Development of Limit States Design Method for Joints with Dowel Type Fasteners

Part 3: Basis of European Yield Model Design Procedure
Development of Limit States Design Method for Joints with Dowel Type Fasteners

Basis of European Yield Model Design Procedure

Prepared for the

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by

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Executive Summary

The current design procedure and design values for timber joints with dowel-type fasteners in AS 1720.1 have been based on empirical fit of limited Australian joint test data, and the procedures to determine design values were neither consistent nor fully understood. This means that application of current design values to new products and materials used in timber construction may not be appropriate, and that different safety factors (or levels of reliability) may be obtained from different timber joints in current design (without the intention of the designer).

The aim of this project was to develop a new strength limit states design procedure for timber joints fabricated using Australian pine and dowel-type fasteners that address the limitations of the current joint design procedure and design values in AS 1720.1. The project produced four reports:

- BCE Doc 01/081 Proposed Limit States Design Procedure for Timber Joints with Dowel-Type Fasteners and Australian Pine (Foliente et al. 2002)

The current report (Part 3) presents the background details and related technical information behind the proposed design procedures outlined in BCE Doc 01/081.

The new design procedures are based on the widely accepted European Yield Model (EYM), providing both consistency and flexibility for the design of joints with dowel-type fasteners. Timber design codes in the US, Canada and Europe all base the design of joints with dowel-type fasteners on Johansen’s yield model (Johansen 1949, Larsen 1979). Known in North America as EYM, this mechanics-based model presumes both the fastener and the wood foundation upon which it bears behave as ideal rigid plastic materials. Deformation of joints is not covered by this design procedure.
Tests used to validate the application of the EYM approach and a database of material properties including the timber embedment strength and the yield moment of fasteners for the EYM equations are summarised. A detailed description is given regarding the determination of the component design values for use in the design procedure outlined in BCE Doc 01/081.

A procedure for determination of the yield load from test data is described. These whole joint test results are employed to calibrate the EYM prediction. The calibration is made via the coefficients in the equation of the embedment strength. These coefficients were originally fitted from embedded test data using transformed linear regression fit and analysis of prediction errors. They were then calibrated so that the EYM predicted yield loads for the joints are in good agreement with the measured yield load from the joint tests. Comparisons with nominal joint capacities from the current timber design code AS 1720.1 are also made.

The new design procedures address the limitations of the current code. It has the following features:

- It is based on a comprehensive experimental testing program with matched specimens for joint testing and component/material testing (i.e., embedment strength and fastener strength).
- The EYM-based equations of Whale et al. (1987) were selected based on a comprehensive investigation of various EYM-based equations and comparison with experimental data.
- The equations have been carefully calibrated to Australian test data, obtained from a wide range of joint configuration.
- The proposed design method allows the use of new components/materials (i.e., not limited to just those tested for AS 1720.1) as long as appropriate properties are known or can be obtained by testing.
- The equations can be used for a variety of materials in the one joint, instead of assuming the lowest capacity for all components within a joint.
- The bases for determining component/material properties and establishing the design values of joint with dowel-type fasteners are consistent and well documented.

When implemented, the proposed design procedure would place Australian timber joint design at par with world’s best practice.
1 Introduction

The current joint design procedure and design values in AS 1720.1 ‘Timber Structures, Part 1: Design methods’ (SAA 1997) have two primary limitations: (1) they were based on early American tests which were subsequently revised using an empirical fit of limited Australian test data obtained between 1940 and mid-1970; and (2) the controlling criteria then in use to determine design values are not fully known (i.e., are they related to strength or deformation?) and the load factors vary considerably from one connector type to another for no obvious reasons (Foliente and Leicester 1996). Because of the first limitation, the applicability of current AS 1720.1 joint design values to new products or materials may be questionable. In the last couple of decades, there has been a shift in the timber used in house framing in Australia (from use of unseasoned to seasoned timber, and from predominantly hardwood to predominantly softwood timbers). There has also been introduction of a wider variety of fasteners, new sheathing panels and composite timber products that are not explicitly addressed by the design standard. By default, whether appropriate or not, the existing provisions and design values in AS1720.1 are often used for these new products. Because of the second limitation, it is likely that different safety factors (or levels of reliability) are obtained for different types of timber joints in current design (without the intention of the designer).

The aim of this project was to develop a new strength limit states design procedure for timber joints fabricated using Australian pine and dowel-type fasteners that addresses the limitations of the current joint design procedure and design values in AS 1720.1. Part 1 reviewed the current design practice in Australia, USA, Canada and Europe, and identified issues and experimental parameters that needed to be considered in order to apply the so-called European Yield Model (EYM) for joints with dowel-type fasteners (Foliente and Smith 2000). Based on that literature review and results of a Connector Survey conducted by the then Pine Research Institute (PRI), currently Plantation Timber Research (PTR), an experimental test program was developed which:

1. Validated the applicability of the EYM equations in design of timber joints with Australian Pine species; and
2. Established a database of material properties needed to use EYM-based design equations for joints.
The positioning of these objectives in the overall logic for developing a new Australian design procedure is shown in Fig. 1.1, encircled items 1 and 2.

The Part 2 report (Smith et al. 2000) presented details of the experimental program that included tests on complete joints, embedment specimens and fasteners, and compared experimental results with predictions from EYM-based equations. Alternative predictions were considered based on the EYM equations and derivatives (see Appendix A) as follows:

- Johansen (1949) (referred to as ‘Original EYM’)
- Whale et al. (1987) (referred to as ‘Simplified-1’)
- Blass et al. (1999) (referred to as ‘Simplified-2’), and;
- US National Design Specifications (NDS) for wood construction (AF&PA 1997; 1999) for wood and coach screws only (referred to as ‘NDS-Screw’).

Recommendations were made for the next phase of work that encompassed model simplification, and development of design values and procedures (see Fig. 1.1 encircled items 3, 4 and 5). These recommendations included adoption of the Whale et al. (Simplified-1) EYM equations as the most appropriate for the development of a set of code rules for design of timber joints with dowel-type fasteners and Australian pine.

An accompanying document, CSIRO BCE Doc 01/081 (Foliente et al. 2002), details the set of code rules developed as part of the third stage of this project. The current report (Part 3) presents the basis of the design procedure outlined in CSIRO BCE Doc 01/081.

![Figure 1.1](image-url)
2 Model Selection

The equations of the original EYM model and its derivatives are presented in Appendix A. The Whale et al. (Simplified-1) EYM equations from the Part 2 report (Smith et al 2000) were chosen for the following reasons:

- Whilst all the EYM-type models considered in Part 2 of the project produced conservative estimates of the joints’ ultimate capacity, the Blass et al. (Simplified-2) model was in some instances highly conservative. This occurred when one of the two ‘interpolation’ equations governed. Although the Blass et al.’s equations were the simplest set among the models considered, for some cases their conservative results are difficult to justify.

- The NDS Screw equations did not produce predictions very different to those obtained using the Johansen (Original) or Whale et al. (Simplified-1) equations. The NDS Screw equations are the most complex and gave conservative results.

- The Johansen (Original) and Whale et al. (Simplified-1) EYM equations produced similar predictions for all the joints tested in Part 2 of the project. As calculations are more streamlined using the Whale et al. equations, it seemed appropriate to choose those equations for the recommended design procedure. This mirrors current practice in Canada.

