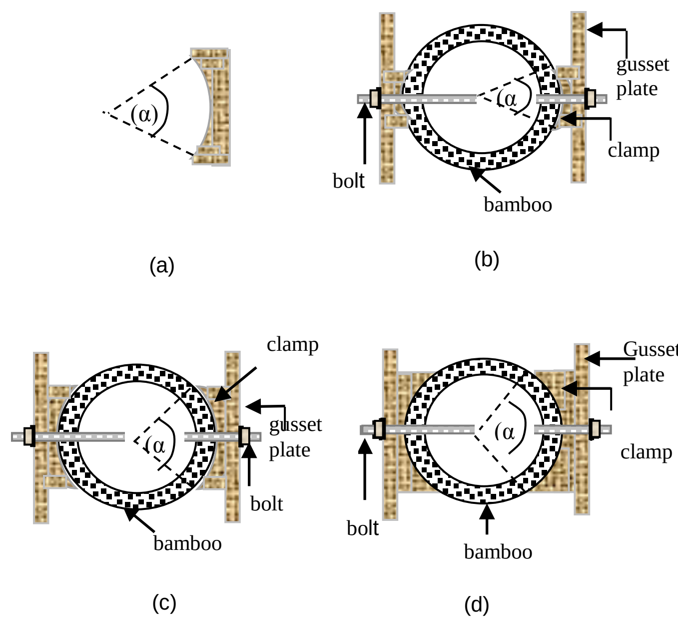


Figure 4 (a) Clamp variation in the form of angles (α); (b) Clamp angle 60^o; (c) Clamp angle 90^o; (d) Clamp angle 120^o[10]

Based on the tensile tests on the connection [10], it can be concluded that the greater the contact area between the wood clamps and bamboo, a higher strength will be produced.

Although in theory the variation of wooden clamp with ring angle of120^o is higher, based on experimental results obtained, the increased of the strength of that variation is in significant compared to the circumference of the wooden clamp with ring angle of 60^o to 90^o. This phenomenon happens because the bamboo section is nota perfect circle such that the contact are a between wooden clamps and bamboo are not always optimal. Technically, an increase in the strength of the connection with clamp ring angle of 60^o to 90^o was around 30%, while from 90^o to 120^o angle was only 10%. Because of the connection system must not be damaged prior to being spliced, the wooden clamp with ring angle of 90^o was determined to be optimal and thus recommended to be applied to connections of bamboo truss structure.

The use of wood clamps is very influential on strength of the connection. Increased of the strength on the connection system along with the increasing of the wide of contact area between the wood gusset plate and bamboo can be determined, as well as the choice of wood clamps that produce optimal connection strength can be known from a study conducted by Masdar [10]. However, the magnitude of the increase in the strength and behavior on the connection system against connection system that used wood gusset plate and bolt without wood clamps is not yet known. This paper presents the results of a study aiming at determining the increase of the strength of bamboo connections that used wooden clamps against bamboo connections that did not used wooden clamps.

2.0 THE STRENGTH OF BAMBOO CONNECTION

Equations related to the strength of the connection components need to be made to determine the strength of the connection [11-12]. The component of the connection system determines the strength of bamboo connections. A formula to estimate the strength of connection is available. In this research, analytical method considering failure mode and the strength of bamboo connection will be verified with result from experimental work. The strength of connection of bamboo and the failure mode can be estimated from the following formulas shown in Figure 5.

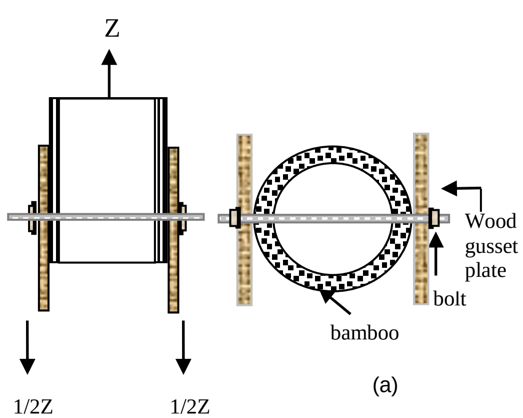


Figure 5 Component of connection system that are determine the strength of the connection

Failure Mode I occurs when the bearing strength that occurs excessively between the bolt and bamboo. In this case the strength of connection can be obtained from the Equation (1):

$$Z_1 = 2t_m \,.\, fem.D \tag{1}$$

where, t_m is thickness of main member (bamboo); fem is the bearing strength parallel to grain (bamboo), and D is bolt diameter.

