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Abstract

This paper study the safety factor of timber connection designed with PKKI NI-5 (2002). Johansen yield model is used to evaluate the nominal design value of single bolted connection. Double-shear bolted connection, with the side members and the main member from wood, is chosen for this study. A comparison study of safety factor between SNI-5 (2002) and NDS for timber construction of U.S (1997) is also conducted. Finally, the safety factor is analyzed for both directions parallel and perpendicular to wood grain of four possible yield modes.

From the study, both SNI-5 (2002) and NDS (1997) use higher safety factor for bolted connection sustaining load perpendicular to grain than that sustaining load parallel to grain. Smaller safety factor is used in both codes when the plastic hinge of bolt is created such as the yield modes III, and IV. However, in this case, the safety factor of NDS is significantly much higher than that of SNI-5 (2002).

Keywords: Bolted connection, yield mode, and safety factor.

1. Introduction

Bolts are commonly used as fasteners in timber connection. They have the advantage of being easily installed and inspected. They are also economical, and are capable of transmitting high load. Bolts can be used in single-shear (two-member) connection or double-shear (three-member) connection. Generally, connections with mechanical fasteners such as bolts are usually more ductile than that of connection with adhesive materials. Ductile connection leads to better energy dissipation of timber structures. The connection strength of bolted connection is determined by some parameters such as yield bending strength of fastener, the bearing or shear strength of wood member, and the geometry of connection itself [Breyer et al., 2003].

Strength analysis of timber connection using yield model was proposed by Johansen [1949]. In his yield model, Johansen assumed that the bearing capacity of connection is attained when either the compressive strength of wood beneath the bolt is exceeded or simultaneously the timber under the bolt becomes plastic and one or more plastic hinges are formed in the bolt. A set of equations and the corresponding
yield modes obtained by Johansen yield model is currently known as European Yield Model (EYM). Recently, SNI-5 [2002] and NDS [1997] introduce a set of equations to analyze the strength of timber bolted connection in the form that resemble to what Johansen did. Therefore, it is an interesting study to analysis the safety factor provided by these two codes with respect to Johansen yield model.

2. Objectives

The overall goal of this study is to find out the safety factor of bolted timber connection designed by SNI-5 [2002]. In addition, a comparison study of safety factor used in SNI-5 [2002] and NDS [1997] is also carried out. The results of this study are restricted only to double-shear bolted connection where the main member and the side members are from wood.

3. Theoretical Background

Mechanical connections are constructed using two general fastener types: dowel and bearing. Dowel type fasteners such as nails, screws and bolts, transmit either lateral or withdrawal loads. Lateral loads are transmitted by bearing stress developed between the fastener and the members of connection. Withdrawal loads are loads parallel to the fastener axis transmitted through friction or bearing to the connected materials. Bearing type connections transmit lateral load only. Bearing type fasteners, such as shear plate and split ring connection, transmit shear force through bearing of the connected materials. Each connection must be designed to transmit forces adequately and provide satisfactory performance for the life of the structure without causing splitting, cracking, or excessive deformation of the wood members.

The first attempt to discover design values for bolted timber joints was conducted by Trayer [1932]. Trayer’s work focused on developing load-slip curve that can be used to find three important values: the proportional limit load, yield load, and ultimate load. Trayer’s conclusion is derived as an empirical fit of experimental results. This is due to the complexity of the interaction of a bolt in orthotropic non-homogenous material [Gatesco, 1998]. Some of the major conclusions reached by Trayer are: (1) the \( l/D \) ratio is the governing parameter, where \( l \) is the length of bolt in main member and \( D \) is the bolt diameter, (2) connection with steel side plates achieves 20% higher capacity than connection with wood side members for parallel-to-grain loading, and (3) connection with steel side plates and connection with wood side members loaded perpendicular to grain have equal capacities.

The capacity of single bolt depends on the bearing strength of wood, the bending strength and the slenderness ratio of bolt. The slenderness ratio of bolt is the length of bolt in main member divided by the bolt diameter. For bolted-connection with low slenderness ratio, the bolt is relatively stiff and the full bearing strength of wood is developed. As the slenderness increases, bolt stiffness is reduced and bending will occur before full bearing strength is achieved, reducing the capacity of connection [Soltis et al., 1996].