Figures 2.1 to 2.4 show the predictions of the various EYM equations using average values of embedment strength $s_H$ and yield moment $M_Y$, in relationship to the experimental data. Note that the EYM equations predict joint ‘yield’ load and not ultimate load capacity.
**Legend:** Predicted Capacity

- Original EYM
- Simplified-1
- Simplified-2

**Figure 2.1** Nailed joints – Comparing experimental data to predictions:
(a) N4 is a 2-nail joint of 35mm-thick Radiata pine members, and 3.05\(\phi\) x 75mm long nails.
(b) N10 is a 1-nail joint of 45mm-thick Radiata pine members, and a 3.05\(\phi\) x 75mm long nail.
**Legend:** Predicted Capacity

- Original EYM
- Simplified-1
- Simplified-2
- NDS-Screw

---

Figure 2.2 *Type 17 screw joints – Comparing experimental data to predictions:*

(a) S2 is a 1-screw joint of (A) 18mm and (B) 35mm thick Radiata pine members, and a No. 8 x 40mm long type-17 screw with shank $\phi = 3.4\text{mm}$.

(b) S3 is a 1-screw joint of (A) 65mm and (B) 44mm thick Radiata pine members, and a No. 14 x 115mm long type-17 screw with shank $\phi = 5.2\text{mm}$. 
Legend: Predicted Capacity

Original EYM —
Simplified-1 —
Simplified-2 —
NDS-Screw —

Figure 2.3 Coach screw joints – Comparing experimental data to predictions:
(a) CS1 is a 2-coach screw joint of (A) 20mm and (B) 45mm thick Radiata pine members, and 6\(\phi\) x 65mm long coach screw.
(b) CS2S is a 1-coach screw joint of (A) 20mm and (B) 45mm thick Slash pine members, and 6\(\phi\) x 65mm long coach screw.
Figure 2.4 Bolted joints – Comparing experimental data to predictions:
(a) BSS1 is a 1-bolt single shear joint of two 35mm thick Radiata pine members, and an $8\phi$ x 90mm long bolt.
(b) BDS1 is a 1-bolt double shear joint of three Radiata pine members: (A) 35mm, (B) 45mm, (C) 35mm thick, and an $8\phi$ x 130mm long bolt.
The yield modes for two-member joints and three-member joints are shown in Figures 2.5 and 2.6, respectively. Modes I and II correspond to timber bearing failures and modes III and IV to plastic hinge formation in the fastener. Subscript 's' means side member yielding, and 'm' means main member yielding. The characteristic capacity of a joint interface, $Q_{ki}$, for each yield mode is given by the Whale et al. (Simplified-1) EYM equations, as shown below:

2-Member joints

$$Q_{ki} = s_{H} d l$$

$$Q_{ki} = s_{H} d l$$

$$\begin{align*}
Q_{ki} &= s_{H} d l \\
&= \left\{ \begin{array}{ll}
1.0 & \text{I}_s \\
\alpha \beta & \text{I}_m \\
\frac{1 + \alpha \beta}{5} & \text{II} \\
\frac{\beta M_{Y}}{(1 + \beta) s_{H} d l^2} + 0.2 & \text{III}_s \\
\frac{\beta M_{Y}}{(1 + \beta) s_{H} d l^2} + \frac{\alpha}{5} & \text{III}_m \\
\frac{4 \beta M_{Y}}{s_{H} d l^2 (1 + \beta)} & \text{IV}
\end{array} \right. \\
\min &
\end{align*}$$

(2.1)

3-Member Symmetric joints

$$Q_{ki} = s_{H} d l$$

$$Q_{ki} = s_{H} d l$$

$$\begin{align*}
Q_{ki} &= s_{H} d l \\
&= \left\{ \begin{array}{ll}
1.0 & \text{I}_s \\
0.5 \alpha \beta & \text{I}_m \\
\frac{\beta M_{Y}}{(1 + \beta) s_{H} d l^2} + 0.2 & \text{III} \\
\frac{4 \beta M_{Y}}{s_{H} d l^2 (1 + \beta)} & \text{IV}
\end{array} \right. \\
\min &
\end{align*}$$

(2.2)

where terms are defined, with reference to Figures 2.7 and 2.8, as follows:

- $s_{H}$ = characteristic embedment strength of the side member (in a 3-member joint, use the minimum side member $s_{H}$).
- $d$ = diameter of fastener (shank diameter in the case of threaded fasteners)
- $l$ = side member thickness as defined in Figure 2.7 for a 2-member joint and in Figure 2.8 for a 3-member joint.
- $\alpha$ = ratio of the penetration into the main member to the thickness of the side member for a 2-member joint, and as defined in Figure 2.8 for a 3-member joint.
- $\beta$ = ratio of $s_{H}$ of the main member to $s_{H}$ of the side member (in a 3-member joint, use maximum side member $s_{H}$)
\( M_Y \) is the characteristic yield moment of fastener as determined by bending tests or as calculated from tension test results.

**Figure 2.5**  *Yield modes for two-member joints*

**Figure 2.6**  *Yield modes for three-member joints*
Figure 2.7 Illustration of 2-member joint definitions

Figure 2.8 Illustration of 3-member joint definitions
3 Determining Component Capacities

3.1 Timber Embedment Strength $s_H$

In order to estimate the embedment strength of a timber component within a joint, a prediction equation was sought. Based on earlier work (Whale and Smith 1989) the form of the embedment strength equation was assumed to be

$$s_H = a \rho^b d^c \quad \text{(MPa)} \quad (3.1)$$

where

- $\rho = \text{density of wood (kg/m}^3\text{)}$
- $d = \text{shank diameter of fastener (mm)}$
- $a, b, \text{ and } c \text{ are curve fitting coefficients.}$

A regression analysis was performed in order to determine coefficients $a, b$ and $c$ using all individual test replicate data for $s_H$ and $\rho$ for the regression equation $\log s_H = a + b \log \rho + c \log d$. The average diameter for each set of embedment test replicates was calculated and assumed for $d$. Axum Version 6.0 (MathSoft, 1999) – a software for data analysis - was used to perform the regression analysis.

Figures 3.1a and 3.1b show the test set-up for obtaining the embedment strength.
**Figure 3.1a** Embedment test (schematic)

**Figure 3.1b** Embedment test apparatus and test arrangement: (a) apparatus for testing small specimens (load parallel to grain) (b) apparatus for testing large specimens (load parallel to grain) (c) apparatus for testing large specimens (load perpendicular to grain)
Figure 3.2 illustrates the method used for determining embedment strength. This procedure was used to obtain the basic trend for nails, screws, coach screws, bolts loaded parallel to grain (hereafter called ‘bolts parallel’) and bolts loaded perpendicular to grain (hereafter called ‘bolts perpendicular’). The regression analyses determine the mean coefficients $a_m$, $b_m$ and $c_m$, which are used with mean values of $\rho$ and $d$ to determine a mean value for $s_{th}$. The results of this analysis are in Table 3.1.

Table 3.1 Results of regression analysis showing the mean coefficients giving the basic trend.

