MOMENT JOINTS IN TIMBER FRAMES USING GLUED-IN STEEL RODS: EXPERIMENTAL INVESTIGATION OF LONG-TERM PERFORMANCE

Massimo Fragiacomo¹, Mark Batchelar², Chris Wallington³, Andy Buchanan⁴

ABSTRACT: The pull-out performance of steel rods glued into timber is well documented, and short-term tests by many researchers have demonstrated reliable strength. The behaviour of glued-in steel rods in moment-resisting beam-column joints is much more complex, so that interactions of bending moments, axial and shear forces and the possible effects of creep and stress concentrations all need to be considered. These connections are often used as knee joints in timber portal frame structures. This paper describes the results of a series of long-term load tests on moment-resisting joints between glue-laminated timber members, together with separate load tests on the various joint components. Measurements were recorded to identify time dependant stress redistribution within the test joints and possible crushing of the timber-to-timber bearing surfaces leading to excessive joint rotations. Local deformation of timber loaded in compression perpendicular to the grain was found to contribute to excessive joint deformations in tests where the steel rods were not glued over their full length. The research developed a prediction model for the long term deformations and rotations in a knee joint utilising epoxy grouted steel rods.

KEYWORDS: Creep, Epoxied Rods, Glued-in Connections, Glulam, Long-term Behaviour, Moment Joints

1 INTRODUCTION

Joints in timber structures can consume up to 70% of the design effort [1] and contribute significantly to the final cost. The choice of connection type is often governed by the application and ease of manufacture and assembly. Traditionally, moment resisting joints in glulam structures have been constructed with sizeable gusset plates or a large number of bolts. Where appearance is important the use of epoxied steel rods has become popular as all of the steel components are concealed. Additional advantages include high local force transfer, reliable strength under normal conditions, relatively high stiffness, ductile performance, protection of the steel work against corrosion, reasonable cost, and relative ease of fabrication and site assembly.

Epoxied rods have been used in Europe for over 20 years [2] and in New Zealand [1] since 1990. Structures utilizing epoxied rod connections with appropriate materials have demonstrated good structural performance [3]. Fire resistance can be improved by increasing the timber cover thereby providing adequate thermal insulation [3] [4], however, there is still uncertainty regarding long term performance [5], [6]. Three common ways of utilising epoxied rods in moment resisting connections are shown in Figure 1. Configurations A and B involve passing the rods through both the beam and column. The rods in A are only epoxied in the column whilst in B the rods are fully epoxied along their length. The rods in Configuration C are connected to an exposed steel hub. Configurations A and B were tested in this project.

Configuration A is the easiest to assemble as rods can be glued into the column in a controlled environment off site, the beam can be placed onto the column and the rods tensioned to instantly provide moment resistance. Configuration B requires gluing on site and moment resistance is only achieved once the glue has cured. Gluing onsite is largely discouraged [7] as the grouting operation cannot be visually checked. For this reason it is preferable to use configuration A. However questions have been raised regarding how each would perform in the long term, and if the differences would be significant enough to recommend one type of connection.

There is a reasonable amount of research regarding the short term performance of epoxied joints. Short term tests by Deng [8] on large scale moment-resisting connections showed that the axial capacity of epoxied rods is affected by several factors, including difference in stiffness between the rod and wood, embedment length, wood density, wood moisture content, strength and stiffness of the bond.

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The long term behaviour of the epoxied-rod knee joint is thought to be primarily affected by creep in the timber and heterogeneity of the cross section. The stress distribution at the beam-column interface may change over time with localised stresses causing crushing of the timber perpendicular to the grain, leading to excessive rotations in the joint and possible failure.

The objective of this project was to investigate the long term deformations of these joints and to develop a design method for portal frame knee joints.

2 EXPERIMENTAL PROGRAMME

The experimental programme included short- and long-term testing.

2.1 SHORT-TERM TESTING

Material tests were done to determine the following timber properties: elastic moduli parallel to the grain in bending ($E_{b,0}$) and compression ($E_{c,0}$); elastic modulus perpendicular to the grain in compression ($E_{c,90}$); bending strength ($f_b$); compressive strength parallel ($f_{c,0}$) and perpendicular ($f_{c,90}$) to the grain. The results are presented in Table 1 and the testing is described at length in [9]. For each property, Table 1 reports the number of specimens tested, the minimum and maximum values, the standard deviation (Stdv.) and average (Ave.), and the values suggested by the NZS3603:1993 [10] for glulam grade GL10.

