Reference lateral design value of single shear connection of Merbau wood using bolt

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Abstract. The reference lateral design value is the basic load capacity for a fastener subjected to a lateral shear load. The design value is a consideration in designing a wooden connection. The main objective of this research was to determine the reference design value for a single bolt connection using Merbau wood. In this study, the experimental reference lateral design values were determined from the load-deformation curve with a 5% diameter offset method based on connection testing which refers to ASTM D5652 standard test methods for bolted connections in wood and wood-based products. Meanwhile, the prediction reference lateral design values were determined based on the formulas in the national design specification for wood construction. The wood used was Merbau (Intsia spp) using three bolt diameters (1/2, 5/8 and 3/4 in) and several wood thickness combinations. The results showed that the experimental design reference values ranged from 475 kg to 887 kg. The reference lateral design value was influenced by a combination of wood thickness and bolt diameter. The greater the thickness of the wood and the diameter of the bolt, the higher the value of the design obtained. The ratio between predictive Z according to yield mode and minimum Z in NDS and experimental Z showed the range from 0.53 to 1.07 and from 0.53 to 0.91.

1. Introduction

A connection is a construction detail that interconnects a number of elements [1], to obtain specific dimensions of wood and build a structural system of several wood elements. The strength and stability of any structure depend heavily on the fastenings that hold its parts together [2]. Connections between structural elements are an integral part of any structure; therefore, the proper design of connections plays a critical role in the overall performance of wood structures [3, 4].

There are a wide variety of fasteners and many different types of joint details that can be used in wood connections. When the design forces are relatively small, the connections may often be made with nails. However, bolts, lag bolts, and other connectors are normally used for larger loads. Most bolts are used in laterally loaded dowel-type connections [4].

The basic load capacity for a dowel fastener is based on European Yield Model (EYM) or yield limit equations. EYM has adopted in the design standards for wood connection in many countries. For examples, the United States of America has the National Design Specification (NDS) for Wood Construction [5], while Europe has developed Eurocode 5: Design of Timber Structures [6]. Indonesia uses the Indonesian National Standard (SNI) 7973:2013 Design Specifications for Wood Construction [7]. The EYM for bolted wood connections has gained wide acceptance in recent years attributed to its
closed form, simplicity, and accuracy [8]. Some studies showed the EYM could predict the wood connection strength accurately [9, 10], but the accuracy of predictions depended on factors such as connection geometry and the type of wood member involved [11].

Data and equations related to wood connections are generally based on the research of sub-tropical woods in NDS, mainly softwood. The previous study showed that the experimental bearing strength of Merbau wood was higher than the prediction value based on NDS [12]. Therefore, the research of wood connection using tropical hardwoods, especially Indonesian wood species is needed to implement the standard better. This research was part of a study-series on mechanical properties, bolt bearing strength and wood connection, which used six commercial tropical hardwoods with specific gravity ranged from 0.4 to 0.8. In this study, Merbau wood was selected as one of the commercial timbers used for construction with high specific gravity (0.82). The main objective of this research was to determine the reference design value for a single bolt connection using Merbau wood. Next, to evaluate the effect of some combinations of element thickness and bolt diameters, to determine the yield mode and to compare the experimental and prediction reference lateral design values according to NDS.

2. Materials and method
Merbau block specimen was sized 6 cm × 12 cm × 400 cm. The block was cut 50 cm long to make a sample of wood connection test with three variations of thickness namely 2.5, 3.8 and 5.0 cm. Each test sample was bored at three points on one end for setting up to the grip. The other end was bored according to the specified diameter of the bolt at a distance of 7D (D=diameter of the bolt) from the end. The iron plate grip was specially made according to the size of the test samples used. Connection tests were measured on 54 samples which consisted of six combinations of element thickness (2.5-2.5, 3.8-2.5, 3.8-3.8, 5.0-2.5, 5.0-3.8 and 5.0-5.0 cm), three bolt diameters (1/2, 5/8 and 3/4 in) and three replications.

