SCREWED CORBEL CONNECTIONS IN LAMINATED VENEER LUMBER

David Carradine\(^1\), Michael Newcombe\(^2\) and Andrew Buchanan\(^3\)

**ABSTRACT:** Screws have significant potential as fasteners for a myriad of connections throughout timber buildings, particularly for prefabricated systems. New commercial-type, long-span, multi-storey building systems are under development at the University of Canterbury. These systems place high structural demands on corbels to support floor units and gravity beams. While considerable research has been conducted on the use of screws in solid timber connections, there is currently a lack of data on the behaviour of screws when used with laminated veneer lumber (LVL). Because screws may be installed parallel to the laminations (and glue-lines), it is necessary to determine appropriate edge distances, spacings and screw types that can be safely used in these situations. Monotonic testing on screwed connections in LVL has been performed. The results are compared with existing standards that determine screw connection capacity for solid and glue-laminated timber and LVL.

**KEYWORDS:** Composite, Laminated Veneer Lumber, Pres-Lam, Prefabricated, Screw Connections

1 **INTRODUCTION**

In an effort to increase the use of timber for structural applications throughout New Zealand and Australia, research is being conducted on the behaviour and design of multi-storey and long-span timber buildings using a patented post-tensioned timber system to create moment resisting frames and wall systems. These Pres-Lam\(^\circledR\) building systems incorporate large timber sections, constructed of laminated veneer lumber (LVL), joined using steel post-tensioned tendons. These buildings have significant potential to compete with current forms of construction in steel and concrete [1] and allow for open floor plans suitable in a large range of structures. The structural system exhibits excellent seismic performance, having the ability to dissipate energy during an earthquake and re-centre itself after the event. Experimental research on post-tensioned LVL buildings in New Zealand has focused primarily on building components including beam-column joints, and timber-

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concrete floor systems [2] and [3]. Currently a 2/3 scale two-storey structure using this technology has been designed, fabricated by regional glue laminators and erected at the University of Canterbury as shown in Figure 1 [4]. This building has been tested over several months to assess the structural integrity of the system when subjected to biaxial quasi-static lateral loading. Movement of the structure due to lateral loads induced minimal damage to the floors. This was accomplished by using innovative connections for beams and floor joists. The joist and gravity beam connections were designed with cantilevered steel plates fastened by self-drilling screws. The steel plates sat on LVL corbels, which were screwed to the larger building components as seen in Figure 2. Corbel screws were designed using methods provided in SNZ Standard 3603 [5] and the Timber Design Guide [6] for solid sawn and glue-laminated timber connections. The design of these LVL connections have been based on the assumption that the behaviour under load will be the same as solid sawn timber, but research has indicated that caution should be exercised when using existing design standards for structural composite lumber products, such as LVL [7,8]. Because the screws in many of these connections have been installed parallel to the glue lines and are subject to withdrawal loading, there is concern that the failure modes of these connections may not be accounted for in standard timber design methods. While Carradine et al. [8] provided data on the evaluation of the joist attachment for these types of connections, the effectiveness of the corbel attachment remains an unanswered issue.
Studies have been conducted on the behaviour of screws for connections and reinforcement in solid timber and glue laminated structures. Inclined screws in timber were tested and modelled by Bejkta and Blaß [9]. Newcombe et al. [10] expanded on this work by testing laterally loaded connections between LVL floor joists and laminated LVL framing members using screws installed at 90° and 45°. These connections provided adequately strong, stiff and ductile connections intended for use with multiple storey timber structures using LVL. Jöhnsson and Thelandersson [11] investigated the effectiveness of screws used for reinforcement against perpendicular to grain stresses in curved glue laminated structures. Bejkta and Blaß [12] tested dowel connections in timber with screws as reinforcement and developed a model to predict the behaviour of these connections. They also verified the effectiveness of screws as reinforcement in timber supports using tests and developed a model [13].

Because LVL is a proprietary product, very few research projects aimed at quantifying its behaviour have been performed. Kiari [14] investigated bolted connections in LVL fabricated with the laminations oriented diagonally. Hummer et al. [15] included LVL in a study on tension perpendicular to grain strength, which concluded that LVL was weaker than solid timber in tension perpendicular to grain loading. Franke and Quenneville [16] provided test data and discussion on the embedment strength of LVL utilising different international testing standards. LVL manufacturers typically publish design values for their products, but usually do not include values for screws installed parallel to the glue lines subject to shear or withdrawal loads. This lack of information creates a distinct need for testing and validation of design methods for screwed connections in LVL.