Yield model for strength analysis of bolted timber connection was proposed by Johansen [1949]. The bearing capacity of connection is attained when either the compressive strength of wood beneath the bolt is exceeded or simultaneously the timber under the bolt becomes plastic and one or more plastic hinges are formed in the bolt. Yield modes \( I_s \) and \( I_m \) are the results of wood fiber crushing in side members and main member, respectively. Yield mode \( III_s \) is the result of bolt yielding in one plastic hinge, and yield mode \( IV \) is the result of bolt yielding in more than one plastic hinges. These yield modes are shown in Figure 1. Please note that only a half of connection is shown due to symmetric configuration. From these following series of failure modes of connection, lateral load resistances for single fastener connection are given in Table 1.

4. Analysis

The allowable design value of bolted connection \( Z' \) is stated in Equation (1) in terms of the adjustment factor \( C \) and the nominal design value \( Z \). The adjustment factor actually reflects the safety factors which consider the possibility of structures being overloads, timber imperfections, early-splitting failure of multiple-bolt connection, and special environments. SNI-5 [2002] and NDS [1997] obtain the adjustment factor from Equations (2.a) and (2.b), respectively. According to SNI-5 [2002], the value of (connection

\[
Z' = CZ
\]

Table 1. Lateral load resistance of wood to wood bolted connection [Johansen, 1949]

<table>
<thead>
<tr>
<th>Yield mode</th>
<th>Lateral load resistance ( Z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_s )</td>
<td>( 2DX_{f,\text{nom}} )</td>
</tr>
<tr>
<td>( I_m )</td>
<td>( DX_{f,\text{nom}} )</td>
</tr>
</tbody>
</table>
| \( III_s \) | \[
\frac{2kDF_{t,\text{nom}}}{(2+R_t)} \left[ -1 + \left( \frac{2(1+R_t)}{R_t} + \frac{2F_{t,\text{nom}}(2+R_t)D^2}{3F_{s,\text{nom}}^2} \right) \right]^{1/2} \] |
| \( IV \)   | \[
2D^2 \left( \frac{2F_{t,\text{nom}}}{3(1+R_t)} \right) \] |
resistance factor) is equal to 0.65. The nominal design values of single bolt connection for both SNI-5 [2002] and NDS [1997] are given in Table 2.

\[ Z' \leq CZ \]  
(1)

\[ C_{SNI} = \phi_2 \lambda C' g C' \Delta \]  
(2.a)

\[ C_{NDS} = C_D C_M C_I C_g C' \Delta \]  
(2.b)

For a double-shear timber connection with single bolt, if the moisture content of timber is less than 19%, and maximum temperature of environment is less than 38°C, then Equations (2.a) and (2.b) can be simplified to become Equations (3.a) and (3.b), respectively. \( C_D \) and \( \lambda \) are load duration factors, which values are depending on loading combination. The value of \( C_D \) varies from 0.9 to 1.25 [NDS, 1997], and the value of \( \lambda \) varies from 0.6 to 1.0 [SNI-5, 2002].

\[ C_{SNI} = 0.65\lambda \]  
(3.a)

\[ C_{NDS} = C_D \]  
(3.b)

Substituting Equations (3) into Equation (1) yields Equations (4). Equation (4.a) and (4.b) are allowable design value of SNI-5 [2002] and NDS [1997], respectively. Supposed that the nominal design values of bolted connection obtained from Johansen yield mode (equations in Table 1) are called \( Z_{EYM} \), a coefficient (\( k \)) that relates the nominal design values (\( Z \)) of SNI-5 [2002] or NDS [1997] with is shown in Equation (5). The values of \( k \) are given in Table 3. From Table 3, it is obvious that the values of \( k \) in direction perpendicular to wood grain is 1.25 times the values of \( k \) in direction parallel to wood grain.

\[ Z' \leq 0.65\lambda Z \]  
(4.a)

\[ Z' \leq C_D Z \]  
(4.b)

\[ Z = \frac{1}{k} Z_{EYM} \]  
(5)

