EVALUATION OF SCREWS USED IN LAMINATED VENEER LUMBER ROCKING CONNECTIONS

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ABSTRACT

There is a large body of research currently underway in New Zealand investigating the behaviour and design of multi-storey and long-span structures utilizing laminated veneer lumber (LVL) as beam, column and wall components. Screws have significant potential for use as fasteners for a myriad of connections throughout these buildings. There is currently a lack of data on the behaviour of screws when used with LVL. In many cases screws are installed parallel to the laminations (and glue-lines) and subjected to withdrawal loading, so it is necessary to determine appropriate configurations of screws that can be safely used in these situations. Some systems also place high structural demands on corbels to support floor units and gravity beams. Monotonic testing on double shear screwed connections in LVL has been performed on specimens with varying screw configurations, LVL thickness, member depth and corbel configurations. Direct withdrawal tests of screws installed into the edge grain of LVL, parallel to the glue lines were conducted using varying screw penetration depth, screw spacing and numbers of screws. Comparisons are drawn between existing standards for determining screw connection capacity typically used for solid timber and glue laminated material and the capacities of the screwed connections in LVL. Recommendations are made for calculating LVL connection strength using screws as well as the limitations of existing design code predictions when using screws installed parallel to glue lines in LVL.

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 building systems incorporate large timber sections, constructed of laminated veneer lumber (LVL), held together using steel post-tensioning tendons. These buildings have the ability to re-centre themselves after a seismic event, and the inclusion of energy dissipating devices allows for energy absorption and dynamic damping during an earthquake. The buildings have significant potential to compete with current forms of construction in concrete and steel (Smith, 2008 and Smith *et al.*, 2009) and allow for open floor plans suitable in a large range of commercial or office type structures.

Experimental and analytical research on post-tensioned LVL buildings in New Zealand has focused primarily on building components including beam-column joints, and timber-concrete floor systems (Iqbal *et al.*, 2008, Yeoh *et al.*, 2008 and Yeoh *et al.*, 2011). A 2/3 scale two-storey structure using this technology was designed, fabricated by regional glue laminators and erected at the University of Canterbury as shown in Figure 1. This building was tested to assess the structural integrity of the system when subjected to biaxial pseudo-static lateral loading. To accommodate the necessary movement of the structure due to lateral loads and minimise damage to the floors during rocking, innovative connections between beams and floor joists, and supporting post-tensioned frame and wall systems were required. These connections were designed using locally available self-drilling screws to be hung from corbels, which were screwed to the larger building components as seen in Figure 2, using methods provided in NZ Standard 3603 (SNZ, 1993) and the Timber Design Guide (Buchanan, 2007) based on methods for designing connections in solid sawn timber and glue laminated timber. The design of these connections using LVL 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 (Snow *et al.*, 2008). Because the screws in many of these connections have

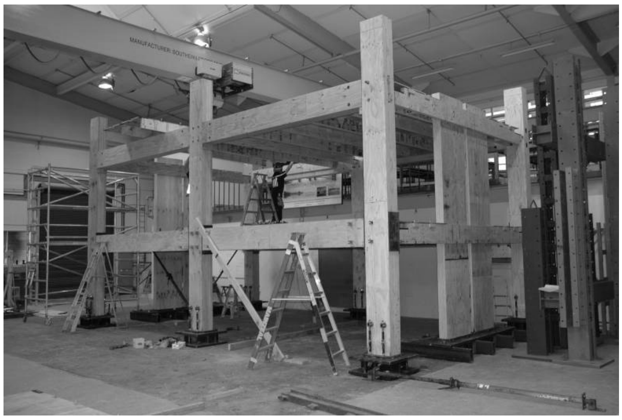

Figure 1. 2/3 Scale post-tensioned test structure at the University of Canterbury.

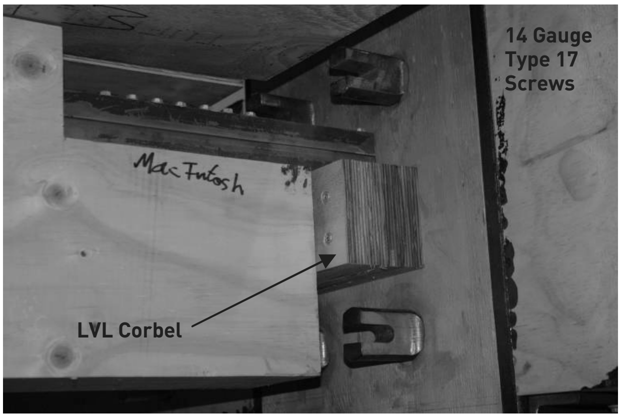

Figure 2. Hanging beam/floor joist connections.

been installed parallel to the LVL glue lines and are subject to withdrawal loading, there is concern that failure modes of these connections have not been accurately covered in standard timber design methods.