Table 1: Properties obtained from short-term testing, compared with NZS 3603 for GL10 radiata pine glulam (values in MPa).

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>$E_{b,0}$</td>
<td>14</td>
<td>8500</td>
<td>12600</td>
<td>1092</td>
<td>10000</td>
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<tr>
<td>$E_{c,0}$</td>
<td>6</td>
<td>8900</td>
<td>10600</td>
<td>546</td>
<td>9780</td>
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<tr>
<td>$E_{c,90}$</td>
<td>10</td>
<td>410</td>
<td>860</td>
<td>137</td>
<td>524</td>
</tr>
<tr>
<td>$f_b$</td>
<td>3</td>
<td>33.7</td>
<td>35.5</td>
<td>0.9</td>
<td>34.6</td>
</tr>
<tr>
<td>$f_{c,0}$</td>
<td>10</td>
<td>4.4</td>
<td>5.4</td>
<td>0.3</td>
<td>4.9</td>
</tr>
</tbody>
</table>

*: no value provided by NZS3603 for glulam – value of $E_{b,0}/30$ shown for radiata pine sawn timber

**: no value provided by NZS3603 for glulam – value shown for radiata pine sawn timber

By comparing experimental and NZS3603 [10] values, it can be noted that the elastic moduli are similar or slightly larger. The experimental bending and compressive strengths parallel to grain are significantly larger than the NZS3603 values, consistent with the former being mean and the latter being characteristic values. However, the average experimental compressive strength perpendicular to grain is markedly lower than the characteristic value suggested by NZS3603.

2.2 LONG-TERM TESTING

The long term testing consisted of two types of specimens: moment-resisting frames and axially loaded specimens using a lever mechanism.

2.2.1 Moment resisting frames

Frames were tested with different joint geometry:

Type ‘B’: Tensioned
Type ‘G’: Fully-Epoxied

The bold formatting indicates the reference from this point on. The “Tensioned” Type B joints were constructed with threaded rods glued 350mm into one glulam member with the second member then fixed to the first by sliding the rods through pre-drilled holes and applying a tensioning force using a nut tightened against a steel bearing plate. For the “Fully-Epoxied” Type G joints the threaded rods were epoxy grouted into pre-drilled holes in both members. The specimens were then further classified according to the geometry of the joint:

Type ‘1’: Long-beam / Short-column configuration
Type ‘2’: Short-beam / Long-column configuration

![Figure 2: Tensioned Specimen 1B (dimensions in mm)](image)

Frames 1B and 2G are shown in Figure 2 and Figure 3, respectively. Frames 2B and 1G are similar. The glulam was 315mm × 90mm grade GL10 according to NZS3603 [10]. Polymer Developments East 221 epoxy was used as it has demonstrated reliable performance and good pullout strength [3]. It also has a relatively low viscosity for providing complete encasement of bars. Threaded 12mm diameter Grade 8.8 high strength steel rods were used for dowels. A 16 mm hole diameter in the glulam was used for all specimens.

In the Type B joints, steel bearing plates were used to distribute the perpendicular to grain bearing stress.
The instrumentation used on all the specimens included: load cells, strain gauges, potentiometers and conductivity meters. Typically 10 potentiometers were used on each specimen with 12 on Specimen 2B. Two additional potentiometers measured the slip of the beams relative to the column. The location of all instruments is given in [9]. A tee frame (Figure 4) was used to reference some potentiometers to a common datum.

All specimens were supported at three points, two roller supports under each beam in the line of the applied load and a third ‘semi-fixed’ support along the column’s axis of symmetry. The specimens were loaded by applying a force at the ends of the cantilevered members using a threaded rod and tensioning nuts.

### 2.2.2 Lever specimens

The lever specimens were instrumented with potentiometers (pots) and strain gauges. Two pots were used for each lever; one pot for deformation of the lower glulam member with the other for deformation of both members, Figure 5. Six strain gauges were used for each specimen. The stress in the glulam lever specimens is summarized in Table 2.