### Table 2. Lateral load resistance of wood to wood bolted connection [SNI-5 [2002] and NDS [1997]]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I(_s)</td>
<td>[ \frac{1.66D_t F_{em}}{K_0} ]</td>
<td>[ \frac{D_t F_{em}}{2K_0} ]</td>
<td></td>
</tr>
<tr>
<td>I(_m)</td>
<td>[ \frac{0.83D_t F_{em}}{K_0} ]</td>
<td>[ \frac{D_t F_{em}}{4K_0} ]</td>
<td></td>
</tr>
<tr>
<td>III(_c)</td>
<td>[ \frac{2.08k_s D_t F_{em}}{(2+R_s)K_0} ]</td>
<td>[ \frac{k_s D_t F_{em}}{1.6(2+R_s)K_0} ]</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>[ \frac{2.08D^2}{K_0} \sqrt{\frac{2F_{em} F_{yb}^2}{3(1+R_s)}} ]</td>
<td>[ \frac{D^2}{16K_0} \sqrt{\frac{2F_{em} F_{yb}^2}{3(1+R_s)}} ]</td>
<td></td>
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</tbody>
</table>

Figure 1. Failure modes and its bearing stress distribution of timber bolted-connection
Substituting Equation (5) and the values of $k$ in Table 3 for direction parallel to wood grain into Equation (1) yields Equations (6) and (7). Equations (6.a) and (6.b) are allowable design value of SNI-5 (2002) when the connection failed without plastic hinge in the bolt (yield modes $I_s$ and $I_m$) and with plastic hinge (yield modes $III_s$ and $IV$), respectively. Similarly with Equation (7.a) and (7.b), these two Equations are allowable design value of NDS [1997] when the connection failed without and with plastic hinge in the bolt, respectively. By introducing the values of $\lambda$ and $C_D$ into Equations (6) and (7), we will come out with one general equation that contain the safety factor ($SF$) of connection as shown in Equation (8). The exact value of safety factor will lie in safety margin of Table 4, and also depending on the type of loading combination. From Table 4, it can be concluded that NDS [1997] gives higher safety factor than SNI-5 [2002].

$$Z' \leq 0.54\lambda Z_{EYM}$$

(6.a)

$$Z' \leq 0.68\lambda Z_{EYM}$$

(6.b)

$$Z' \leq 0.25 C_D Z_{EYM}$$

(7.a)

$$Z' \leq 0.31 C_D Z_{EYM}$$

(7.b)

5. Conclusions

Both SNI-5 [2002] and NDS [1997] use higher safety factor for a bolted connection sustaining load in direction perpendicular to grain than that sustaining load in direction parallel to grain. Safety factor for direction perpendicular to grain is 1.25 times of safety factor for direction parallel to grain. Smaller safety factor is used in both codes when the failure modes of connection are $III_s$ and $IV$ (failure modes with plastic hinge in the bolt). However, in this case, the safety factor of NDS [1997] significantly much higher than that of SNI-5 [2002].

### Table 3. Values of $k$

<table>
<thead>
<tr>
<th>Yield mode</th>
<th>Parallel to wood grain</th>
<th>Perpendicular to wood grain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_s$ and $I_m$</td>
<td>1.2</td>
<td>4.0</td>
</tr>
<tr>
<td>$III_s$ and $IV$</td>
<td>0.96</td>
<td>3.2</td>
</tr>
</tbody>
</table>

### Table 4. Safety factor of timber bolted connection

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$I_s$ and $I_m$</td>
<td>1.85 – 3.0</td>
<td>3.23 – 4.44</td>
</tr>
<tr>
<td>$III_s$ and $IV$</td>
<td>1.47 – 2.45</td>
<td>2.56 – 3.57</td>
</tr>
</tbody>
</table>

### References


### Notation

- $C_D$, $\lambda$ = load duration factors
- $C_g$ = multiple-bolt adjustment factor
- $C_M$ = wet-service adjustment factor
- $C_t$ = temperature adjustment factor
- $C_A$ = connection geometric factor
- $D$ = bolt diameter
- $F_{es}, F_{em}$ = dowel bearing strength of side member and main member, respectively
- $F_{yb}$ = fastener yield stress
- $K_\theta$ = $1 + \theta/360$
- $M_p$ = plastic moment of bolt
- $R_e$ = ratio of $F_{em}$ to $F_{es}$
- $t_s, t_m$ = thickness of side member and main
member, respectively

\[ \theta = \text{angle of load to wood grain} \]

\[ k_3 = -1 + \sqrt{\frac{2(1 + R_e)}{R_e}} + \frac{2F_{sb}(2 + R_e)D^2}{3F_{scn}t_s^2} \]

\[ \text{semeyb} \]

\[ \text{e} \]

\[ \text{tF} \]

\[ \text{DRF} \]

\[ \text{R} \]