Failure mode II occurs when the bearing strength that occurs excessively between the bolt and gusset plates. In this case, the strength of connection can be obtained from the Equation (2):

$$Z_2 = 2t_s \,.\, fes \;\; .D \tag{2}$$

where, t_s is thickness of side member (wooden gusset plate); fes is the bearing strength parallel to grain wooden gusset plate, and D is bolt diameter.

Failure mode III occurs when the bending stress on the bolt exceeded the elastic limit. In this case the strength of connection can be obtained from the Equation (3):

$$Z_3 = \frac{2t_m \,.\, fem.D}{R_t\,(2+R_e)}\left[\sqrt{\frac{2(1+R_e)}{R_e}+\frac{2\,f_y\,(2+R_e)\,R_t^2}{3Fem\;\;(t_m/D)^2}}-1\right] \tag{3}$$

The failure is caused by a type IV bolt shear strength that is exceeded, resulting in 2 areas of the shear on the bolts. The failure of this type of connection can be obtained by the Equation (4):

$$Z_4 = 2\left(\frac{1}{4}\pi D^2\right) f_y \tag{4}$$

where, R_e is fem/fes; R_t is t_m/t_s, and is bolt f_y bending yield strength of bolt.

Wooden clamps placed on the connection system between wooden gusset plate and bamboo contributes to increase the strength of connection. On the connection system which was introduced by Morisco [11], the stuffing in bamboo culms aims to increase the shear strength of bamboo while placement of wood clamps on the connection system proposed by the researchers aim to increase the contact area between wood gusset plate and bamboo, thus its can be reducing shear stress on bamboo culms.

3.0 EXPERIMENTAL

3.1 Research Method

The study was conducted experimentally in two phases of testing. In the early stage of the research preliminary testing on basic properties of the materials used have been conducted. The second phase of the research involved designing and fabricating several types of connections with full scale sizes and tested experimentally in the laboratory. Comparison with other available connection systems then could be done to show the superior of the proposed system. Flow chart of the research steps is presented in Figure 6.

3.2 Material

The proposed connection system consists of wooden gusset plates, bolts and wooden clamps as shown in Figure 7. The type of bamboo used as the main structural material in this study was *bambu wulung* (Gigantochloa atroviolacea). Advantages of bambu wulung over other bamboo species with relatively similar diameter such as *bambu apus* (gigantochloa apus) are related to greater strength, especially on tensile strength. Gigantochloa atroviolacea also has culms that are longer than Gigantochloa apus. Gigantochloa atroviolacea has a higher level of durability and availability, and is still widely available in various regions in

Indonesia. The bamboo was taken from Purwodadi are in the province of Central Java. The average diameter of the bamboo used was 75 mm, while the age of the bamboo varies from 3 to 5 years. The gusset plates ware made of *Keruing* wood (Dipterocarpaceae), while *Mahoni* wood (Swietenia Macrophylla Kings*)* was used for the clamps. Screw types of bolts with a diameter of 12.2 mm were used in this connection. Screw type of bolts with a diameter of 12.2 mm were used in connection system due to the use of bolts with a diameter of 12.2 mm on bamboo will produced bearing strength better than larger diameter [13].

3.3 Specimen Preparations

The specimens of basic properties of material were prepared based on ISO N22157-1 2004 [14] standard for bamboo and ASTM D 143-94 [15] for wood. Bolt specimens were made according to ASTMstandardF1585-03-2008 [16]. Based on the results of preliminary material testing, the connection specimens were designed and fabricated accordingly. Testing was conducted to study the influence of wooden clamp on the strength of the connection system. The details of connection system for joint with two variations of joint developed by authors were shown in Figure 8 which depicts two variations of connection system which are distinguished by component on connection system. The ring angle of the wooden clamps on the connection system (α) is 90º.