![Figure 4: Photo of specimen 2G in the foreground and specimen 1G in the background](image)

![Figure 5: Creep test parallel to the grain (dimens. in mm)](image)

### Table 2: Applied stress in glulam lever Specimens

<table>
<thead>
<tr>
<th>Load orientation</th>
<th>Applied stress (MPa)</th>
<th>Percentage of Member Strength*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Para. to grain</td>
<td>9.7</td>
<td>28.0%</td>
</tr>
<tr>
<td>Perp. to grain</td>
<td>1.3</td>
<td>26.5%</td>
</tr>
</tbody>
</table>

*Obtained from material testing

Two lever mechanisms tested specimens under tensile loading. One lever specimen was designed to measure the creep of the epoxy only, whilst the other measured creep in the timber and creep at the glue-steel-timber interface. More details on those tests are reported in [9]. In order to measure the effects of temperature and relative humidity, three unloaded control specimens were instrumented with strain gauges and potentiometers. These specimens had the same geometry as the actual test specimens and were located in the same environment. The outcomes of those tests were subtracted from the outcomes of the creep tests in order to evaluate the creep coefficients.

### 3 EXPERIMENTAL RESULTS

#### 3.1 MOMENT RESISTING FRAMES

#### 3.1.1 Preliminary loading

In the preliminary loading all of the frame specimens were loaded to 5.67 kN. This load was estimated as the maximum design load using the approach suggested by Batchelor [5]. The critical design parameter was the perpendicular to grain characteristic compressive stress for radiata pine, which was assumed as $f'_{p}=8.9$ MPa according to New Zealand Standard 3603 [10]. A capacity reduction factor $\Phi=0.8$ and duration of load factor of $k_l=0.6$ was applied to the characteristic stress for long term loading. It was observed that the Tensioned specimens had elastic deflections significantly greater than the Fully-Epoxied specimens. Furthermore, strain gauges at the joint interfaces recorded strains in the order of 5,000-10,000 $\mu\varepsilon$, which correspond to stresses of 2.6-5.2 MPa assuming the average experimental elastic modulus perpendicular to grain $E_{c,90}=524$ MPa. This
showed that the timber was highly stressed and possibly near failing due to crushing perpendicular to grain since the actual average experimental stress as measured in the short-term testing was 4.9 MPa. Following the initial loading, the Tensioned specimens needed to be re-stressed more often to maintain a constant applied load. Within a few weeks, the deflections had failed serviceability criteria. They also failed ultimate criteria due to timber crushing perpendicular to grain.

Figure 6 shows the lower joint in Specimen 1B prior to unloading. It can be seen that a considerable gap of about 3 mm has opened along the beam-column interface and crushing has occurred in the compression region.

After Specimens 1B and 2B were unloaded all of the gaps closed up due to the residual tension force in the rods. Significant crushing was observed in timber loaded perpendicular to the grain. The joint was left unloaded for several days and it was observed that most of this deformation was recovered. The Tensioned specimens were reloaded with half of the initial load to limit the compression perpendicular to grain at the beam-column interface to less than the actual measured f<sub>c90</sub> stress. The glulam members loaded perpendicular to the grain were rotated 180 degrees so that a previously unloaded surface was now at the joint interface. Unlike the applied force, the tensioning in each tendon was not halved, although pre-tensioning forces are usually determined as a proportion of applied load. Note that Specimens 1G and 2G were not unloaded as they had shown satisfactory performance under the initial applied load. In the following sections, the experimental results are presented for Tensioned Specimens 1B and 2B subjected to half the design load after the preliminary loading, and for Fully-Epoxied Specimens 1G and 2G subjected to the entire design load.

3.1.2 Long-term applied load

Figure 7 shows the applied force over time for all of the frame specimens as recorded by the load cells. An initial reduction in load is evident due to creep in the loaded frame. To ensure the applied load remained roughly constant the frames were re-stressed to the initial load when needed.