## 2 CORBEL TESTING

The objectives of this project were to evaluate the actual capacity of the corbels designed for the current test building at the University of Canterbury, and to investigate the unique loading scenarios and resulting failure modes for comparison with published design recommendations.

The double shear testing configuration was utilised for the corbel connection tests as shown in Figure 3. Specimens comprised of LVL corbels screwed to large LVL blocks used to simulate the column. For ease of testing, specimens were fabricated as pairs of columns and corbels held in place by four threaded rods so that steel plates, representing the joint or gravity beam hangers, could be used to apply loads to both corbels simultaneously. Additional tests were performed with the corbels attached parallel to the glue lines of the columns, as shown in Figure 4. Due to the unique nature of the connections, ASTM Standard D 7147 – 05 Standard Specification for Testing and Establishing Allowable Loads for Joist Hangers [17] was used as a guideline for test procedures. Loads were applied to corbels monotonically via steel plates. Based on the time to failure, the loading rate was approximately 10 kN per minute. Displacement measurements were obtained on both of the corbels relative to the column members. A typical test specimen of Configuration 1C is shown in Figure 5.
Testing configurations are described in Table 1. Screws were locally purchased, self-drilling, 14 Gauge Type 17 screws having a shank diameter of 5.3mm. Some Configuration 1 specimens were fabricated using 150mm by 6.4mm diameter screws having two regions of threaded length with slightly different thread pitches manufactured by SFS in Switzerland. Observations indicated that splitting was likely to occur when installing the screws, therefore tests were conducted with screws installed in pre-drilled holes having a diameter consistent with Eurocode 5 [18] and NZS 3603 [5] recommendations. The LVL used for corbels and column members came primarily from one of the two major LVL manufacturers in New Zealand. Corbels were fabricated from 45mm thick LVL, except for Configuration 4, which used 63mm thick LVL. Sample sizes were typically three, with some having only two specimens each, due to limitations on available materials. Sample sizes were kept small due to the complexity of the connections and for the reason that once effective corbel connection configurations were determined, additional testing would be conducted using larger sample sizes if needed.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Screws</th>
<th>Corbel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>5.3 mm x 150 mm Type 17</td>
<td>2 x 100 mm x 220 mm, grain parallel to loading</td>
</tr>
<tr>
<td></td>
<td>40 mm o.c.</td>
<td></td>
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<tr>
<td>1B</td>
<td>5.3 mm x 150 mm Type 17</td>
<td>2 x 100 mm x 220 mm, grain perpendicular to loading</td>
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<tr>
<td></td>
<td>40 mm o.c.</td>
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<tr>
<td>1C</td>
<td>6.4 mm x 150 mm SFS</td>
<td>2 x 100 mm x 220 mm, grain parallel to loading</td>
</tr>
<tr>
<td></td>
<td>40 mm o.c.</td>
<td></td>
</tr>
<tr>
<td>1D</td>
<td>5.3 mm x 150 mm Type 17</td>
<td>2 x 100 mm x 220 mm, grain perpendicular to loading</td>
</tr>
<tr>
<td></td>
<td>40 mm o.c.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.3 mm x 150 mm Type 17</td>
<td>2 x 100 mm x 290 mm, grain parallel to loading</td>
</tr>
<tr>
<td></td>
<td>50 mm o.c.</td>
<td></td>
</tr>
<tr>
<td>3A</td>
<td>5.3 mm x 100 mm Type 17</td>
<td>1 x 100 mm x 220 mm, grain parallel to loading</td>
</tr>
<tr>
<td></td>
<td>40 mm o.c.</td>
<td></td>
</tr>
<tr>
<td>3B</td>
<td>5.3 mm x 100 mm Type 17</td>
<td>1 x 100 mm x 220 mm, grain perpendicular to loading</td>
</tr>
<tr>
<td></td>
<td>40 mm o.c.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5.3 mm x 150 mm Type 17</td>
<td>1 x 100 mm x 220 mm, grain perpendicular to loading</td>
</tr>
<tr>
<td></td>
<td>40 mm o.c.</td>
<td></td>
</tr>
</tbody>
</table>

Note: o.c. means the screw spacing “on centres”