<table>
<thead>
<tr>
<th>Fastener type</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_m$</td>
</tr>
<tr>
<td>Nails</td>
<td>0.0176</td>
</tr>
<tr>
<td>Screws</td>
<td>0.111</td>
</tr>
<tr>
<td>Coach screws</td>
<td>0.165</td>
</tr>
<tr>
<td>Bolts parallel</td>
<td>0.0965</td>
</tr>
<tr>
<td>Bolts perpendicular</td>
<td>1.98</td>
</tr>
</tbody>
</table>
The goodness of the fit was evaluated by analysing the prediction error. The prediction error was defined as follows:

\[
prediction \ error = \left( \frac{\text{predicted} - \text{tested}}{\text{tested}} \right) \times 100 \% \tag{3.2}
\]

The predicted $s_H$ by Eq (3.1) with the coefficients listed in Table 3.1 were compared to the average tested $s_H$ values for each type of fasteners. The results, including the average, the standard deviation, the maximum and the minimum values of the prediction errors for each type of fastener are shown in Table 3.2.

**Table 3.2 Results of the analysis of prediction error**

<table>
<thead>
<tr>
<th>Fastener type</th>
<th>Prediction error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Nails</td>
<td>-0.4</td>
</tr>
<tr>
<td>Screws</td>
<td>4.2</td>
</tr>
<tr>
<td>Coach screws</td>
<td>-2.0</td>
</tr>
<tr>
<td>Bolts parallel</td>
<td>-1.6</td>
</tr>
<tr>
<td>Bolts perpendicular</td>
<td>-4.9</td>
</tr>
</tbody>
</table>

An ideal fit would give an average prediction error of $\pm 2\%$, minimum and maximum error within $\pm 15\%$ with $90\%$ of prediction within $\pm 10\%$. The results shown in Table 3.2 are not unreasonable – considering the range of differences in the joint system, detailed nature of joint action and predominant failure modes - and for practical design purposes would be acceptable (note that the design values are eventually taken from the lower 5th percentile range).

When observing the results of embedment strength calculations for bolts shown in Tables B5 and B6 of the accompanying document, CSIRO BCE Doc. 01/081 (Foliente et al, 2002), it is interesting to compare bolts parallel with bolts perpendicular to grain. For the larger diameter fasteners, the embedment strengths for bolts perpendicular are significantly less than for bolts parallel to grain. This difference reduces as the fastener diameter reduces. In one case (8 mm diameter, JD5), the embedment strength of the bolt perpendicular is greater than that for the bolt parallel. With reference to the embedment strength tests given in Smith et al,
2000, the ratio of the average values of embedment strength perpendicular to embedment strength parallel decrease with increasing bolt diameter as shown in Figure 3.3 below.

![Figure 3.3](image-url)

**Figure 3.3** Effect of bolt diameter on the ratio between embedment strengths observed when loaded perpendicular and parallel to grain

When characteristic values were subsequently calculated (a procedure that takes into account variability in test data), this effect was further compounded to the point where the 8 mm diameter, JD5 embedment strength perpendicular was greater than the parallel embedment strength.

Embedment test data from the testing reported (Smith et al. 2000) showed that generally the embedment strength when the thread is bearing against the timber is slightly higher than when the shank of the fastener is bearing against the timber. The embedment strength in this case was calculated assuming the shank diameter for the bearing area for both the thread bearing and shank bearing on the timber. It is therefore slightly conservative to assume that the embedment strength for the threaded portion of the fastener is the same as for the shank portion.
3.2 Fastener Yield Moment $M_Y$

3.2.1 Characteristic Yield Moment

The average $M_Y$ for each set of bending test replicates was calculated. The characteristic value for $M_Y$ was taken as the 5th percentile value of the test results calculated assuming a normal distribution. The 5th percentile of the yield moment, $M_{Y,0.05}$, was calculated as

$$M_{Y,0.05} = M_{Y,\text{mean}} (1 - 1.645 V)$$  

(3.3)

where $M_{Y,\text{mean}}$ is the average $M_Y$ for each set of bending test replicates; $V$ is the assumed coefficient of variation, taken as 0.08 based on the average coefficient of variation observed in the $M_Y$ test results for all fasteners (Smith et al. 2000).

Figures 3.4 and 3.5 show the test set-up for obtaining the yield moment. Figure 3.6 illustrates the method for determining yield moment.

![Figure 3.4 Principle of bending apparatus for small diameter fasteners](image-url)
Figure 3.5  Bending apparatus for small diameter (d ≤ 8mm) fasteners
In the case of fasteners that were too large \((d > 8\text{mm})\) to fit into the CSIRO bending test rig, tension tests according to AS/NZS 4291.1 (SAA 1995) were carried out and the yield moment calculated using the following formula (Whale and Smith 1987, Ehlbeck and Larsen 1993)

\[
M_Y = \left( \sigma_y + \sigma_{ult} \right) d_{shank}^3 / 12 \tag{3.4}
\]

where \(\sigma_y\) is the yield stress, \(\sigma_{ult}\) is the ultimate stress and \(d_{shank}\) is the diameter in the shank (unthreaded portion) of the fastener.

Based on previous studies (AF&PA 1999) and checks with the configuration of Australian bolts (SAA/SNZ, 1996a) and type-17 screws (SAA 2002), \(M_Y\) for the threaded portion was assumed to be 0.75 times the calculated value for the shank of bolts and type-17 screws. Given the relatively tight tolerances on the minimum thread diameter of bolts and type-17 screws in the standards, the factor of 0.75 should be adequate for fasteners produced in accordance with those standards.

For coach screws, \(M_Y\) for the threaded portion of the fastener was assumed to be 0.5 times the calculated value for the shank. This assumption was based on the average geometry of coach screws used in the CSIRO test program (Smith et al. 2000). But it should be noted that the minimum thread diameter of those coach screws was greater than the minimum allowed according to SAA/SNZ (1996b). It is therefore possible that coach screws may be produced in accordance with the Standard that have a threaded portion \(M_Y\) value less than...
that given in the proposed design procedure. Due to the broad tolerances for the minimum thread diameter in the standard, the properties of the coach screws that are used in Australia construction should be monitored to ensure that minimum thread diameters are not significantly less than those observed during the CSIRO tests.

Figure 3.7 shows tension test specimens for the bolts and coach screws that were too large to fit into the bending test rig. Figure 3.8 depicts the yield and ultimate stress levels used in Eq. (3.4) to determine yield moment.
Figure 3.7 Typical tension test specimens for large bolts, and large coach screws (d > 8mm)

Figure 3.8 Interpretation of tension test data for large bolts and large coach screws
3.2.2 Validation of the conversion of tension test results to the yield moment

The approach used to validate the conversion of tension test results to \( M_Y \) values in Eq. (3.4) was to compare \( M_Y \) values obtained by tension tests to those obtained by bending test. Bending tests on a range of Australian produced bolts and coach bolts were performed at the University of Karlsruhe, Germany on their bending test machine. The University of Karlsruhe bending test machine was similar to the one constructed and used at CSIRO but had the capacity to test fasteners up to 20 mm in diameter.

Four types of Australian fasteners, including coach screws with nominal diameters of 20 and 12 mm, and bolts with nominal diameters of 20 and 16 mm were tested by the bending test machine at the University of Karlsruhe. The number of replicates for each type of fastener was 3. The measured yield moments were then averaged to give the \( M_Y \) result for each type of the fasteners.

In a parallel experiment, tension tests of the same types of fasteners were carried out at CSIRO. The number of replicates for each type of fastener was also 3. Yield loads were calculated by Eq. (3.4) and then averaged over the 3 replicates for each type of fastener.

