Analysis and optimization of the bearing capacity of connecting wooden structures with application of dowel type self-drilling

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Abstract: The multiple shear connection with slotted-in steel plates and dowel-type self-drilling is a very efficient timber connections for frame and truss. It is used in practice, due to its high capacity and faster construction method. However, when the complex connection and many parameters affect the bearing capacity, instead of a ductile mechanism, brittle failure may govern its capacity. To achieve the desired working connection, the relationship between the connection configuration parameters is established but no standard specifically with this kind of connection. A series of parameters changes affecting the bearing capacity of the connection are given. Calculate and compare with many previous research methods in ductile failure modes to assess their prediction accuracy and optimal connection. A model for the optimization of the ductile failure mode for the multiple shear connections with slotted-in steel plates and dowel-type self-drilling is then proposed.

1. Introduction

The development of the wood industry has led to the increasing popularity of the building of wooden structures, which have high bearing capacity due to its benefits related to sustainability and replacing traditional concrete and steel materials [1-5]. An important issue in the overall wood structure is the connection between the components, where local stresses and structural damage often occur. The bearing capacity of the structure depends heavily on the structure of the connections. Many solutions for connectivity are given and applied. Connections were reported to be involved in almost 25% of recent collapses of timber structures. Half of them were connections with dowel-type fasteners [6,7].

The multiple-shear dowel connection with slotted-in steel plates is one of the most efficient timber joints for large cross-sections and gathers the former requirements. During the last years, a large research project was carried out. For example, this type of connection appeared in the 1940 ties (Gehri [8]), solution for a large span truss made of nodes with slotted-in steel plate and dowels by Crocetti [9], the “Treet” building in Bergen (Norway), a 14-story timber building made of vertical trusses application of this kind of connection is explained by Malo et al. [10], the Swiss Federal Institute of Technology in Zurich (ETH), Switzerland in the research project to optimize the design of SBS type of connection (Mischler 1998a, 1999) [11].

Although the multiple shear connection with slotted-in steel plates with dowel-type fasteners has been applied in practice during a long time [2,3,12,13], the standards and methods of calculating are still limited, not specific with this type of connection. In previous studies, failure mechanisms of the connection were considered through experiments but without created systematic relationship of parameters affecting bearing capacity connecting to optimize the connection as desired. As in any other type of timber connections, the joint may fail in two different ways: ductile or brittle failure mode. It is advisable to design the structure to reach ductile failure before the brittle one, to achieve ductility. In this study, consider the connection under the plastic limit state in the change of construction parameters:
the number of steel plates, the number of dowels (diameter 5-7mm) in the joints and the arrangement of the dowels in the structure of the connection [11].

2. Methods

2.1. Geometry of the connection

Fig. 2 shows a typical example of a connection with slotted-in steel plates and four shear planes. The main dimensions of the joint of the timber member are defined by the width and the thickness $bh$ (mm²) [5]. The two steel plates with thickness $t_p$, the timber thickness $h$ is divided in three parts: the two outer members with thickness $t_1$ and one in the centre with thickness $t_2$.

For an overview of Working mechanism of wood connection with application of dowel type self-drilling, see the block diagram (fig. 3), In this study similar research models are considered.
In this study, we only consider the operation of the connection according to the plastic failure mechanism, optimize parameters to bring out the desired topology.

**Purpose of the study:** The connecting calculation methods are considered, the plastic working state; formulate a common formula for connecting; compare results with other calculation models by checking the formula. Proposal standard for calculating connection with shear plate and dowels type self-drilling [1]

### 2.2. Brittle failure mode

![Figure 4. The models brittle failure](image_url)

Three methods consider somehow all the possible brittle failure modes of a connection: Quenneville and Zarnani [14], Eurocode 5 [1] and Hanhijärvi and Kevarińmäki [12]. Also the CSA Standard O86-09 [15] provides a full brittle failure model. The proposals for brittle failure provide formulae for obtaining the capacity of each one of the timber members. Hence, the capacity of the connection against brittle failure mode for cases of single or double shear will be the sum of the capacities of each timber member. Correlation formula table corresponding to brittle failure.
Table 1. Bearing capacity of dowels in connections with models brittle failure