3 TESTING RESULTS

Presented in this section are experimental test values for double shear corbel connection capacity tests and descriptions of failure mechanisms observed. Comparisons are provided between average test data and predicted design capacities from Eurocode 5 [18]. The average strengths of the two connections are presented in Table 2 for each configuration. Also provided in Table 2 are the predicted failure loads using the Johansen methods for predicting single shear connection capacities as found in Eurocode 5 [18] as these methods were considered to be more rigorous than those found in NZS 3603 [5] as discussed in Buchanan [6].
Failure modes of the fasteners for all configurations were well predicted by Eurocode 5 [18] equations as being Failure Mode f, where there were two plastic hinges formed in the set of fasteners at the interface between the corbel and the column members. Figure 6 shows an example of Type 17 screws that were removed following testing. Attempts were made to remove corbels and screws following testing for all configurations and it was apparent that not all of the screws in a given specimen were taking equal amounts of load. This was particularly evident in specimens which were tested with the applied load being parallel to the grain of the corbels. In these cases there was significant bending of the corbels about the steel plate which was used to apply the loads, which were only 100mm wide in order to simulate the conditions in the previously described test building. Figure 7 shows an example of a corbel tested for Configuration 1A where it is clear that the corbel has split around the screws and deformed around the steel plate, providing information on the shortcomings of this corbel orientation which was typical of throughout testing.

Specimens where the corbels were loaded perpendicular to the grain also displayed failure modes that were not predictable using generalised shear beam theory which assumes only vertical translation of the corbels. Observations following tests indicated that the manner in which the corbels were loaded led to rotation of the corbels away from the face of the columns, which would have induced additional tension stresses into the screws. Figure 8 presents an example of this movement as viewed from the side of the test specimen. While this behaviour may have affected the ultimate failure load of the connections it occurred at large displacements, beyond design deflection limitations.

It was also observed that significant crushing of the corbels by the steel loading plates occurred on specimens loaded perpendicular to the grain of the corbel, and was most pronounced in Configuration 3 specimens using only a single layer of 45mm thick LVL for the corbel, as shown in Figure 9.
For Configuration 4 columns were orientated with the glue lines parallel to the screws and the corbels were made from 63mm thick LVL. The resulting failure modes were similar to the other configurations, but included a noticeable amount of screw withdrawal from the column as loads were increased and approached ultimate failure. This can be seen in Figure 10 as the screw heads have exhibited less pull-through and corbel crushing than similar Configuration 3 tests. The increased tendency for Configuration 4 specimens to withdraw was attributed to the grain orientation of the columns and a possible difference in the tension strength properties of the LVL of different thickness. Similar findings were documented by Carradine et al. [8].

Relative displacement between the column member and corbels was measured throughout testing. This is plotted against the applied load up to the point of failure. Designers can utilise this information to determine the effectiveness of connections from a serviceability perspective, and account for the effects of this movement on other parts of the structure and establish ultimate limit state failure modes.

The joist hanger portions of the rocking connections were investigated previously by Carradine et al. [8] and found to be adequate both for demonstration building (Figure 1) considering NZS 3603 [5] capacity predictions and deflection criteria. When compared with data from this previous study, the deflections obtained for the corbel to column connections were more than adequate at the design loads required for each of the configurations tested. In general the corbel connections were very stiff and little displacement was observed during the early loading stages. Significant displacements were not induced until the design loads had been achieved. These trends can be seen in Figures 11 and 12 for Configuration 1 and 2 specimens, respectively.

Figure 11. Load versus displacement for both sides of Configuration 1A specimen

Figure 12. Load versus displacement for both sides of Configuration 2 specimen (Note: Rolling shear refers to corbel peeling away from column)

Configurations 3 and 4 utilised only single thickness LVL for the corbels and consequently had greater initial displacements, but these were still within acceptable limits for these connections considering the design load levels. A comparison between Configuration 3 specimens having the corbel grain oriented perpendicular and parallel to the applied load shows (Figure 13) that
there is little difference in deflections for the initial loading, again up to and beyond design load levels, but that they do diverge at higher loads.

Interestingly, with the corbels loaded parallel to grain slightly higher stiffness as the load versus displacement plots begin to diverge, but then lose stiffness more quickly and have lower ultimate load values, as shown in Figure 13 (hence stiffer in bearing but a more brittle failure mode). These differences are explained by the splitting failure mode observed in parallel to load tests. The more subtle change in stiffness in the perpendicular to load grain orientation was attributed to the crushing and rolling behaviour previously described. Configuration 4 specimens exhibited overall slightly lower initial stiffness than the other configurations as seen in Figure 14, but otherwise had basically the same behaviour as other specimens with corbel grain oriented perpendicular to the applied load.