3.1.3 Long-term rod forces

The force in some rods was also monitored over time. In the Tensioned Specimens these forces were monitored via load cells and bolt strain gauges. In the case of the Fully-Epoxied Specimens, strain gauges were placed on some of the steel rods. The results for specimens 2B, 1B, 2G and 1G are shown as solid lines in Figure 8, Figure 9, Figure 10 and Figure 11, respectively. In the legend of the figures, LC, BSG and ST signify the readings from the load cells, bolt strain gauges, and strain gauges, respectively.
that the forces in the inner rods became unstressed after approximately 1 year from the initial loading. Note that inner rods (rod 2 and rod 3) in all of the Tensioned Specimens are still in tension after the initial load application. This is because although the applied load was halved, the initial tensioning stresses were not, as noted in 3.1.1. In most practical situations these inner rods would most likely be unstressed after this period. Unlike the Tensioned Specimens, there is a significant difference between the results for the two Fully-Epoxied Specimens. The forces for Specimen 1G (Figure 11) are roughly half those of Specimen 2G (Figure 10). Intuitively there should not be a large difference between the two specimens. Also, force equilibrium suggests that the results from Specimen 1G may not be correct; this is discussed further in later sections.

3.1.4 Long-term frame displacements

The following section presents data obtained from the potentiometers located on the frame specimens. The deflection at the cantilevered end of the frames was due to several contributions:

1. deflection due to bending in the beam;
2. bending in the column, which causes a rotation at the end section of the column, and therefore, an additional deflection at the end of the beam due to rigid rotation of the joint;
3. joint rotation $\Theta$, which is the relative rotation of the beam with respect to the column due to the flexibility of the joint; the joint rotation is given by $\Theta=\frac{x_1-x_2}{d}$, where $x$ is the displacement measured by the potentiometers reading across the joint interface, and $d$ is the distance between them (Figure 12);
4. slip in the joint (Specimen 2B only), which is the relative shear displacement of the beam with respect to the column in the load direction.

Figure 12: Labelling for geometry type 1 (left) and 2 (right) specimens

Figure 13 shows the deflection results for the bottom half of Specimen 2B. The deflections have been plotted in the following way: the top curve is the sum of all components of deflection ($1+2+3+4$); the intermediate curve is the sum of the components due to bending in the beam and bending in the column ($1+2$); and the bottom curve is due to bending in the beam ($1$). Since the slip component was found to be negligible, the difference between the top and the intermediate curve in Figure 13 provides the displacement due to joint rotation which makes a significant contribution to the total deflection. Also, the deflections of the beam and column were quite close to the values calculated using elastic theory. Similar results were obtained for Specimen 1B. Figure 14 shows the vertical deflection for Specimen 2G. Unlike Figure 13, in this case the curves refer to both halves of the frame specimen. Again, the significant
contribution of the joint flexibility, usually ignored in the design of glued-in joints, can be recognized. Similar results were obtained also for Specimen 1G.

3.1.5 Long-term creep coefficients
The joint creep coefficients for the Frame Specimens 2B and 2G are shown in Figure 15 and Figure 16. Also shown on these graphs are analytical curves fitted to the data. These curves are in power form $y=ax^b$ where ‘a’ and ‘b’ are coefficients that give the best result in a least mean square approximation. In Figure 15 it can be seen that there is a significant increase in creep during the first 20 days from loading, it is then fairly constant for the next 100 days, and then steadily increases at around the 120 day mark. This trend was also evident in Specimen 1B and in the creep coefficients obtained from the strain gauges located along the joint interface. This is expected as equilibrium should hold in the joint region. It is worth noting that the forces in the rods decrease at about the 120 day mark, the likely reason being climatic effects. From about the 120 day mark both the average relative humidity and temperature dropped (see Figure 17). Due to this sudden increase in creep the analytical curves do not fit the data as well.

The joint creep coefficients for the Fully-Epoxied Specimen 2G is shown in Figure 16. This specimen, as well as Specimen 1G, appears to creep roughly half of that observed for the Tensioned Specimens. This same trend was also seen in the predictions at the end of service life, see Table 3. The most likely reason for this is that the Tensioned Specimens relied on bearing perpendicular to the grain, which has very significant creep effects. Conversely, the Fully-Epoxied Specimens have less reliance on the timber bearing strength perpendicular to the grain.