Wood connection tests followed ASTM D5652–15: Standard Test Methods for Bolted Connections in Wood and Wood-Based Products [13] (figure 1). The wood connections were tested on a universal testing machine Merk Baldwin type 60WHVL-1017 with a capacity of 300 kN. Testing was conducted approximately 10 min to reach the maximum load, however, reaching the maximum load was not less than 5 and not more than 20 min with a constant rate of motion of the movable crosshead of the testing machine of 0.040 in. (1.0 mm)/min.

![Figure 1. Assembly for testing bolted connection parallel to grain in tension.](image-url)
Based on the relationship between the load and the displacement graph obtained from the test, the yield load was determined using the 5% offset method. The reference lateral design value (Z) was determined using the yield load value (Py) divided by the normalization factor (Kc) or reduction factor (Rd) based on the yield mode according to the failure type. Kc or Rd value was 4 for yield mode I, 3.6 for yield mode II and 3.2 for yield mode III and IV, for fastener diameter 0.25 to 1 inch in parallel to grain loading [5, 14]. The reference lateral design value based on NDS was calculated according to the following formulas [5]:

Mode Im: 
\[
Z = \frac{D_{lm}F_{em}}{4K_\theta}
\]  
(1)

Mode I: 
\[
Z = \frac{D_{l}F_{es}}{4K_\theta}
\]  
(2)

Mode II: 
\[
Z = \frac{k_1D_{lm}F_{em}}{3.6K_\theta}
\]  
(3)

Mode III: 
\[
Z = \frac{k_2D_{lm}F_{em}}{3.2(1+2R_t)K_\theta}
\]  
(4)

Mode IV: 
\[
Z = \frac{k_3D_{ls}F_{es}}{3.2(2+R_t)K_\theta}
\]  
(5)

Mode IV: 
\[
Z = \frac{D^2}{3.2K_\theta\sqrt{\frac{2F_{em}r_{yb}}{3(1+R_t)}}}
\]  
(6)

3. Results and discussion

3.1. Reference lateral design values (Z) according to yield modes in NDS

Table 1 presents the average Z values according to yield modes in NDS. Z values were calculated based on the equations (1) – (6) in NDS. The bearing strength of Merbau wood was taken from the previous study [12] as well as the values of the bolt bending yield strength [15].

Z = reference design value for a single-fastener connection

k_1 = \frac{\sqrt{R_t+2R_c^2(I+R_t)^2+R_c^2R_t-I(1+R_t)}}{1+R_t}

k_2 = -1 + \sqrt{2(I+R_t) + \frac{2F_{em}(1+2R_t)D^2}{3F_{em}r_e}}

k_3 = -1 + \sqrt{2(I+R_t) + \frac{2F_{em}(1+2R_t)D^2}{3F_{em}r_e}}

R_t = \frac{F_{em}}{r_e}

R_c = \frac{F_{em}}{F_{es}}

K_\theta = \frac{I + \theta}{360}

D = bolt diameter

l_m = dowel bearing length in the main member

l_s = dowel bearing length in the side member

F_{em} = dowel bearing strength of the main member

F_{es} = dowel bearing strength of the side member

F_{yb} = bending yield strength of the bolt

\theta = maximum angle of load to grain (0 \leq \theta \leq 90 degrees) for any member in connection
In general, the Z values in yield mode I were higher than in other yield modes. Meanwhile, Z in yield mode II showed the opposite, generally lower than the other yield modes. The Z value in each yield mode increased with increasing the thickness of the wood element, as well as the larger diameter of the bolt used. Z was taken as the smallest value from all applicable yield limit equations for use in connection design [4].