Fasteners used for the rocking connections were primarily 14 gauge Type 17 screws sourced from local New Zealand suppliers. These screws have a hexagonal head and a wood cutting tip (Buchanan, 2007) so that pre-drilling is not required. Variations in diameter and length of threaded portion have been found from suppliers, even in cases where identical specifications were requested. These screws have often been used to secure light roofing materials to timber framing and are gaining popularity as a quick and effective means for securing timber members in structural applications. Some testing was also performed using SFS screws manufactured in Switzerland which have very consistent dimensions and threaded lengths, but are not currently able to be purchased locally in New Zealand.

Several studies have been conducted on the behaviour of screws for connections and reinforcement in solid timber and glue laminated structures. Inclined self-tapping screws in timber were tested and modelled by Bejkta and Blaß (2002). Newcombe *et al*. (2009) expanded on this work by testing laterally loaded connections between LVL floor joists and laminated LVL framing members using 14 gauge Type 17 screws installed at 90º and 45º. These connections provided adequately strong, stiff and ductile connections intended for use with multiple storey timber structures using LVL. Jöhnsson and Thelandersson (2005) investigated the effectiveness of self-tapping screws (8.2 mm x 300 mm and having two separate threaded portions) used for reinforcement against perpendicular to grain stresses in curved glue laminated structures. Bejkta and Blaß (2005) tested dowel connections in timber with fully threaded, self-tapping screws as reinforcement and developed a model to predict the behaviour of these connections. They also verified the effectiveness of fully threaded, self-tapping screws as reinforcement in timber supports using tests and developed a model (Bejkta and Blaß, 2006). All three previously mentioned studies verified the effectiveness of using screws as reinforcement in timber.

Because LVL is a proprietary product, research projects aimed at quantifying its behaviour have been performed, but mostly by manufacturers providing data on mechanical properties for use by designers and other users of the products. In New Zealand, fastener capacities in wood-based products are tested according to AS 1649-1974 Methods for determination of basic working loads for metal fasteners for timber (AS, 1974) and are then placed into strength groups (SNZ, 1993) rather than providing specific design values. Kairi (2004) investigated bolted connections in LVL fabricated with the laminations oriented diagonally. Hummer *et al*. (2006) 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. Bier (2003) provided test data and discussion on issues raised regarding highly loaded structures fabricated from LVL. Gaunt *et al*. (2007) described testing on fastener behaviour in a range of LVL manufactured by Carter Holt Harvey. Franke and Quenneville (2009) provided test data and discussion on the embedment strength of LVL utilising different international testing standards. In general, LVL manufacturers publish design values for their products which are based on testing, and while for some manufacturers this includes values for screws installed parallel to the glue lines subject to shear or withdrawal, these data are not included in existing design standards. This lack of information creates a distinct need for testing and validation of design methods for specific screwed connections in LVL, such as those described in this paper.

2. EXPERIMENTAL METHODS AND MATERIALS

The objectives of the project were on the one hand to assess the actual capacity of the rocking connections designed for the current demonstration building constructed at the University of Canterbury, and secondly to determine the withdrawal strength of screws installed parallel to the glue lines of LVL, for comparison with published design recommendations. In New Zealand and Australian timber design, data for connections is assessed through testing according to AS 1649-1974 (SAA, 1974) and the timber or timber based material is classified into strength classes or groups. This has significant limitations for materials such as LVL and provides limited information on load-slip characteristics, failure modes and potential hazards of using specific types of timber composite materials. More detailed information on connection behaviour is therefore required for the building system under investigation.

2.1. TOP HUNG CONNECTION TESTING

The testing configuration utilised for the connection tests was double shear as shown in Figure 3. Due to the unique nature of the connections, ASTM Standard D 7147

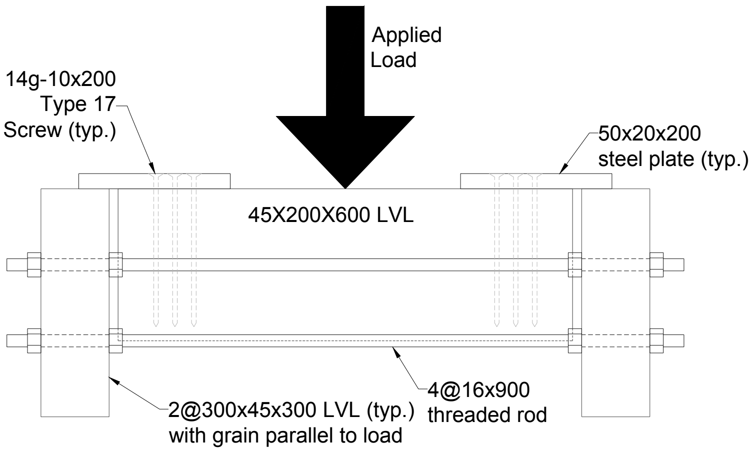

Figure 3. LVL connection testing configuration.