| Failure mode                | Row shear and splitting | Block shear | Net tension |
|-----------------------------|-------------------------|-------------|-------------|
| **Method**                  |                         |             |             |
| Eurocode 5 [1]              | \( n_{sf} = \min \left( \frac{n_r}{d_{1}}, \frac{n_{0.9}}{\sqrt[13]{d}} \right) \) | \( F_{b, \text{hovk}} = \max \left( \frac{1.5 A_{\text{net}} f_{\sigma,k}}{0.7 A_{\text{net}} f_{\tau,k}} \right) \) | \( \sigma_{f,0.d} = f_{f,0.d} \) [1] |
| Quenneville and Zarnani [13,20] | \( F_{b,\text{row}} = R_n n_r \) | \( F_{b,\text{block}} = R_n + 1.25 f_{f,0.d} A_{\text{net},d} \) | \( F_{b,\text{net}} = f_{f,0.d} A_{\text{net}} \) |
| Hanhijärvi and Kevärinmäki [12,14] | Proposed a comprehensive calculation model which integrates all the possible brittle failure modes for connections with dowels. | \( F_b = \min \left( \frac{F_{b,1} \left(2 + \frac{t_2}{t_1}\right)}{t_1}, \frac{F_{b,2} \left(1 + 2 \frac{t_2}{t_1}\right)}{t_2} \right) \) | Failure of outer member |
|                             |                         |             | Failure of inner member |

2.3. Ductile failure mode

As stated in introduction, no standard provides a calculation method of the ductile failure mode in multiple shear plane connections. The models proposed by Pedersen [2], with four shear planes connections (which is the studied case in this paper) and Sawata et al. [3], for connections of any number of shear planes are presented below.

![Figure 5. The models ductile failure](image)

2.3.1. Eurocode 5

According to clause 8.1.3 (2) of EN 1995-1-1, the load-bearing capacity of a multi-shear joint in each shear plane is determined under the assumption that each shear plane is part of several compounds of three elements. Thus, a four-shear joint is calculated as the sum of the two-shear and single-shear joints (Fig.6).
Figure 6. Shear planes in multiple shear joints

\[ F_{v,Rk} = 2F_{v,Rk(b)} + 2F_{v,Rk(c)} \]  
(8) 

\[ F_{v,Rk}(b) = \min \left\{ f_{h,1,k} \cdot t_1 \cdot d, \quad f_{h,1,k} \cdot t_1 \cdot d \left[ 2 + \frac{4M_{y,Rk}}{f_{h,1,k} \cdot d \cdot t_1^2} \right] - 1 + \frac{F_{ax,Rk}}{4} \right\} \]  
(9) 

\[ F_{v,Rk}(c) = \min \left\{ 0.5f_{h,2,k} \cdot t_2 \cdot d, \quad 1.15\sqrt{2M_{y,Rk}f_{h,2,k}d} + \frac{F_{ax,Rk}}{4} \right\} \]  
(10) 

2.3.2. Pedersen

Pedersen [2] proposed a method based on the EYM (European Yield Model) which modified the equations for the case of a joint with four shear planes. The load capacity of a joint, considering a ductile failure, can be defined as:

\[ F_D = F_y n_s n_i n_r \]  
(14)

Where \( F_D \) is the load capacity of the connection for a ductile failure, \( n_s \) is the number of shear planes, and \( F_y \) is the load capacity of each shear plane in a single fastener defined as:
\[
F_y = \min\left\{ \begin{array}{l}
\frac{1}{4} \left( 2t_1 + t_2 \right) d \cdot f_{h,0} \\
\frac{1}{2} t_1 + \frac{1}{4} \sqrt{\frac{2M_y}{d \cdot f_{h,0}}} \cdot d \cdot f_{h,0} \\
\sqrt{4M_y \cdot d \cdot f_{h,0}} \\
\left( \frac{1}{2} t_1 + \frac{1}{2} \sqrt{1 + \frac{2M_y}{d \cdot f_{h,0}}} \right) \cdot d \cdot f_{h,0} \\
\left( \frac{1}{2} t_1 + \frac{1}{2} \sqrt{1 + \frac{2M_y}{d \cdot f_{h,0}}} \right) \cdot d \cdot f_{h,0} \\
\left( \frac{1}{2} t_1 + \frac{1}{2} \sqrt{1 + \frac{2M_y}{d \cdot f_{h,0}}} \right) \cdot d \cdot f_{h,0} \\
\left( \frac{1}{2} t_1 + \frac{1}{2} \sqrt{1 + \frac{2M_y}{d \cdot f_{h,0}}} \right) \cdot d \cdot f_{h,0} \\
\end{array} \right. 
\]

Where \( f_{h,0} \) (embedment strength) and \( M_y \) (plastic bending capacity of a fastener) are those defined in Eurocode 5 [1].