### Table 1. Average Z values according to yield modes in NDS.

| Combinations of element thickness (cm) | Bolt diameters (in) | Z I<sub>m</sub> (kg) | Z I<sub>s</sub> (kg) | Z II (kg) | Z III<sub>m</sub> (kg) | Z III<sub>s</sub> (kg) | Z IV (kg) |
|----------------------------------------|---------------------|----------------------|----------------------|---------|----------------------|----------------------|---------|
| 2.5−2.5                                | 1/2                 | 502                  | 503                  | 260     | 323                  | 324                  | 403     |
|                                        | 5/8                 | 635                  | 633                  | 328     | 501                  | 501                  | 677     |
|                                        | 3/4                 | 756                  | 758                  | 392     | 704                  | 705                  | 981     |
|                                        | 1/2                 | 758                  | 502                  | 338     | 397                  | 323                  | 403     |
| 3.8−2.5                                | 5/8                 | 962                  | 635                  | 428     | 573                  | 501                  | 677     |
|                                        | 3/4                 | 1155                 | 764                  | 514     | 772                  | 707                  | 984     |
|                                        | 1/2                 | 759                  | 758                  | 393     | 397                  | 396                  | 403     |
| 3.8−3.8                                | 5/8                 | 967                  | 965                  | 500     | 574                  | 574                  | 677     |
|                                        | 3/4                 | 1156                 | 1158                 | 599     | 773                  | 773                  | 984     |
|                                        | 1/2                 | 992                  | 504                  | 422     | 477                  | 324                  | 403     |
| 5.0−2.5                                | 5/8                 | 1253                 | 636                  | 533     | 660                  | 501                  | 677     |
|                                        | 3/4                 | 1504                 | 758                  | 639     | 862                  | 706                  | 984     |
|                                        | 1/2                 | 986                  | 761                  | 459     | 474                  | 398                  | 403     |
| 5.0−3.8                                | 5/8                 | 1247                 | 959                  | 579     | 658                  | 572                  | 677     |
|                                        | 3/4                 | 1495                 | 1159                 | 696     | 859                  | 773                  | 984     |
|                                        | 1/2                 | 978                  | 978                  | 506     | 472                  | 472                  | 403     |
| 5.0−5.0                                | 5/8                 | 1249                 | 1246                 | 646     | 658                  | 657                  | 677     |
|                                        | 3/4                 | 1517                 | 1502                 | 782     | 866                  | 861                  | 984     |

In general, the Z values in yield mode I were higher than in other yield modes. Meanwhile, Z in yield mode II showed the opposite, generally lower than the other yield modes. The Z value in each yield mode increased with increasing the thickness of the wood element, as well as the larger diameter of the bolt used. Z was taken as the smallest value from all applicable yield limit equations for use in connection design [4].

### 3.2. Experimental reference lateral design values

Figure 2 plots the load versus displacement curves during the connection tests for the whole samples. In general, the graph shows the same pattern. Initially, the load increased with a very small displacement, then the load increase was in line with the increase in displacement. Finally, the smaller increase of the load produced larger displacement before reaching the maximum load and splitting occurred. Increasing bolt diameter produced increasing the load achieved in the testing. However, there is no clear boundary between one bolt diameter and others because it is also affected by the thickness combination of the wood element. The load used to calculate Z values was determined from yield load at 5% offset diameter of the load-displacement graph. The line intersection between the offset line and load-displacement curve to obtain the yield load occurred before the maximum load.

Table 2 presents the average experimental Z values, yield modes, and the ratio Z values in NDS to experiment values. The experimental Z value ranged from 475 to 887 kg. The Z value increased with the increase in the bolt diameter used and generally the increase in the thickness combination of the wood element connected. It showed the ability of the bolt to bear the given load was greater. This result was in line with the yield load obtained in the testing of the bolt bending yield strength, which showed the greater the bolt diameter, the higher the value of the yield load obtained.

In the statistical analysis, the experimental Z values were significantly influenced by the combination of wood thickness and bolt diameter (sig. = 0.00), but the interaction between the combination of wood thickness and bolt diameter did not significantly affect (sig. = 0.23) at the 95% level. The combinations of thickness from 2.5-2.5 cm to 5.0-2.5 cm were not significantly different, but the combination of 5.0-3.8 and 5.0-5.0 cm thickness was substantially different. The combination of 5.0-3.8 cm was not
different from 5.0-5.0 cm thickness. Furthermore, the three sizes of bolts diameter used showed the difference between one and another.