![Figure 15: Specimen 2B joint creep coefficients](image)

![Figure 16: Specimen 2G joint creep coefficients](image)

3.1.6 Long-term strain measurements
Strains in the main frame specimens were measured at the beam-column interface and across the sections in bending. Control strain gauges were also used on unloaded specimens to monitor the climatic strains due to temperature and relative humidity. In all the strain plots the climatic strains (measured on the unloaded specimens) have been subtracted from the total strains. The strains due to bending for Specimen 2B are shown in Figure 18. They were measured on the column, in the cross-sections at 375 mm from the bottom (strain gauges L1, L2 and L3) and from the top (strain gauges L4, L5 and L6). Strain gauges L1, L3, L4 and L6 were located at 5 mm from the outermost fibres of the columns, whilst strain gauges L2 and L5 were located 85 mm from the outermost fibre in tension. The increase in bending strains over time was quite limited in all the frame specimens and in all locations. Figure 19 is a plot of the strains measured in the column of Specimen 2B, perpendicular to grain, at the beam-column interface. Strain gauges S1, S2 and S3 were in the lower joint, whilst strain gauges S7, S8 and S9 were in the upper joint. Strain gauges S3/S7, S2/S8 and S1/S9 are located 5 mm, 55 mm and 105 mm from the outermost fibre in compression of the beam. In this plot there is no obvious increase in strains. Overall there is an increase but most of this deformation occurred over the first two weeks. Also note that there is no significant redistribution of strains and stresses with time.

![Figure 17: Temperature and relative humidity histories](image)

![Table 3: Summary of joint creep coefficient predictions](image)
The strain profile across the joint interface was also investigated at various different stages throughout the test, namely after tensioning (1B and 2B only), after loading, 200 days from loading and at 275 days from loading. The strain profiles for specimens 2B and 2G are shown in Figure 20 and Figure 21, respectively.

The strain profile after the initial tensioning is clearly illustrated in Figure 20. This profile indicates that the whole section is in compression but is more compressed towards the top (as the outer tendon was tensioned more than the inner one). In all of the plots it is seen that the timber strain at the extreme compression fibre increases 200 days from loading. This is the result of creep deformations in timber. A number of strain gauges were used to measure the strain (and consequently force) profile along the length of some of the tendons. Figure 22 relates to rod 1 (in tension) of Specimen 2G. Note that rods in Specimen 2G are fully epoxied along their length. The force is maximum at the beam-column interface as there is a discontinuity in the timber members at this point. The force then decreases approximately linearly to zero at each of the rod ends. The profile becomes more linear with time. A possible justification is that a redistribution of stresses in the timber and glue may have occurred due to creep strains. Very similar curves were obtained for rod 2 (in compression). For Specimen 2B, which has rods glued only in the beam, the stresses along the glued interface were found to vary slightly less than linearly [9]. Also in this case, however, the curves become more linear as time goes by. The linear relationship for rods glued perpendicular to the grain is consistent with research by Bernasconi [11] that shows a constant load transfer along the length of the rod.

3.2 LEVER SPECIMENS

The curves of the creep coefficient calculated from the potentiometer readings are shown in Figure 23 and Figure 24 for the lever specimens loaded parallel and perpendicular to the grain, respectively. Note that the analytical curves were fitted to data from two different time intervals due to difficulties with sampling. Hence there may be some error in the predicted values at the end of service life.
A summary of the predicted creep coefficients (minimum, maximum and average) parallel and perpendicular to grain at the end of service life (50 years) is shown in Table 4 together with the coefficients a and b to use in the power-type function describing the trend over time.

In these Tables, also the readings from the strain gauges were used to evaluate the creep coefficients. It can be seen that there is a large difference in the predictions between using the potentiometers (Pot) and strain gauges (SG). The creep coefficient parallel to the grain is likely to range between 1.0 and 3.0. The creep coefficient perpendicular to the grain (at the end of service life) is around 4.0 to 8.0. An average value of 6 may be assumed for the final creep coefficient perpendicular to grain of glulam made from New Zealand radiata pine.