Table 3.3 provides the comparison of the average \( M_Y \) results for the bolts and coach screws tested from the bending test apparatus at University of Karlsruhe with those calculated from tension tests' results at CSIRO. The % difference was calculated as:

\[
\text{Difference} = \left( \frac{\text{calculated} - \text{tested}}{\text{tested}} \right) \times 100 \quad (\%) \quad (3.5)
\]

On average, the yield moments \( M_Y \) from Karlsruhe’s bending tests are about 20% higher than those calculated from tension tests. It is noted that the thread of the fastener was subjected to bending in the Karlsruhe bending tests, so the minor diameter of the thread was used in the calculation of \( M_Y \) by Eq.(3.4). This would underestimate \( M_Y \) because the stress area of thread (which should be used to calculate \( M_Y \)) is greater than minor thread diameter area. The stress area of the threads for the tested fasteners was not readily available.
Table 3.3  Comparison of average $M_Y$ results derived from bending test with those derived from tension tests.

<table>
<thead>
<tr>
<th>Fastener type</th>
<th>Nominal diameter (mm)</th>
<th>$M_Y$ calculated from tension tests at CSIRO (Nmm)</th>
<th>$M_Y$ tested from Karlsruhe’s bending test (Nmm)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coach Screw</td>
<td>20</td>
<td>238509</td>
<td>317000</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>64614</td>
<td>70000</td>
<td>8</td>
</tr>
<tr>
<td>Bolt</td>
<td>20</td>
<td>507747</td>
<td>657250</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>222304</td>
<td>283600</td>
<td>22</td>
</tr>
</tbody>
</table>

The bolts tested in tension were machined quite significantly to reduce the cross-section as required for testing according to AS/NZS4291.1 (SAA 1995). A possible reason for the discrepancy is the removal of hardened outer layers of steel in large diameter bolts. As those are the layers that would do most work in bending, the negative effect on strength could be significant. Although this would seem to fit with the diameter dependence of the error, whether it is a correct explanation depends on how the bolts were actually manufactured.

A check on the accuracy of the CSIRO bending test apparatus for small diameter fasteners was also undertaken by comparing test results from the CSIRO bending test apparatus with those obtained from the University of Karlsruhe bending test apparatus for 8 mm bolts. Number of the test replicates was 5. The average $M_Y$ values for an 8 mm diameter bolt measured in the CSIRO and University of Karlsruhe bending test apparatus were 33928 Nmm and 35080 Nmm, respectively, which were only 3% different from each other. This very small difference proved the accuracy of the CSIRO bending test apparatus.

In summary, it is concluded that for large diameter fasteners ($d > 8$mm), the tension test procedure and the conversion equation in Eq.(3.4) provide a simple and effective method to estimate their yield moment. And for small diameter fasteners ($d \leq 8$mm), yield moment can be obtained directly using the CSIRO bending test apparatus.
4. Calibration/Validation of Simplified Equations and Component Capacities

4.1 Measured Yield Load from the Joint Tests

The experimental program in the Part 2 Report (Smith et al. 2000) included a total of 360 complete joint system tests with materials matched with those used in the component tests described in the previous Section. The ultimate load $P_u$ and yield load $P_y$ for all individual joints were determined. From the load-displacement plot of each joint, they were obtained as follows:

- The ultimate load, $P_u$, is taken as the maximum load.
- The yield load, $P_y$, is taken as the load co-ordinate at the intersection of a tangent representing maximum slope within the initial slip region, and a tangent representing the stabilised slope region of the load-slip curve that follows the first onset of reduced stiffness (Figure 4.1). Any irregularities in the load-slip curve close to when load equals zero are neglected while fitting the tangent in the initial slip region. It is possible for the load-slip curve to recover stiffness after the region of stabilised slope. However, that is due to gap closure, friction and string effects and is not reflective of the yield point which normally will be the load level at which a plastic hinge(s) forms in the fastener(s). The length of the stabilised region can be quite small but this does not mean that it should be discounted. Figure 4.1 shows four examples of application/implementation of this procedure for different types of load-displacement plots.

Normalised characteristic loads $P_{u\text{,norm}}$ and $P_{y\text{,norm}}$ were calculated for each set of joint test replicates, using the following equations:

$$P_k = \left[ 1 - \left( \frac{2.7V}{\sqrt{n}} \right) \right] P_{0.05}$$

(4.1)

$$P_{\text{norm}} = (0.85 - 0.95V) P_k / 0.8$$

(4.2)

where $P_{0.05}$ is the fifth percentile value of measured data, $P_k$ is characteristic load, $n$ is number of joint test replicates, and $V$ is the coefficient of variation of the measured data. These equations are recognised in engineering statistics and are consistent with equations
proposed for the draft of the Australian/New Zealand Standard for timber connections 'Methods for evaluation of mechanical joint systems' (SAA 1998, Bryant and Hunt 1999).

The nominal capacities (i.e. without application of capacity reduction factor $\phi$) for each joint test configuration were also calculated in accordance with AS 1720.1 (SAA, 1997) for reference.

![Diagram](image)

**Figure 4.1** Determination of Yield Load for 4 different types of load-displacement curves
4.2 Calculated Yield Load by the EYM Equations

The group fifth percentile density $\bar{\rho}_{0.05}$ for each set of test replicates was used for the calculation. It is assumed that:

- The densities are normally distributed.
- The coefficient of variation ($V$) is 10%, based on the coefficients of variation of the density of wood members in the embedment tests (Smith et al. 2000).
- The mean density $\bar{\rho}_{\text{mean}}$ is equal to the minimum group mean density from Table 1 of AS 1649 (SAA 2001).

With these assumptions, the fifth-percentile density $\bar{\rho}_{0.05}$ can be computed as

$$\bar{\rho}_{0.05} = \bar{\rho}_{\text{mean}} (1 - 1.645 V) \quad (4.3)$$

The fifth-percentile densities for JD3, JD4, and JD5 joint groups are determined in Table 4.1. The average diameter of the fasteners was calculated for each set of joint test replicates and taken as $d$.

Table 4.1 Determination of the fifth percentile density for joint groups

<table>
<thead>
<tr>
<th>Joint group</th>
<th>Group mean density range (kg/m³) (Table 1, AS1649)</th>
<th>Group mean density, $\bar{\rho}_{\text{mean}}$ (kg/m³)</th>
<th>Group fifth-percentile density $\bar{\rho}_{0.05}$ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JD3</td>
<td>600 to 745</td>
<td>600</td>
<td>500</td>
</tr>
<tr>
<td>JD4</td>
<td>480 to 595</td>
<td>480</td>
<td>400</td>
</tr>
<tr>
<td>JD5</td>
<td>380 to 475</td>
<td>380</td>
<td>320</td>
</tr>
</tbody>
</table>

The characteristic embedded strength $s_H$ was then calculated by Eq. (3.1), using the coefficients $a_m$, $b_m$, and $c_m$ listed in Table 3.1, and the group fifth percentile density $\bar{\rho}_{0.05}$ and the average diameter $d$. Smith and Foliente (2001) have shown that it is appropriate to use the characteristic $s_H$ to predict the characteristic joint strength.