![Figure 2. Load versus displacement curve in the connection strength tests.](image)

**Table 2.** Average experimental Z values, yield modes and ratio NDS to experimental Z values.

| Combinations of element thickness (cm) | Bolt diameters (in) | Z experimental | Yield mode | Z NDS YM to Z experiment$^1$ | Z NDS min to Z experiment$^2$ |
|---------------------------------------|---------------------|----------------|------------|-----------------------------|-----------------------------|
| 2.5 - 2.5$^a$                         | 1/2$^a$             | 489            | IV         | 0.82                        | 0.53                        |
|                                       | 5/8$^b$             | 510            | II         | 0.64                        | 0.64                        |
|                                       | 3/4$^c$             | 739            | II         | 0.53                        | 0.53                        |
| 3.8 - 2.5$^a$                         | 1/2                 | 503            | IV         | 0.80                        | 0.64                        |
|                                       | 5/8$^b$             | 585            | II         | 0.73                        | 0.73                        |
|                                       | 3/4$^c$             | 784            | II         | 0.66                        | 0.66                        |
| 3.8 - 3.8$^a$                         | 1/2                 | 475            | IV         | 0.85                        | 0.83                        |
|                                       | 5/8                 | 631            | IV         | 1.07                        | 0.79                        |
|                                       | 3/4$^c$             | 778            | II         | 0.77                        | 0.77                        |
| 5.0 - 2.5$^a$                         | 1/2$^a$             | 485            | IV         | 0.83                        | 0.67                        |
|                                       | 5/8$^b$             | 653            | IV         | 1.04                        | 0.77                        |
|                                       | 3/4$^c$             | 759            | II         | 0.84                        | 0.84                        |
| 5.0 - 3.8$^b$                         | 1/2                 | 523            | IV         | 0.77                        | 0.76                        |
|                                       | 5/8$^b$             | 708            | IV         | 0.96                        | 0.81                        |
|                                       | 3/4$^c$             | 862            | II         | 0.81                        | 0.81                        |
| 5.0 – 5.0$^b$                         | 1/2$^a$             | 514            | IV         | 0.79                        | 0.79                        |
|                                       | 5/8$^b$             | 711            | IV         | 0.95                        | 0.91                        |
|                                       | 3/4$^c$             | 887            | II         | 0.88                        | 0.88                        |

Values superscripted by the same letter are not significantly different

Z NDS YM: Z value according to NDS yield mode in Table 1
Z NDS min: Z value according to NDS minimum in Table 1

There were two yield modes occurred in wood connection testing namely mode II and IV (figure 3). In all combinations of thickness, bolt diameters 1/2 in had yield mode IV, while bolt diameters 5/8 in had yield mode IV starting from 3.8-3.8 cm combinations. Connections with bolt diameters 3/4 in, in all
thickness combinations, showed the same mode yield, mode II. Yield mode IV involved failure, not only in the wood but also in the bolt. The failure type observed was adjusted to the failure model found in the yield mode. Failure could occur to the main elements, sides, and fastener. The different failure type in the connection caused difference in the normalization factor value (Kc), or reduction factor (Rd) used to determine the value of experimental design and NDS. Determination of experimental design values of connections for failure in type II was used Kc of 3.6 and type IV of 3.2. Meanwhile, the determination of the design value based on NDS in the failure connection of type II used equation (3), and type IV used equation (6).

![Figure 3.](image)

- (a) Wood connection samples after testing, (b) bolt hole in wood, (c) bolt in yield mode II, (d) bolt in yield mode IV.

The ratio of Z predicted values based on NDS according to the yield mode to the Z experimental value ranging from 0.53 to 1.07. Meanwhile, the ratio of Z predictions based on the minimum NDS to Z experimental values ranged from 0.53 to 0.91. This difference values due to a mode yield that was not in accordance with the prediction.

![Figure 4.](image)

Figure 4. Z experimental versus Z NDS curve.

### 4. Conclusion

The experimental reference design values ranged from 475 to 887 kg. The reference lateral design values were influenced by combinations of wood element thickness and bolt diameters. The greater the
thickness of the wood element and the diameter of the bolt, the higher the value of the design obtained. There were two yield modes occurred in wood connection testing namely mode II and IV. The ratio between predictive $Z$ according to yield mode and minimum $Z$ in NDS and experimental $Z$ showed the range from 0.53 to 1.07 and from 0.53 to 0.91.

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