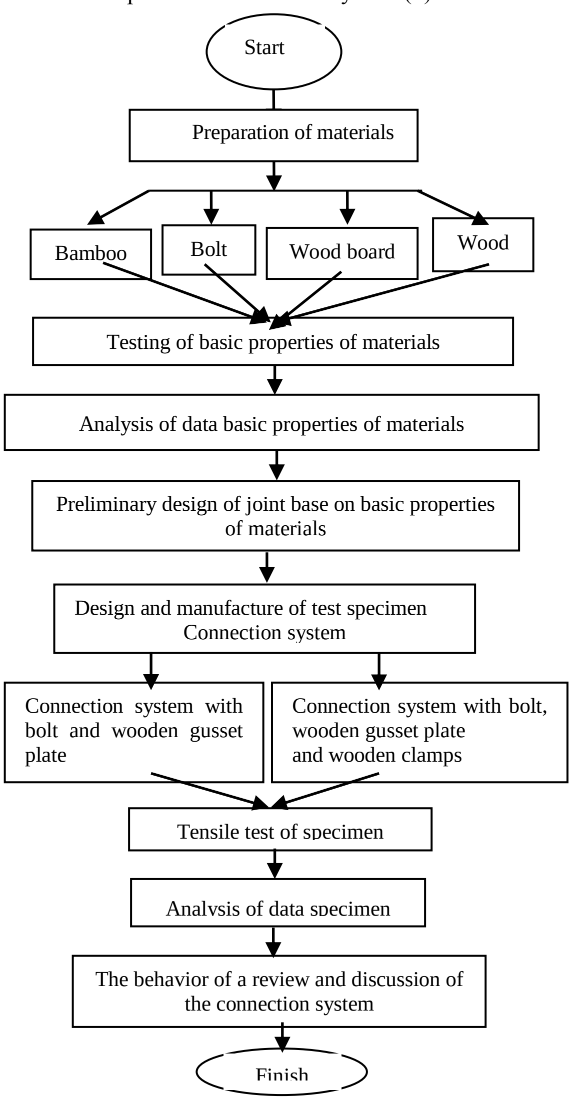


Figure 6 Flow chart of the implementation of research

(a) (b)

Figure 7 Material of specimen (a) bamboo (b) bolt with a diameter of 12.2 mm, wooden clamps and wood board

2.3 Experimental Setup

The testing method of basic material properties was based on ISO N22157-2 [17] for bamboo and ASTM D 143 for wood [15]. The testing method of bearing strength of bamboo was adopted from ASTM D 5764 standard test method for evaluating dowel bearing strength of wood and wood based products [16]. Bearing strength test has been carried out on bamboo and wood with deformed bolt diameter of 12.2 mm. Material were tested under compression and tensile using Universal Testing Machine which was integrated with data logger. The test set-up for tensile test for proposed various connection systems are shown in Figure 9. Tensile load was applied gradually by a tensile testing machine. The relative displacement of joint was measured by two displacement transducers.

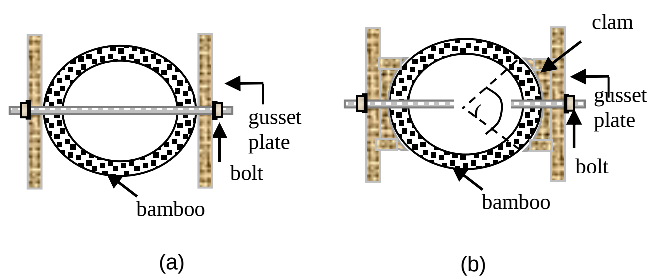


Figure 8 Variations of connection system; (a) Connection system without wooden clamps and (b) connection system with wooden clamps (α=90º)