The calculated characteristic yield load $P_{y,EYM}$ was then evaluated as the characteristic capacity of a joint interface $Q_{ki}$ in the EYM equations (2.1) and (2.2), using the characteristic $s_H$ as computed above and the characteristic $M_y$ derived in Section 3.2 for each joint test configuration.
4.3 Calibration

The characteristic yield loads $P_{y,norm}$ determined from the actual joint tests as in Section 4.1 were compared with the calculated $P_{y,EYM}$ determined by EYM model as in Section 4.2. Comparisons of the calculated $P_{y,EYM}$ with the nominal capacity determined by AS 1720.1 were also made for reference. These comparisons are shown on plots (a) and (b), respectively, in Figures 4.2 to 4.6 for 5 different types of fasteners. In plots (a) of these figures, the location of a point relative to the diagonal indicates if the calculated value is conservative or not. The conservative region is above the diagonal, and the non-conservative region is shaded under the diagonal. It can be seen that the calculated and the joint test’s yield loads were in generally good agreement, but in some cases, minor calibrations may be needed.

The calibration was made by first rounding and then adjusting (if necessary) the coefficients $a_m$, $b_m$, and $c_m$ to give joint-calibrated coefficients $a_j$, $b_j$, and $c_j$ to be used in Eq. (3.1). The target of the calibration was to match the calculated $P_{y,EYM}$ to the joint test’s normalised characteristic $P_{y,norm}$ (left plots in Figs 4.2 to 4.6). The calculated $P_{y,EYM}$ was also compared to the AS 1720.1’s nominal capacities (right plots in Figs 4.2 to 4.6). The final results of the calibrations for different joint configurations are shown in Tables 4.2 to 4.6 and plots (b) in Figs. 4.2 to 4.6. The new joint-calibrated coefficients $a_j$, $b_j$ and $c_j$ are listed in Table 4.7.

Some remarks on the calibration process are given below:

- In the calibration for nails, the coefficients were adjusted to bring the calculated $P_{y,EYM}$ down to the joint test’s $P_{y,norm}$ values, tempered somewhat by the fact that the existing AS 1720.1 values were consistently well above both the $P_{y,norm}$ and $P_{y,EYM}$ values (except in one case where the AS 1720.1’s value was 2% below the $P_{y,norm}$ value). The ratio of $P_{y,EYM}$ to AS 1720.1’s nominal capacity was relatively consistent indicating that the empirically based AS 1720.1 system gave similar trends to the mechanics based EYM system. In order to be consistent with all dowel fastener types, the $P_{y,EYM}$ values had to be brought back toward the joint test’s $P_{y,norm}$ values. The calibration result is in Table 4.2 and Figure 4.2(b).

- Calibration for the screw fasteners was less certain because of significant fluctuations of test results about the EYM predictions and a relatively small sample size. Due to dimensional considerations the first three screw test configurations could not strictly be given an AS 1720.1 capacity (one was given, ignoring the rule nominating the joints as
non-load bearing). A slightly conservative calibration was given for the above reasons. The calibration result is in Table 4.3 and Figure 4.3(b).

- The EYM prediction $P_{y,EYM}$ was calibrated to $P_{y,norm}$ for coach screws. The calibration result is in Table 4.4 and Figure 4.4(b). Very small adjustments were made for this case.

- Comments regarding the calibration for nails apply similarly to the calibration for bolts loaded parallel to grain. The calibration result is in Table 4.5 and Figure 4.5(b).

- The EYM prediction $P_{y,EYM}$ was calibrated to $P_{y,norm}$ for bolts loaded perpendicular to grain. The calibration result is in Table 4.6 and Figure 4.6(b).

Tables 4.2 to 4.5 show the result of the calibration for each type of fastener. Each table provides the calculated $P_{y,EYM}$, the AS1720.1 nominal capacity and the normalised characteristic loads $P_{u,norm}$ and $P_{y,norm}$ of the joint tests for each set of the test replicates. Comparisons between these values are then made in terms of their ratios to each other. The comparisons are then summarised by computing the average, minimum and maximum of these ratios. These values are considered during the calibration process, and the main target is to bring the average of the ratio $P_{y,EYM} / P_{y,norm}$ as close to 1 as possible. It is also noted that for all types of fasteners except for the type-17 screw, the AS 1720.1 nominal capacity is higher than the joint test $P_{y,norm}$.

Figures 4.7 to 4.11 show the joint tests' load-displacement curves and their corresponding calculated $P_{y,EYM}$, nominal capacity from AS1720.1, and normalised characteristic yield load $P_{y,norm}$ for some typical groups of joint configurations. It is seen that the calculated $P_{y,EYM}$ values consistently provide reasonable estimates of the joints' yield load. AS 1720.1 can be either overly conservative [as in Fig.4.8(a) for screw joint S1] or dangerously non-conservative [as in Figs.4.9(b), 4.10(a) and (b) for coach screw joint CS3 and bolted joints BSS1 and BDS3, respectively].

In summary, the set of slightly adjusted coefficients for $s_H$ calculation as presented in Table 4.7 provides $P_{y,EYM}$ values that are, for practical design purposes, consistently good enough compared to test data.

Thus, the final $s_H$ equations for calculation of $P_{y,EYM}$ are:

- For nails,

$$s_H = 0.02 \rho^{1.2} d^{-0.2} \quad (4.4)$$
• For Type 17 screws,

\[ s_H = 0.1 \rho^{1.1} d^{-1.0} \] (4.5)

• For coach screws,

\[ s_H = 0.2 \rho^{0.9} d^{-0.3} \] (4.6)

• For bolts parallel to grain,

\[ s_H = 0.1 \rho d^{-0.2} \] (4.7)

• For bolts perpendicular to grain,

\[ s_H = 1.9 \rho^{0.6} d^{-0.5} \] (4.8)

where

- \( s_H \) = characteristic embedment strength, in MPa
- \( \rho \) = group 5\(^{th}\) percentile air dry density of timber at 12 % moisture content (see Table 4.1), in kg/m\(^3\)
- \( d \) = diameter of fastener (shank diameter in the case of threaded fasteners), in mm.
## Table 4.2 Result of calibration for nail joints