2.3.3. Sawata et al.

Sawata et al. [3] developed a similar method based on the EYM. However, instead of obtaining a value for each shear plane, they proposed a set of equations that provides the effective thickness \( t_{ef} \) of the fastener along the entire connection, which is defined as:

\[
t_{ef} = \min\left\{ \begin{array}{l}
2t_1 + (n_s - 1)t_2 \\
2t_1 \left( 2 + \frac{2}{3} \cdot \frac{M_y}{d \cdot f_{h,0}} \left( \frac{d}{t_1} \right)^2 \right) - 1 + (n_s - 1)t_2 \\
n_s \cdot d \cdot \sqrt{\frac{8}{3} \cdot \frac{M_y}{d \cdot f_{h,0}}} \\
2t_1 + (n_s - 1) \sqrt{\frac{8}{3} \cdot \frac{M_y}{d \cdot f_{h,0}}} \\
d \sqrt{\frac{8}{3} \cdot \frac{M_y}{d \cdot f_{h,0}}} + (n_s - 1)t_2 \\
2t_1 \left( 2 + \frac{2}{3} \cdot \frac{M_y}{d \cdot f_{h,0}} \left( \frac{d}{t_1} \right)^2 \right) - 1 + (n_s - 1)d \sqrt{\frac{8}{3} \cdot \frac{M_y}{d \cdot f_{h,0}}} \\
\end{array} \right. 
\]

The total ductile capacity \( F_D \) of the joint is defined as:

\[
F_D = t_{ef} f_{h,0} d n_s n_r 
\]
2.3.4. Comparison of ductile failure models
In order to verify the accuracy of the two described models, their predictions have been compared with the tests performed by Rossi et al. [16]. As the method of Pedersen [2] is only valid for cases of 4 shear planes, only the nine configurations from Rossi et al. [16] with 2 slotted-in steel plates have been considered. Fig. 7 compares both models with the test results. Both methods achieve a very good correspondence with the test results. As the method from Pedersen [2] is slightly more accurate, it has been used in this work to obtain the ductile capacity of the performed tests.

Figure 7. Comparison between the test results performed by [16] and the predicted values of the methods proposed by [2,3].

3. Calculate and optimize connection

3.1. Input parameters
In order to study the plasticity working of connection with dowels type self-drilling, we built a connection model with variable parameters including: the position of cross-sections in the connection, the number of dowels, the diagram the position of the dowels in the connection (including the characteristic spacing).

Selecting materials of connection in the calculation, Dowel type self- drilling WS-7x133, Ø7 mm, L=133 (mm), f_u=600 N/mm², My=31930 Nmm [11]. Two steel plate thick 5 (mm) with a characteristic yield strength, f_y; of 300 N/mm². Timber structure LVL with geometric dimensions bxh = 140x140(mm²); f_t,0;k=22,5 N/mm². F_v,k=2,6N/mm² [17].

3.2. Determine the optimal position of the steel plates in the connection
It is evident in the formulas of the previous research that the parameters t₁ and t₂ appear, that is, the dependence of the bearing capacity of the connection on the position of the sections (the position of steel plates). With compression-resistant bonds, the external force is symmetrical, the relationship between t₁ and t₂ follow equation:

\[ t_2 = h - 2(t_1 + t_p) \]  

(29)

In the structure of the connection, consider the variation of t₁ with step 5(mm) \((10mm \leq t_1 \leq b=140mm)\). Bearing capacity of a dowel in connections following to Table 2. (Optimize the position of steel plates).
Table 2. Bearing capacity of a dowel in connections

a. Follow Eurocode 05 [1]

| № | t₁ | t₂ | Mode f | Mode g | Mode h | Mode l | Mode m | Fᵥ,Rk(b) | Fᵥ,Rk(c) | Fᵥ,α,5 (kN) |
|---|----|----|--------|--------|--------|--------|--------|----------|----------|-------------|
| 1 | 10 | 110 | 2.03   | 3.81   | 5.85   | 11.16  | 4.14   | 2.03     | 4.14     | 12.34       |
| 2 | 15 | 100 | 3.04   | 3.62   | 5.85   | 10.14  | 4.14   | 3.04     | 4.14     | 14.36       |
| 3 | 20 | 90  | 4.06   | 3.61   | 5.85   | 9.13   | 4.14   | 3.61     | 4.14     | 15.50       |
| 4 | 25 | 80  | 5.07   | 3.72   | 5.85   | 8.11   | 4.14   | 3.72     | 4.14     | 15.73       |
| 5 | 30 | 70  | 6.09   | 3.91   | 5.85   | 7.10   | 4.14   | 3.91     | 4.14     | 16.11       |
| 6 | 35 | 60  | 7.10   | 4.16   | 5.85   | 6.09   | 4.14   | 4.16     | 4.14     | 16.59       |
| 7 | 40 | 50  | 8.11   | 4.44   | 5.85   | 5.07   | 4.14   | 4.44     | 4.14     | 17.16       |
| 8 | 45 | 40  | 9.13   | 4.75   | 5.85   | 4.06   | 4.14   | 4.75     | 4.06     | 17.61       |
| 9 | 50 | 30  | 10.14  | 5.08   | 5.85   | 3.04   | 4.14   | 5.08     | 3.04     | 16.24       |
| 10| 55 | 20  | 11.16  | 5.42   | 5.85   | 2.03   | 4.14   | 5.42     | 2.03     | 14.90       |
| 11| 60 | 10  | 12.17  | 5.78   | 5.85   | 1.01   | 4.14   | 5.78     | 1.01     | 13.59       |