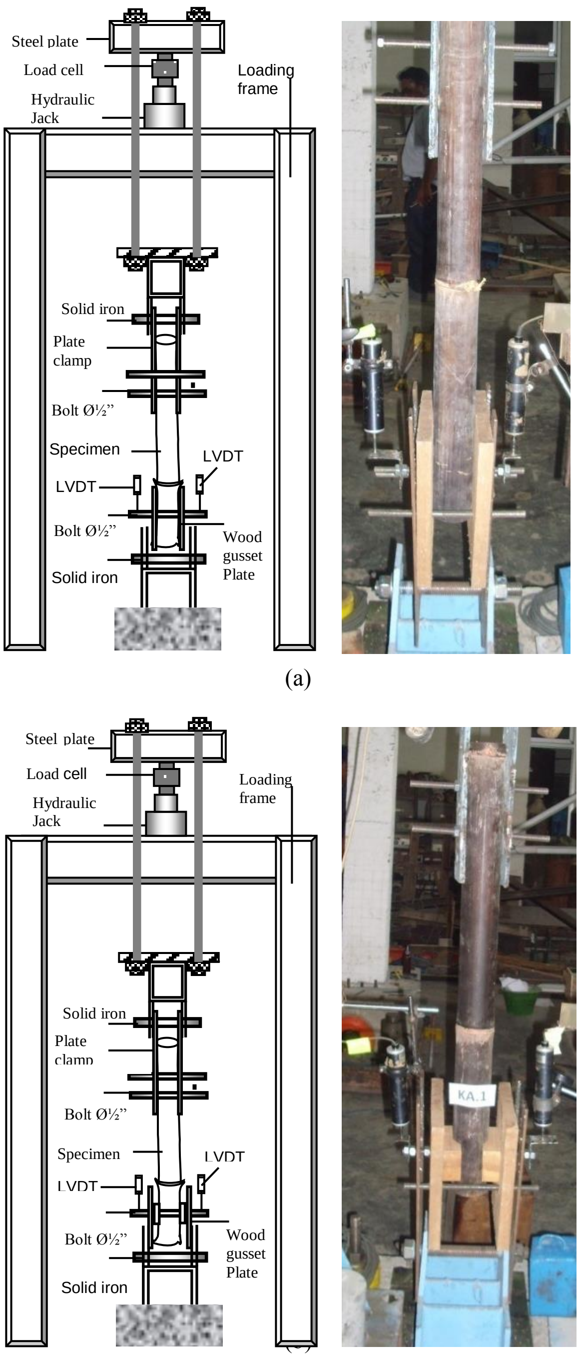


Figure 9 Test set-up for tension of the connection; (a)detail of the test set up for connection system without wooden clamps (b) detail of the test set-up for connection system with wood clamps

■3.0 RESULTS AND DISCUSSION

The results of the average basic properties of material (density, moisture content and bearing strength) were obtained and listed in Table 1. The average bending moment on bolt obtained from the tests are listed in Table 2 and depicted in Figure 10.

Table 1 Results of the testing the basic properties of material

Material	Grain direction	Density	Moisture content	Bearing strength (σ)	σ 5% offset
		(g/cm^3)	(%)	(MPa)	(MPa)
Gigantochloa atroviolacea	Parallel	0.62	13	40	37
Dipterocarpaceae	Parallel	0.56	12	62	62
	Perpendicular	0.56	12	29	26
Swietenia Macrophylla Kings	Parallel	0.75	12	47	46
	Perpendicular	0.75	12	30	22

Table 2 Result of the testing bending moment of bolt

Specimen	Bending moment max (N-mm)	Bending moment 5% offset (N-mm)
B1	126240	96000
B2	125280	95000
B3	123360	98000
Average	124960	96333.33

Figure 10 Testing of bending moment of bolt

Testing of the specimen that is related to the bending moment of bolt is necessary to know connection strength. Component of connection system that consists of bamboo, wood gusset plate system determines the strength of bamboo connections. Failure mode I occurs in the specimen without wood clamps and with wood clamps (Z_1). In Figure 11, it appears that the damage occurred is in the middle of the connection system (bamboo).

Figure 11 Failure mode in the connection system in tension (a) Without wooden clamps(NKA); (b) with wooden clamps (KA)

The strength of the connection be formulated in theory by using the approach based on European Yield Method (EYM) presented by Johansen [12] and Morisco [11]. Based on the failure mode that occurs in the connection system, comparison on the results of strength between experimental and the theoretical value can be made. Comparison of theoretical values with the experimental value of the connection can be seen in Table 3.