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Fastener diameter $d$ (mm)</th>
<th>Joint group</th>
<th>Calculated $P_{Y,EYM}$</th>
<th>AS 1720.1’s Nominal Capacity</th>
<th>Joint Tests</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$P_{Y,norm}$</td>
<td>$P_{U,norm}$</td>
<td>$P_{Y,EYM} / P_{Y,norm}$</td>
<td>$P_{Y,EYM} / AS1720.1$</td>
</tr>
<tr>
<td>N1</td>
<td>2.8</td>
<td>JD5</td>
<td>471</td>
<td>545</td>
<td>333</td>
<td>588</td>
</tr>
<tr>
<td>N2</td>
<td>2.8</td>
<td>JD4</td>
<td>542</td>
<td>665</td>
<td>358</td>
<td>558</td>
</tr>
<tr>
<td>N3</td>
<td>3.15</td>
<td>JD5</td>
<td>617</td>
<td>680</td>
<td>368</td>
<td>798</td>
</tr>
<tr>
<td>N4</td>
<td>3.05</td>
<td>JD5</td>
<td>589</td>
<td>641</td>
<td>652</td>
<td>940</td>
</tr>
<tr>
<td>N5</td>
<td>3.05</td>
<td>JD4</td>
<td>678</td>
<td>769</td>
<td>597</td>
<td>793</td>
</tr>
<tr>
<td>N4S</td>
<td>3.05</td>
<td>JD4</td>
<td>678</td>
<td>769</td>
<td>558</td>
<td>534</td>
</tr>
<tr>
<td>N5S</td>
<td>3.05</td>
<td>JD3</td>
<td>775</td>
<td>1076</td>
<td>637</td>
<td>890</td>
</tr>
<tr>
<td>N6</td>
<td>3.75</td>
<td>JD5</td>
<td>809</td>
<td>915</td>
<td>714</td>
<td>1210</td>
</tr>
<tr>
<td>N7</td>
<td>4.5</td>
<td>JD5</td>
<td>1056</td>
<td>1255</td>
<td>1163</td>
<td>1089</td>
</tr>
<tr>
<td>N8</td>
<td>3.15</td>
<td>JD5</td>
<td>617</td>
<td>680</td>
<td>476</td>
<td>585</td>
</tr>
<tr>
<td>N9</td>
<td>3.05</td>
<td>JD5</td>
<td>617</td>
<td>641</td>
<td>567</td>
<td>890</td>
</tr>
<tr>
<td>N10</td>
<td>3.05</td>
<td>JD4</td>
<td>678</td>
<td>769</td>
<td>660</td>
<td>929</td>
</tr>
</tbody>
</table>

|         | Average | 1.21 | 0.87 | 0.75 |
|         | Max     | 1.68 | 0.96 | 1.02 |
|         | Min     | 0.90 | 0.72 | 0.54 |

**Notes:**
- Tests N1 to N7 were performed using two nail joints. Values shown are reduced to single nail values.
- All joint tests were 2-member
### Table 4.3 Result of calibration for type-17 screw joints

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Fastener diameter d (mm)</th>
<th>Joint group</th>
<th>Calculated $P_{y,EYM}$</th>
<th>Joint Tests</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>AS 1720.1’s Nominal Capacity</td>
<td>$P_{y,norm}$</td>
<td>$P_{u,norm}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AS 1720</td>
<td>AS1720</td>
</tr>
<tr>
<td>S1</td>
<td>3.40 JD5</td>
<td>482</td>
<td>361 (NLB)</td>
<td>444</td>
<td>492</td>
</tr>
<tr>
<td>S2</td>
<td>3.80 JD5</td>
<td>565</td>
<td>523 (NLB)</td>
<td>1641</td>
<td>2049</td>
</tr>
<tr>
<td>S2S</td>
<td>3.80 JD5</td>
<td>565</td>
<td>523 (NLB)</td>
<td>1013</td>
<td>1566</td>
</tr>
<tr>
<td>S2S E</td>
<td>3.40 JD4</td>
<td>702</td>
<td>656</td>
<td>316</td>
<td>308</td>
</tr>
<tr>
<td>S3</td>
<td>5.20 JD4</td>
<td>1531</td>
<td>3103</td>
<td>1537</td>
<td>3583</td>
</tr>
</tbody>
</table>

**Average**

<table>
<thead>
<tr>
<th></th>
<th>$P_{y,norm}$</th>
<th>$P_{u,norm}$</th>
<th>$P_{y,EYM} / P_{y,norm}$</th>
<th>$P_{y,EYM} / P_{y,norm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>2.22</td>
<td>1.33</td>
<td>3.14</td>
<td>3.14</td>
</tr>
<tr>
<td>Min</td>
<td>0.34</td>
<td>0.49</td>
<td>0.48</td>
<td>0.48</td>
</tr>
</tbody>
</table>

**Notes:**
- ‘NLB’ denotes that strict interpretation of AS 1720.1 would give this fastener configuration as non-load bearing.
- All joint tests were 2-member

### Table 4.4 Result of calibration for coach screw joints

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Fastener diameter d (mm)</th>
<th>Joint group</th>
<th>Calculated $P_{y,EYM}$</th>
<th>Joint Tests</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>AS 1720.1’s Nominal Capacity</td>
<td>$P_{y,norm}$</td>
<td>$P_{u,norm}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AS1720</td>
<td>AS1720</td>
</tr>
<tr>
<td>CS1</td>
<td>5.50 JD4</td>
<td>1614</td>
<td>2100</td>
<td>1784</td>
<td>1428</td>
</tr>
<tr>
<td>CS2</td>
<td>5.50 JD5</td>
<td>1401</td>
<td>1690</td>
<td>968</td>
<td>2796</td>
</tr>
<tr>
<td>CS2 S</td>
<td>5.50 JD4</td>
<td>1614</td>
<td>2100</td>
<td>1646</td>
<td>2711</td>
</tr>
<tr>
<td>CS3</td>
<td>11.50 JD4</td>
<td>5736</td>
<td>7400</td>
<td>4663</td>
<td>7203</td>
</tr>
<tr>
<td>CS4</td>
<td>18.70 JD4</td>
<td>12844</td>
<td>20400</td>
<td>8967</td>
<td>9850</td>
</tr>
</tbody>
</table>

**Average**

<table>
<thead>
<tr>
<th></th>
<th>$P_{y,norm}$</th>
<th>$P_{u,norm}$</th>
<th>$P_{y,EYM} / P_{y,norm}$</th>
<th>$P_{y,EYM} / P_{y,norm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>1.45</td>
<td>0.83</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Min</td>
<td>0.90</td>
<td>0.63</td>
<td>0.44</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**Notes:**
- Test CS1 was performed using a two-screw joint. Values shown are reduced to single screw values.
- All joint tests were 2-member
Table 4.5  Result of calibration for bolts joints with member loaded parallel to grain

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Fastener diameter (d) (mm)</th>
<th>Joint group</th>
<th>Calculated (P_{y,EM})</th>
<th>AS 1720.1’s Nominal Capacity</th>
<th>Joint Tests</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(P_{y,\text{norm}})</td>
<td>(P_{u,\text{norm}})</td>
<td>(P_{y,EM}/P_{y,\text{norm}})</td>
<td>(P_{y,EM}/P_{y,\text{norm}})</td>
</tr>
<tr>
<td>BSS 1</td>
<td>7.00</td>
<td>JD4</td>
<td>2663</td>
<td>4350</td>
<td>2402</td>
<td>3636</td>
</tr>
<tr>
<td>BSS 2</td>
<td>7.00</td>
<td>JD5</td>
<td>2108</td>
<td>3650</td>
<td>1582</td>
<td>4501</td>
</tr>
<tr>
<td>BSS 2S</td>
<td>7.00</td>
<td>JD4</td>
<td>2663</td>
<td>4350</td>
<td>848</td>
<td>722</td>
</tr>
<tr>
<td>BDS 1</td>
<td>7.00</td>
<td>JD5</td>
<td>5087</td>
<td>7800</td>
<td>5267</td>
<td>8550</td>
</tr>
<tr>
<td>BDS 2</td>
<td>7.00</td>
<td>JD5</td>
<td>5087</td>
<td>7800</td>
<td>3717</td>
<td>6691</td>
</tr>
<tr>
<td>BDS 3</td>
<td>14.75</td>
<td>JD5</td>
<td>12302</td>
<td>20200</td>
<td>15598</td>
<td>16263</td>
</tr>
<tr>
<td>BDS 4</td>
<td>18.30</td>
<td>JD4</td>
<td>24621</td>
<td>42800</td>
<td>23011</td>
<td>20355</td>
</tr>
</tbody>
</table>