b. Follow Pedersen [2]

| № | mode1 | mode2 | mode3 | mode4 | mode5 | mode6 | mode7 | Fᵥ,α (kN) |
|---|-------|-------|-------|-------|-------|-------|-------|-----------|
| 1 | 6.59  | 7.49  | 5.09  | 3.08  | 3.56  | 8.12  | 3.60  | 12.32     |
| 2 | 6.59  | 6.88  | 5.09  | 3.88  | 4.07  | 7.62  | 3.38  | 13.52     |
| 3 | 6.59  | 6.37  | 5.09  | 4.74  | 4.57  | 7.11  | 3.23  | 12.91     |
| 4 | 6.59  | 5.92  | 5.09  | 5.65  | 5.08  | 6.60  | 3.12  | 12.48     |
| 5 | 6.59  | 5.51  | 5.09  | 6.58  | 5.59  | 6.10  | 3.04  | 12.15     |
| 6 | 6.59  | 5.12  | 5.09  | 7.53  | 6.10  | 5.59  | 2.98  | 11.90     |
| 7 | 6.59  | 4.76  | 5.09  | 8.50  | 6.60  | 5.08  | 2.93  | 11.71     |
| 8 | 6.59  | 4.40  | 5.09  | 9.47  | 7.11  | 4.57  | 2.89  | 11.55     |
| 9 | 6.59  | 4.06  | 5.09  | 10.45 | 7.62  | 4.07  | 2.85  | 11.42     |
| 10| 6.59  | 3.73  | 5.09  | 11.44 | 8.12  | 3.56  | 2.83  | 11.31     |
| 11| 6.59  | 3.40  | 5.09  | 12.43 | 8.63  | 3.05  | 2.81  | 11.22     |

b. Follow Sawata et al.[3]

| № | mode1 | mode2 | mode3 | mode4 | mode5 | mode6 | mode7 | Fᵥ,n (kN) |
|---|-------|-------|-------|-------|-------|-------|-------|-----------|
| 1 | 71.00 | 92.54 | 116.37| 16.53 | 96.04 | 112.87| 8.26  |           |
| 2 | 66.94 | 85.11 | 116.37| 18.55 | 89.95 | 111.53| 9.28  |           |
| 3 | 62.89 | 77.93 | 116.37| 20.58 | 83.86 | 110.44| 10.29 |           |
| 4 | 58.83 | 70.98 | 116.37| 22.61 | 77.78 | 109.57| 11.31 |           |
| 5 | 54.77 | 64.23 | 116.37| 24.64 | 71.69 | 108.91| 12.32 |           |
| 6 | 50.72 | 57.67 | 116.37| 26.67 | 65.61 | 108.43| 13.33 |           |
| 7 | 46.66 | 51.26 | 116.37| 28.70 | 59.52 | 108.10| 14.35 |           |
| 8 | 42.60 | 44.98 | 116.37| 30.73 | 53.44 | 107.92| 15.36 |           |
| 9 | 38.54 | 38.83 | 116.37| 32.75 | 47.35 | 107.85| 16.38 |           |
| 10| 34.49 | 32.78 | 116.37| 34.78 | 41.26 | 107.88| 16.39 |           |
| 11| 30.43 | 26.82 | 116.37| 36.81 | 35.18 | 108.01| 13.41 |           |
In this study, Eurocode 05 standards are used as an optimal basis and compared to other calculation models. The connection is optimal when the bearing capacity of the connection is greatest. In the calculation, get $F_{max}=\max(F_{min})=17.61\text{(kN)}$ corresponding to valuation $t_1=45\text{(mm)}$; $t_2=40\text{(mm)}$ and $F_{max}$ is reached in the plastic failure model $(g+l)$. As a result, each calculation method offers a different optimal connection model with four shear planes. According to [2] derived an optimal connection with the plastic damage model (7) and according to [3] for model (5). According to Eurocode 05 obtained the most reasonable results in the Stress–Deformation state (VAT). Figure 9 shows the results from the calculations.