Table 4: Summary of material creep coefficient predictions

<table>
<thead>
<tr>
<th>Instrument type</th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
<th>a</th>
<th>b</th>
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<tbody>
<tr>
<td>Pot – para.</td>
<td>1.7</td>
<td>2.7</td>
<td>2.2</td>
<td>0.15</td>
<td>0.28</td>
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<tr>
<td>SG – para.</td>
<td>0.6</td>
<td>2.8</td>
<td>1.8</td>
<td>0.04</td>
<td>0.37</td>
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<tr>
<td>Pot – perp.</td>
<td>3.9</td>
<td>4.4</td>
<td>4.1</td>
<td>0.38</td>
<td>0.24</td>
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<tr>
<td>SG – perp.</td>
<td>4.3</td>
<td>8.7</td>
<td>7.9</td>
<td>0.28</td>
<td>0.34</td>
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</table>

4 ANALYTICAL COMPARISONS

This Section compares the experimental results measured in the frame specimens and the analytical results obtained using the design approach suggested by Batchelar [5] with some modifications.

4.1 ANALYTICAL DESIGN METHOD

Batchelar’s analytical approach uses the method of the transformed section to design a glued-in moment resisting joint. The approach is based on assumptions:

- Plane sections remain plane
- Linear stress distribution in compression zone
- Force equilibrium at the design load
- Adhesive stiffness greater than timber stiffness

A design issue is whether the modulus of elasticity of timber perpendicular or parallel to the grain should be used in the neutral axis and transformed second moment of area evaluation. Another issue is how to account for creep of timber in ultimate limit state design. Batchelar [5] recommends the modulus of elasticity perpendicular to the grain, \( E_{\text{perp}} \), in the transformed section method, and the use of a reduced modulus of elasticity \( E_{\text{eff,perp}} \) (effective modulus method) to account for creep:

\[
E_{\text{eff,perp}}(t) = \frac{E_{\text{perp}}}{1 + \phi_{\text{perp}}(t)}
\]

where \( \phi_{\text{perp}} \) is the creep coefficient of glulam in compression perpendicular to grain.

For Tensioned joints, the effect of initial prestressing is usually ignored in normal design, and the joints are designed without compression rods (simplified method). To investigate this, analytical formulas based on the transformed section and equilibrium (rigorous approach) were derived from first principles [9].

4.2 STRESS COMPARISON

Figure 8 to Figure 11 compare the experimental forces measured in the rods of the different frame specimens with the predictions of the rigorous approach in two hypotheses: use of the modulus of elasticity of timber perpendicular to the grain, \( E_{\text{perp}} \), as suggested by Batchelar [5], and parallel to the grain, \( E_{\text{para}} \). The solution in the long-term was calculated using the effective modulus method, assuming a creep coefficient of glulam perpendicular and parallel to the grain by:

\[
\phi_{\text{perp}}(t) = 0.276t^{0.342} \quad \phi_{\text{para}}(t) = 0.040t^{0.339}
\]

where \( t \) is the load duration in days. Eqs. (2) and (3) are derived from the lever testing. The values \( E_{\text{perp}} = 450 \) MPa and \( E_{\text{para}} = 10 \) GPa were based on the results of the short-term testing.

In both the Tensioned Specimens (Figure 8 and Figure 9) the load in the outer (tension) rods were measured via load cells. The elastic rod forces were nearly identical for both Tensioned Specimens. After loading, all of the rods remained in tension. The forces were about 26 kN in the outer (tension) rods and 6 kN in the inner (compression) rods. Using the modulus parallel to the grain (for the timber modulus, \( E_{\text{eff}} \)) provided a much closer prediction. In both Tensioned Specimens, the stresses measured at the extreme compression edge ranged between 2 to 4 MPa and the neutral axis was seen to lie around 100 mm from the compression edge. This supports using the modulus parallel to the grain in Tensioned connections as the predicted values were 3.45/3.13 MPa and 77.5/82.4 mm for Specimens 2B/1B as opposed to 1.59/1.69 MPa and 217/217 mm if the modulus of elasticity perpendicular to grain was used. However there was a problem with the level of tensioning, so more testing with less tensioning is needed before final conclusions can be drawn. Figure 10 shows the predictions for Specimen 2G. The modulus perp. to the grain provided best predictions, hence this should be used for Fully-Epoxied type connections.

Table 5 shows the predicted quantities for Specimen 2B using both methods, where the simplified approach overestimates the maximum compressive stress in the timber but underestimates the rod forces. Table 5 shows
that the simplified approach is best when the elastic modulus perpendicular to the grain is used.