Average: 1.40 0.61 0.52
Max: 3.14 0.65 0.77
Min: 0.79 0.58 0.20

Notes:
- Splitting occurred in 5/10 joint tests for the BDS4 configuration
- Splitting occurred in 9/10 joint tests for the BSS2S configuration
Table 4.6 Result of calibration for bolts joints with member loaded perpendicular to grain

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Fastener diameter ( d ) (mm)</th>
<th>Joint group</th>
<th>Calculated ( P_{Y, EYM} )</th>
<th>AS 1720.1’s Nominal Capacity</th>
<th>Joint Tests</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>( P_{Y,norm} )</td>
<td>( P_{u,norm} )</td>
<td>( P_{Y,EYM} ) / ( P_{Y,norm} )</td>
<td>( P_{Y,EYM} ) / ( P_{Y,norm} )</td>
</tr>
<tr>
<td>BSS 3</td>
<td>14.75</td>
<td>JD5</td>
<td>3238</td>
<td>4900</td>
<td>5692</td>
<td>15492</td>
</tr>
<tr>
<td>BSS 4</td>
<td>20.10</td>
<td>JD4</td>
<td>7455</td>
<td>15300</td>
<td>8356</td>
<td>15501</td>
</tr>
<tr>
<td>BDS 5</td>
<td>7.03</td>
<td>JD4</td>
<td>5871</td>
<td>7000</td>
<td>3806</td>
<td>8095</td>
</tr>
<tr>
<td>BDS 6</td>
<td>7.03</td>
<td>JD5</td>
<td>5311</td>
<td>5000</td>
<td>2994</td>
<td>6479</td>
</tr>
<tr>
<td>BDS 6S</td>
<td>7.03</td>
<td>JD4</td>
<td>5871</td>
<td>7000</td>
<td>4946</td>
<td>6789</td>
</tr>
<tr>
<td>BDS 7</td>
<td>14.75</td>
<td>JD5</td>
<td>10409</td>
<td>9800</td>
<td>14420</td>
<td>15838</td>
</tr>
<tr>
<td>BDS 8</td>
<td>18.30</td>
<td>JD4</td>
<td>17785</td>
<td>30600</td>
<td>18447</td>
<td>33628</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.09</td>
<td>1.77</td>
<td>0.57</td>
</tr>
<tr>
<td>0.79</td>
<td>1.06</td>
<td>0.49</td>
</tr>
<tr>
<td>0.80</td>
<td>1.47</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 4.7 Final coefficients for \( s_H \) calculation based on the calibration with joint test results

<table>
<thead>
<tr>
<th>Fastener type</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a_i ) (original ( a_m ))</td>
</tr>
<tr>
<td>Nails</td>
<td>0.02 (0.0176)</td>
</tr>
<tr>
<td>Screws</td>
<td>0.1 (0.111)</td>
</tr>
<tr>
<td>Coach screws</td>
<td>0.2 (0.165)</td>
</tr>
<tr>
<td>Bolts parallel</td>
<td>0.1 (0.0965)</td>
</tr>
<tr>
<td>Bolts perpendicular</td>
<td>1.9 (1.98)</td>
</tr>
</tbody>
</table>
Figure 4.2 Comparison of calculated $P_{y,EYM}$ by EYM model with Joint test’s $P_{y,norm}$ (left) and with AS1720.1’s nominal capacities (right) for nail joints.
Figure 4.3 Comparison of calculated $P_{y,EYM}$ by EYM model with Joint test’s $P_{y,norm}$ (left) and with AS1720.1’s nominal capacities (right) for type-17 screw joints.
(a) *Calculated using original mean coefficients* $a_m$, $b_m$, and $c_m$

(b) *Calculated using joint-calibrated coefficients* $a_j$, $b_j$, and $c_j$

**Figure 4.4** *Comparison of calculated* $P_{y,EYM}$ by EYM model with Joint test’s $P_{y,norm}$ (left) and with AS1720.1’s nominal capacities (right) for coach screw joints.*
Figure 4.5 Comparison of calculated $P_{y,EYM}$ by EYM model with Joint test’s $P_{y,norm}$ (left) and with AS1720.1’s nominal capacities (right) for bolts joints loaded parallel to grain.
Figure 4.6 Comparison of calculated $P_{y,EYM}$ by EYM model with Joint test’s $P_{y,norm}$ (left) and with AS1720.1’s nominal capacities (right) for bolts joints loaded perpendicular to grain.
**Legend**: Nominal Capacity

- EYM’s yield load $P_{y,EMY}$
- AS 1720.1 nominal capacity
- Joint test’s yield load $P_{y,norm}$

**Figure 4.7** Nailed joints – Comparing experimental data to EYM’s yield load $P_{y,EMY}$, AS 1720.1’s nominal capacity and joint test’s yield load $P_{y,norm}$

(a) N6 is a 2-nail joint of (A) 37.5mm and (B) 45mm thick Radiata pine members, and $3.75\phi \times 75$mm long nails.

(b) N9 is a 1-nail joint of 45mm-thick Radiata pine members, and a $3.05\phi \times 75$mm long nail.
Figure 4.8  Type 17 screw joints – Comparing experimental data to EYM’s yield load $P_{y,EYM}$, AS 1720.1’s nominal capacity and joint test’s yield load $P_{y,norm}$

(a) S2 is a 1-screw joint of (A) 18mm and (B) 35mm thick Radiata pine members, and a No. 8 x 40mm long type-17 screw with shank $\phi = 3.4$mm.

(b) S3 is a 1-screw joint of (A) 65mm and (B) 44mm thick Radiata pine members, and a No. 14 x 115mm long type-17 screw with shank $\phi = 5.2$mm.
Figure 4.9 Coach screw joints – Comparing experimental data to EYM’s yield load $P_{y,EYM}$, AS 1720.1’s nominal capacity and joint test’s yield load $P_{y,norm}$

(a) CS2 is a 1-coach screw joint of (A) 20mm and (B) 45mm thick Radiata pine members, and 6φ x 65mm long coach screw.

(b) CS3 is a 1-coach screw joint of (A) 35mm and (B) 90mm thick Radiata pine members, and 12φ x 130mm long coach screw.
Figure 4.10  Bolted joints parallel to grain – Comparing experimental data to EYM’s yield load $P_{y,EYM}$, AS 1720.1’s nominal capacity and joint test’s yield load $P_{y,norm}$

(a) BSS1 is a 1-bolt single shear joint of two 35mm thick Radiata pine members, and an $8\phi$ x 90mm long bolt.

(b) BDS3 is a 1-bolt double shear joint of three Radiata pine members: (A) 35mm, (B) 45mm, (C) 35mm thick, and a $16\phi$ x 130mm long bolt.
**Legend:** Nominal Capacity

EYM’s yield load $P_{y,EYM}$  
AS 1720.1 nominal capacity  
Joint test’s yield load $P_{y,norm}$

![Graph](image)

**Figure 4.11** Bolted joints perpendicular to grain – Comparing experimental data to EYM’s yield load $P_{y,EYM}$, AS 1720.1’s nominal capacity and joint test’s yield load $P_{y,norm}$

(a) BDS6S is a 1-bolt double shear joint of 3 Slash pine members: (A) 35mm, (B) 45mm, and (C) 35mm thick, and an 8$\phi$ x 130mm long bolt.