– 05 Standard Specification for Testing and Establishing Allowable Loads for Joist Hangers (ASTM, 2008a) was used as a guideline for test procedures. Loads were applied to joist members using a 250 mm x 250 mm steel plate attached to the cross head of an Avery testing frame and were applied at a consistent rate such that failure did not occur before 5 minutes. Displacement measurements were obtained at both ends of the joist member with respect to the LVL end blocks. Load and displacement data were obtained using a computer controlled data acquisition system.

Testing configurations are described in Table 1, below. Screws were locally purchased, self-drilling, 14 Gauge Type 17 screws having a measured shank diameter of 5.3 mm. Observations indicated that splitting could occur when installing the screws, therefore tests were also conducted with screws installed in pre-drilled holes having a diameter consistent with Eurocode 5 (EC5, 2004) and NZS 3603 (SNZ, 1993) recommendations. The LVL used came primarily from one of the two major LVL manufacturers in New Zealand, although a partial set of tests was also performed using LVL from the other manufacturer for comparison. Sample sizes were a minimum of three, with most having between five and nine specimens tested. The specimens using the other LVL manufacturer contained only two specimens each and were used only as a spot check of possible difference between the two manufacturers. Sample sizes were kept small due to the complexity of the connections and for the reason that once effective connection configurations were determined, additional testing would be conducted using larger sample sizes.

As testing progressed on these initial four connection types, other connection possibilities became apparent and were tested also. Configuration 2 from Table 1 was tested using 6 mm diameter high tensile strength threaded rods and a 6 mm thick steel plate beneath the joist instead of relying on the withdrawal or tensile capacity of the screws but this was not included in the results as the capacity was based on threaded rod capacity. Additionally it was observed that the first screw in the row of three used for Configuration 1 was the screw taking most of the load, therefore Configuration 1A reconfigured the three screws so that the first row contained two screws rather than one as shown in Figure 4 and was only tested using pre-drilled holes.

Figure 4. LVL test connection Configuration 1A.

Table 1. LVL connection testing configurations.

Configuration	Joist Thickness (mm)	Number of Screws per Side	Depth of Joist (mm)	Steel Plate Dimensions (mm)	Screw Length (mm)
1	45	3	200	20x50x200	200
2	45	3	100	20x50x200	100
3	65	7	200	25x50x342	200
4	3x65	28	200	2@25x125x342	150

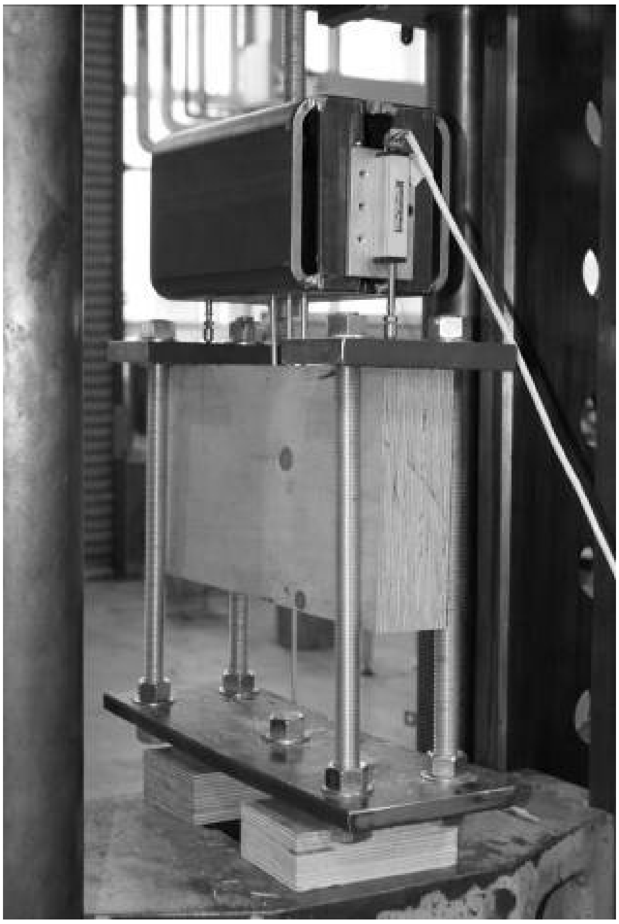

Figure 5. Direct withdrawal testing apparatus for screws in LVL.