**Table 5: Short term predictions for Specimen 2B using the simplified and rigorous methods**

<table>
<thead>
<tr>
<th>Method</th>
<th>Inner Rod Force (kN)</th>
<th>Outer Rod Force (kN)</th>
<th>Neutral Rod Force (kN)</th>
<th>Max Comp. Stress (MPa)</th>
<th>Timb. Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplified ($E_w = E_{typ}$)</td>
<td>0</td>
<td>22.2</td>
<td>210</td>
<td>2.4</td>
<td></td>
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<tr>
<td>Simplified ($E_w = E_{pum}$)</td>
<td>0</td>
<td>18.1</td>
<td>83</td>
<td>5.0</td>
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<tr>
<td>Rigorous ($E_w = E_{pum}$)</td>
<td>0</td>
<td>36.6</td>
<td>217</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Rigorous ($E_w = E_{pum}$)</td>
<td>7.1</td>
<td>27.2</td>
<td>78</td>
<td>3.5</td>
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<tr>
<td>Experimental values</td>
<td>6.2</td>
<td>26.0</td>
<td>90-190</td>
<td>0.4-3.5</td>
<td></td>
</tr>
</tbody>
</table>

4.3 **DEFLECTION COMPARISON**

Often in design, connections are assumed to be rigid, but in all the frames tested the joint rotation contributed about 50% of the total deflection (see Figure 13 and Figure 14). It is therefore important to add the rotational flexibility of the joint for an accurate evaluation of frame deflection. A simplified way is to model the joint as an elastic rotational spring. The elastic approximation is more than adequate at serviceability limit state as the experimental moment-rotation θ curves during the loading ramp were linear (see Figure 25 for Specimen 2B). The elastic rotational stiffness derived from the experimental curves using linear fit approximations are displayed in Table 6 for all specimens and joints (Upp/Low = Upper/Lower joint). It can be seen that both the Tensioned and Fully-Epoxied type joints have similar stiffness.

**Figure 25: Specimen 2B joint stiffness**

Table 6 compares the deflection at the cantilevered end of the frames after 200 days. The flexible model allows for the rotational flexibility of the joint, whereas the rigid model assumes the joint as rigid. Creep was considered using the effective modulus method, i.e. by dividing the actual modulus of elasticity of the beams and columns measured in a non-destructive preliminary loading test, by one plus the creep coefficient of glulam parallel to the grain calculated at 200 days using Eq. (3). For the flexible model, the elastic rotational stiffness was divided by one plus the creep coefficient given by Table 3. The analyses were carried out by implementing both models in SAP 2000 [12]. The Rigid Model predictions are roughly half that of the measured values. However the Flexible Model gives much better estimates, showing good correlation between the Flexible Model and the measured values. Hence it is important to take into account the joint flexibility and the creep of the individual members as well as of the joint itself.

**Table 6: Rotational stiffness of joints and comparison against measured deflections at 200 days from load application**

<table>
<thead>
<tr>
<th>Joint</th>
<th>Elastic Stiffness (kNm/rad)</th>
<th>Deflection at cantilevered end (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rigid Model</td>
<td>Flexible Model</td>
</tr>
<tr>
<td>2B Upp</td>
<td>1861</td>
<td>4.2</td>
</tr>
<tr>
<td>2B Low</td>
<td>2276</td>
<td>4.3</td>
</tr>
<tr>
<td>1B Upp</td>
<td>1617</td>
<td>3.2</td>
</tr>
<tr>
<td>1B Low</td>
<td>1644</td>
<td>3.5</td>
</tr>
<tr>
<td>2G Upp</td>
<td>1940</td>
<td>8.6</td>
</tr>
<tr>
<td>2G Low</td>
<td>1671</td>
<td>8.5</td>
</tr>
<tr>
<td>1G Upp</td>
<td>1656</td>
<td>7.3</td>
</tr>
<tr>
<td>1G Low</td>
<td>1744</td>
<td>7.7</td>
</tr>
</tbody>
</table>

5 **DISCUSSION**

5.1 **FULLY EPOXIED vs TENSIONED JOINTS**

The most important finding of this research is that the Fully-Epoxied connection performed significantly better than the Tensioned connection both in short and long term loading. The preliminary loading tests showed that both the Tensioned specimens were unable to carry the applied load, failing at serviceability and ultimate limit states. The Fully-Epoxied specimens loaded to the same stress level demonstrated superior performance. The Tensioned connection relies entirely on glulam compression perpendicular to the grain, which has approximately 15% of parallel to grain strength and 5% of parallel to grain stiffness. In the Fully-Epoxied connection the compression force is transferred mainly through the inner rods located in the compression zone. The percentage of load resisted by the compression rod in the Fully-Epoxied specimen was 81% of the total compression force transferred through the connection and cannot be neglected.