(b) BDS7 is a 1-bolt double shear joint of three Radiata pine members: (A) 35mm, (B) 45mm, and (C) 35mm thick, and a 20$\phi$ x 240mm long bolt.
5. Concluding Remarks

This document has presented the background details and related technical information behind the proposed limit-states design procedure for timber joints fabricated using Australian pine with dowel-type fasteners. The proposed design procedure, presented in BCE Doc 01/081 (Foliente et al. 2002), is based on the widely accepted European Yield Model (EYM), providing both consistency and flexibility for the design of joints with dowel-type fasteners.

The current joint design procedure and design values for dowel-type fasteners in AS 1720.1 have been based on empirical fit of limited Australian data, and the procedures to determine design values are neither consistent nor fully understood. This means that application of current design values to new materials used in timber construction may not be appropriate, and that different safety factors (or levels of reliability) may be obtained from different timber joints in current design (without the intention of the designer).

The proposed EYM-based design procedure addresses these limitations of the current code. It has the following features:

- It is based on a comprehensive experimental testing program with matched specimens for joint testing and component/material testing (i.e., embedment strength and fastener strength).
- The EYM-based equations of Whale et al. (1987) were selected based on a comprehensive investigation of various EYM-based equations and comparison with experimental data.
- The proposed EYM equations have been carefully calibrated to test data.
- The proposed design method allows the use of new components/materials as long as appropriate properties are known or can be obtained by testing.
- The basis for determining component/material properties and establishing the design values of joint with dowel-type fasteners is consistent and well documented.

Once implemented, the proposed design procedure would place Australian timber joint design at par with world’s best practice.
References


SAA 2002, AS 3566.1, Self-drilling screws for the building and construction industries - General requirements and mechanical properties. Standards Australia, The Crescent, Homebush, NSW.


Original EYM Model

The following equations describe the original model proposed by Johansen (1949) and Larsen (1979). Notations are defined in Appendix B.

- **2-Member joints**

\[
P_y = s_{\mu}dl \\
\begin{align*}
\text{I}_s & \quad \frac{1.0}{\alpha \beta} \\
\text{I}_m & \quad 1 + \beta \\
\text{II} & \quad \frac{\sqrt{\beta + 2 \beta^2 (1 + \alpha + \alpha^2) + \beta^3 \alpha^2 - \beta (1 + \alpha)}}{1 + \beta} \\
\text{III}_s & \quad \frac{2 \beta (1 + \beta) + 4 \beta (2 + \beta) \frac{M_y}{s_{\mu}dl^2} - \beta}{2 + \beta} \\
\text{III}_m & \quad \frac{\alpha \left( \sqrt{2 \beta^2 (1 + \beta) + 4 \beta (1 + 2 \beta) \frac{M_y}{s_{\mu}d\alpha^2l^2} - \beta} \right)}{2 \beta + 1} \\
\text{IV} & \quad \min \left( \frac{4 \beta M_y}{s_{\mu}dl^2 (1 + \beta)} \right)
\end{align*}
\]
• 3-Member joints

\[
P_y = s_n dl \\
\begin{align*}
&= \left[ 1.0 \\
&\quad + \alpha \beta / 2 \right] \\
&= \min \left( \frac{2 \beta (1 + \beta) + 4 \beta (2 + \beta) \frac{M_y}{s_n dl^2}}{2 + \beta} \right) \\
&\quad - \beta \\
&\quad = \frac{4 \beta M_y}{s_n dl^2 (1 + \beta)} \\
&\quad = III_s \quad \text{or} \quad IV
\end{align*}
\]
Simplified-1 Equations

Whale et al. (1987) proposed these simplified equations, which include Eqs (2.1) and (2.2) presented in section 2. These equations are chosen for the development of the LSD procedure in this project.

Simplified-2 Equations

The proposal by Blass et al. (1999) is given below:

\[
P_Y = s_H d l \min \left\{ \frac{1}{1+(1+\beta)/\beta^{1/2}} \right\}
\]

\[
P_Y = s_H d l \min \left\{ \frac{\alpha \beta}{1+(1+\beta)^{1/2}} \right\}
\]

\[
P_Y = s_H d l \min \left\{ \frac{\{4 \beta M_Y\}/\{s_H d l^2 (1+\beta)\}}{1/2} \right\}
\]

**Mode/ (Equation)**

interpolation

interpolation

IV

**NOTE:** interpolation equations apply when members are too thin to generate a mode IV failure

Notations are defined in Appendix B.
NDS-Screw Model

This model is from the NDS - the US National Design Specification (AF & PA 1997; 1999). The following equations are written in terms of the EYM notations, which are defined in Appendix B.

- **2-Member joints**

\[
P_y = \begin{cases} 
  s_{\mu} dl & \text{I}_s \\
  \alpha \beta s_{\mu} dl & \text{I}_m \\
  -\frac{l}{2} \left(1 + \alpha \right) + \frac{l^2}{4} \left[ 1 - \alpha \right]^2 + \left( 1 + \frac{1}{\beta} \right) \left( 1 + \alpha \beta \right) \\
  \frac{1}{2s_{\mu} d} \left( 1 + \frac{1}{\beta} \right) & \text{II} \\
  -\frac{l}{2} + \sqrt{\frac{l^2}{4} + \frac{2}{s_{\mu} d} \left( \frac{1}{2} + \frac{1}{\beta} \right) \left( s_{\mu} dl^2 - s_{\mu} dl^2 / 4 + 0.75M_y \right)} \\
  \frac{1}{s_{\mu} d} \left( 1 + \frac{1}{2\beta} \right) & \text{III}_s \\
  -\frac{\alpha l}{2} + \sqrt{\frac{l^2 d^2}{4} + \frac{2}{s_{\mu} d} \left( 1 + \frac{1}{\beta} \right) \left( \alpha^2 \beta^2 s_{\mu} dl^2 - s_{\mu} dl^2 / 4 + M_y \right)} \\
  \frac{1}{s_{\mu} d} \left( 1 + \frac{1}{2\beta} \right) & \text{III}_m \\
  \frac{3.5M_x}{s_{\mu} d} \left( 1 + \frac{1}{\beta} \right) \\
  \frac{1}{s_{\mu} d} \left( 1 + \frac{1}{\beta} \right) & \text{IV} \\
  \end{cases}
\]
Appendix B. NOTATIONS

$\alpha$ = ratio of thickness of main/centre member to thickness of side member
$\beta$ = ratio of embedment strength of main member to embedment strength of side member
$\phi$ = capacity factor (known as a resistance factor in North America)
$d$ = diameter of fastener
EYM = European Yield Model
$l$ = thickness of side member(s)
       = thickness of head-side member in a single-shear nailed joint
LSD = Limit States Design
$M_Y$ = yield moment of fastener
$n$ = number of fasteners
$P_Y$ = yield load per fastener per joint plane
$Q_k$ = characteristic capacity of a fastener
$s_H$ = embedment strength of side member(s)

Notation for EYM-modes:
- Mode I and II correspond to timber bearing failures,
- Modes III and IV correspond to plastic hinge formation in the fastener,
- Subscript ‘s’ means side member yielding,
- Subscript ‘m’ means main member yielding.