Table 3 Comparison of the strength of the connection between theories and experimental

Specimen	The strength of the connection in tension (kNm)					Different of strength
	Theories				Experimental	
	Z_1 (a)	Z_2 (b)	Z_3 (c)	Z_4 (d)	Z_E (e)	$\left(\frac{e-a}{e}\right)x1$
NKA	7.2	32.7	16.4	16.6	5.8	-19.7
KA	7.5	31.6	16.3	16.6	9.4	20.2

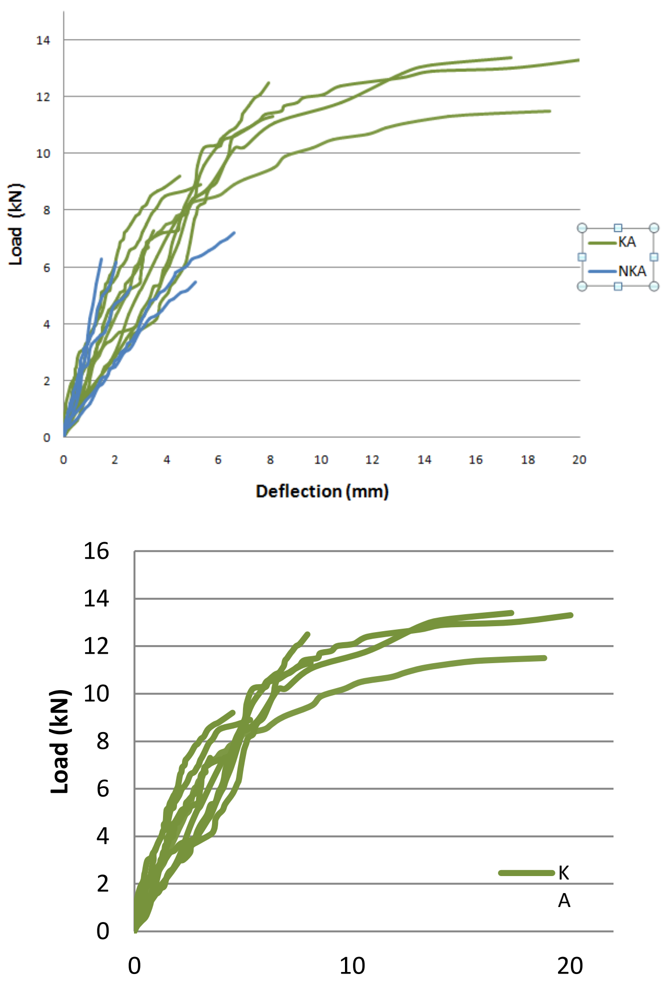


Figure 12 Relationship between load and displacement obtained from tensile test of the connection

The relationship between load and displacement obtained from the test are shown in Figure 12. Based on the results of tensile tests of the connection illustrated in Figure 12 and listed in Table 3, the maximum strength of the test result that obtained form experimental study smaller than 20% of the result of theorical calculation for the connection system without wooden clamps and for connection system with wooden clamps, the maximum strength of the test result that obtained form experimental greater than 20% of the result of theorical calculation. The results showed an increase in the strength of the proposed connection about 40% of the wood gusset plate system using wooden clamps than connection system without using wooden clamps. Based on the results of tensile tests of the connection illustrated in Figure 12 and listed in Table 3, it can be concluded that wooden clamp in the connections system can increase the strength of the connection.

4.0 CONCLUSION

The use of wooden clamps is influential on the strength of the connection. Component of connection system determines the strength of bamboo connections. Component of connection system that consists of bamboo, wooden gusset plate, wooden clamps and bolt determines the strength of bamboo connections. In this research, analytical method considering failure mode and the strength of bamboo connection are verified with the results from the experimental work. Failure mode I occurs in the specimen without wooden clamps and with wooden clamps (Z_1). The results showed an increase in the strength of the proposed connection about 40% of the wooden gusset plate system using wooden clamps than connection system without using wooden clamps, it can be concluded that wooden clamp in the connections system can increase the strength of the connection.

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