![Figure 8](image1.png)

**Figure 8.** Chart of bearing capacity of a dowel in connections

In this study, Eurocode 05 standards are used as an optimal basis and compared to other calculation models. The connection is optimal when the bearing capacity of the connection is greatest. In the calculation, get $F_{max}=\max(F_{min})=17.61\text{(kN)}$ corresponding to valuation $t_1=45\text{(mm)}$; $t_2=40\text{(mm)}$ and $F_{max}$ is reached in the plastic failure model $(g+l)$. As a result, each calculation method offers a different optimal connection model with four shear planes. According to [2] derived an optimal connection with the plastic damage model (7) and according to [3] for model (5). According to Eurocode 05 obtained the most reasonable results in the Stress–Deformation state (VAT). Figure 9 shows the results from the calculations.

![Figure 9](image2.png)

**Figure 9.** Bearing capacity of the connection and geometry from the calculation results

### 3.3. Development of calculation models of plastic failure in connection with several shear planes

The calculation equation for the shear strength of a wood connection with dowels is based on the original proposed theory by author Johansen. When increasing the number of steel plates of connection for compressing and stretching loads, the position of the steel plates is symmetrically positioned to ensure load distribution, therefore, the two geometric parameters that affect the bearing capacity of the connection are still equal to $t_1$ and $t_2$ in connection with several steel plates. From the calculation results of clause 3.2, we get the optimal connection types for different models (Fig. 10). When increasing the number of steel plates, perform calculations for each connection type (optimized using the calculation model) in accordance with the two remaining calculation models. According to the calculation models, we perform the calculation process with an increase in the number of steel plates in the joint. The result is a diagram of the value of the bearing capacity of the dowel in the connection.
Determine the optimal number and position dowels in the connection

The brittle calculations for the preliminary design of the calculations model have been performed following the model from Quenneville and Zarnani [12,14], while the ductile failure has been originally calculated with a combination of the model from Eurocode 05 (Optimize the number of dowels, the diagram the position of the dowels in the connection). The following factors were used as input variable factors for conducting a three-factor calculation [18,19]:
- The distance between the dowels along the load $a_1 (X_1)$;
- Number of dowel $n (X_2)$;
- The distance between the rows of dowels $a_2 (X_3)$.

| Units measuring | Symbol | (-) | (0) | (+) | Range of variation |
|------------------|--------|-----|-----|-----|--------------------|
| mm               | $a_1$  | 35  | 50  | 65  | 15                 |
| pieces           | $n$    | 6   | 15  | 24  | 9                  |
| mm               | $a_2$  | 21  | 30  | 39  | 9                  |

The connection model from the calculation results follow Euro code 05. The graph shows the dependence of the number of ($n_{df}$) dowels in the connection (3 rows, 15 nagels) on the step of $a_1$ dowels in a row at 20, 25, 35, 45 dowels.
Fig. 11. Dependence of the quantity dowels from the step of placement of dowels

4. Conclusions
The study provides models for calculating failure plasticity of connections, in which the two models, [2] and [3], are tested experimentally [16]. Euro code 05 [1] ratings compare to these two models. Calculated according to Euro code 05 on the position of the steel plates to the results consistent with the principle of distribution and transmission force. This value is similar in the two methods [2], [3]. In method [3] considering the influence between the cross-sectional on the dowels instead of considering the bearing capacity on each individual cross-section increases the bearing capacity of dowels. However, according to previous research and experimental results, this method is less accurate than that of [2] (fig. 6) Recommended application of the calculation method depending on the number of steel plates in the connection. The applied areas are determined based on the calculation results and characteristics of the methods when developing the calculation formula. The author's recommendations on applying calculation models to Russian standards (clause 3.3) Methods of calculating and optimizing by Euro code 05 standard the connection parameters are given, method of determining the optimum cross-sectional position and the relationship between the parameters of the connection. When calculating the connection under plastic failure and optimizing the connection parameters, there are still conflicting results. In some cases, the connection is still brittle failure. For Eurocode 05, it is necessary to conduct experiments to determine the reliability coefficient of formulas and calculation theory.

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