5.2 **COMPONENTS OF DEFLECTION**

The frame deflections over time show some interesting trends. In all specimens there was a small amount of creep due to bending in the beam and column. A significantly larger portion of the creep deformation was observed to come from the joint, most notably from about 120 days from loading. Also at this point in time the average relative humidity dropped considerably.

5.3 **STRAIN DISTRIBUTION**

In most of the strain profiles the strain distribution in the compression block is approximately linear, supporting the use of a linear strain profile, as used by Batchelor [5]. The strain profiles from all members in bending and at the joint interfaces of the frame Specimens showed minimal increase from the elastic values.
5.4 CREEP BEHAVIOUR
Creep behaviour was observed in the timber members loaded in compression parallel and perpendicular to the grain. From the predictions made, the creep coefficient perpendicular to the grain is about 3 to 4 times that parallel to the grain. The creep coefficient of glulam parallel to the grain (at the end of service life) was calculated to be about 1.0-3.0, whilst perpendicular to the grain it is around 4.0-8.0. Creep parallel to the grain was also observed in the lever specimen loaded in tension. It was predicted that creep parallel to the grain may be lower for members in tension (about 0.5) than in compression. The creep coefficient of the epoxy (at the end of service life) is about 0.5-0.6.

In the frame specimens, the Tensioned connection crept approximately 2.5 times the Fully-Epoxied connection. The average joint creep coefficient (at the end of service life) was 3.6 for the Tensioned specimens and 1.4 for the Fully-Epoxied specimens.

5.5 ANALYTICAL PREDICTIONS
The analytical-experimental comparisons matched quite well for both the Tensioned and Fully-Epoxied Specimens, provided that the elastic modulus perpendicular to the grain should be used for Fully-Epoxied Specimens and the modulus parallel to grain for Tensioned Specimens. This enables an accurate prediction of the forces in the rods and stresses in the timber for any value of applied moment. Long term effects could be accounted for by using the Effective Modulus Method. Joint flexibility contributed significantly to the overall deflections. A model gave results that corresponded quite well to the experimental values, but the proposed model requires the joint stiffness. For the joints tested it was observed that both the Tensioned and Fully-Epoxied connections had similar stiffness, but this is only for the geometry tested. More research is needed to propose a general method of evaluating the stiffness of an epoxied connection of any given geometry.

6 CONCLUSIONS
The main outcome of this research was the significant difference in the performance of the Fully-Epoxied and Tensioned Specimens. With the same applied load the Tensioned Specimens deflected significantly more than the Fully-Epoxied Specimens in the short and long term. It was shown that creep of materials mostly affects deflection rather than strength.

From lever testing, the creep coefficient of glulam was calculated to range from 1.0 to 3.0 parallel to the grain, or 4.0 to 8.0 perpendicular to the grain, at the end of the service life.

Most of the glulam strengths were higher than the characteristic values in NZS 3603. The one exception was the compressive strength of glulam perpendicular to the grain, where the average value was only 4.9 MPa, much less than the strength specified for sawn Radiata Pine of 8.9 MPa. A 50% reduction in the code value is strongly recommended.

For design, Batchelar’s transformed section approach, was modified to take account of eccentric axial loads and epoxied rods in the compression block, giving good predictions when using the elastic modulus perpendicular to the grain for Fully-Epoxied connections and the elastic modulus parallel to the grain for Tensioned specimens. These results cannot be considered as final and further research should be undertaken. The experimental results also showed that joint flexibility could contribute up to 50% of the total deflection. This is of real importance in timber engineering as it is not uncommon for the design of timber structures to be governed by deflections.

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REFERENCES