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All of the discussed results have been with regard to the Type 17 screws typically available throughout New Zealand. It is worth noting that the corbel connections tested using the SFS screws resulted in greater load resistance for Configuration 1. Specimens with corbel grain oriented parallel to the applied load obtained an average maximum load 18%, and specimens with corbel grain oriented perpendicular to grain reached an average maximum load 34% greater, using SFS screws. The SFS screw specimens failed similarly to the other Configuration 1 specimens with splitting and crushing of the corbels depending on the orientation of the grain, as can be seen in Figure 15. The SFS screwed corbels were stiffer than the Type 17 connections and exhibited reduced translation of the corbels as in Figure 15.

All connections were able to achieve maximum loads without resulting failures that would be considered brittle. Figures 11 through 14 provide load versus displacement plots that clearly show the significant amount of energy required to fail these joints while avoiding large drops in load resistance. This indicated that the connections were ductile in nature and were configured to maximise the ductility capacity of the metal fasteners. This suggests that these types of connections are robust for structural applications and would provide a suitable method for attaching floor joists and beams to columns in systems that require rotating connections designed to minimise damage to floors during earthquake and high wind loading.
scenarios. Future testing of cross-banded LVL for corbels is recommended, as a means of reducing the observed splitting failures.

4 DESIGN COMPARISONS
The load demands for corbel connections, based on the design of the demonstration building, were achieved with a significant factor of safety [8]. It is important to consider comparisons of the experimentally obtained connection capacities and capacities that would be predicted using available design methods. Specimens with corbels oriented so the grain was perpendicular to the applied loads resulted in maximum loads that were greater than predictions made using Eurocode 5 [18] design procedures. Configuration 1 specimens with corbel grain oriented parallel to applied loads resulted in maximum loads that were less than predicted values. The remaining specimens with corbels oriented parallel to the applied loads were greater than design predictions. These trends can be seen in Table 2, above. The amount that the design procedures over-predicted the test results ranged from 3% up to approximately 30%, which is generally considered to be rather low with regard to a factor of safety. In general connection tests should exceed predicted design values by 150% in order to provide a reasonable factor of safety according to some model code requirements [19]. The lower test values were likely a result of the small corbel size with respect to the large number of fasteners in each corbel which led to splitting and crushing of the corbels so that the fasteners did not in the end have enough supporting timber around them to resist loads at the higher end of the load range.

5 CONCLUSIONS
Experimental testing of screwed corbel connections for new seismic resistant timber buildings has shown that design methods in Eurocode 5 [18] provide somewhat un-conservative predictions of connection failure when loaded vertically. Subsequent testing on a 2/3 scale 2-storey demonstration building at the University of Canterbury has assessed the load behaviour of the screwed connections and provided additional data for the design of these structures. In conjunction with previously published connection testing data [8], the strength of the connections have proven to be dictated more by the joist or gravity beam hanger connections rather than the corbel to column connections. Therefore, while the connections provide a safe attachment of the corbels for the intended use, there remain some issues to be addressed. As long as the design of these connections is contingent on the performance of the attachment of the joist hanger to the top of the joist, the connections should be safely designed, but it is critical for designers to check corbel connections as well and it is recommended that the test data presented for this research be considered along with design methods provided by building codes.

The use of small (100mm x 220mm and 100mm x 290mm) LVL corbels with 10 screws for attachment to columns provided resistance to single shear loads that could be described as a Mode f (according to EC5 [18]) type failure with double plastic hinges forming in the screws and crushing of the timber around the screws up to the point where the corbel material began to fail. These crushing and splitting failures of the LVL compromised the material around the fasteners and caused premature failure of the joints. Considering this behaviour, it is not surprising that the tested capacities were not significantly greater, and in some configurations less than the predicted design values. This also supports the use of pre-drilling prior to installing fasteners so that the splitting behaviour of corbels is not exacerbated by the screw installation. Corbel connections of this type are still under investigation, but were deemed as acceptable for the specific application described herein. Future testing of cross-banded LVL for corbels is recommended, as a means of reducing the observed splitting failures.

Development of connections similar to these and also for gravity resisting systems that do not require the ability to rotate are currently underway and will continue to be studied as part of the post-tensioned LVL buildings under development in New Zealand.

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REFERENCES