2.2. WITHDRAWAL TESTING

Direct withdrawal tests of 14 Gauge Type 17 screws installed into the edge of LVL members, parallel to the glue line, were conducted using ASTM D 1761-06 (ASTM, 2008b) as a guideline. LVL used was from a single New Zealand supplier and were prisms 200 mm deep and 400 mm long, using the apparatus shown in Figure 5. In all cases screws were installed at the centre top face of the prisms, with the screws installed parallel to the glue lines and perpendicular to the top face. Configurations were varied based on number of screws (1, 2, 3 and 5), penetration depth (40, 60 and 80 mm), screw spacing (25 and 50 mm) and LVL thickness (45 and 65 mm). Sample sizes were a minimum of three, with most having between five and ten specimens tested. Table 2 describes the specific screw withdrawal combinations tested. Most withdrawal tests were conducted without pre-drilling, but some configurations using 65 mm thick LVL were pre-drilled to assess the effects.

2.3. CORBEL TESTING

The double shear testing configurations utilised for corbel connection tests are shown in Figure 6. 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

Table 2. LVL screw withdrawal testing configurations.

Number of Screws	LVL Thickness (mm)	Screw Spacing (mm)	Penetration Depth (mm)
1	45 and 65	0	40, 60 and 80
2	45 and 65	25 and 50	60 and 80
3	45 and 65	25 and 50	60 and 80
5	45 and 65	25 and 50	60 and 80

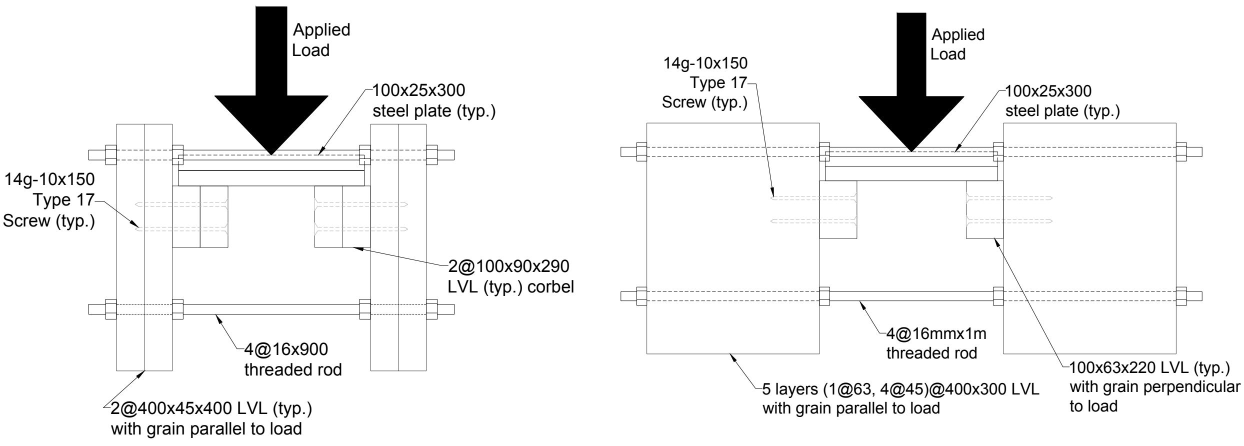

Figure 6. Corbel testing specimen example for Configurations 1 through 3 (left) and Configuration 4 (right).

simultaneously. Additional tests were performed with the corbels attached parallel to the glue lines of the columns, also shown in Figure 6. ASTM Standard D 7147 – 05 (ASTM, 2008a) 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 7.

Figure 7. Corbel testing specimen for Configuration 1C.

Testing configurations are described in Table 3. Screws were the same as previously described. Some Configuration 1 specimens were fabricated using 150 mm by 6.4 mm 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 (2004) and NZS 3603 (1993) recommendations. Corbels were fabricated from 45 mm thick LVL, except for Configuration 4, which used 63 mm thick LVL. 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.

2.4. SUPPLEMENTAL TESTING

In addition to withdrawal and double shear connection tests describe above, moisture content specimens were obtained from tested specimens and examples of 200 mm long, 14 gauge Type 17 wood screws in tension to determine the average ultimate capacity of 17.56 kN.

3. RESULTS AND COMPARISONS

Presented in this section are experimental test values for double shear connection capacity and withdrawal strength tests performed, and descriptions of failure mechanisms observed. Comparisons are provided between average test data and predicted design capacities from NZS 3603:1993 (SNZ, 1993).

3.1. TOP HUNG CONNECTION TESTING RESULTS

Testing previously described was conducted on a series of connections subject to double shear and averages of each configuration are presented in Table 4, which represent the applied loads for each side of the tested specimens. Failure modes for Configurations 1 and 1A were primarily due to screw breakage, most often starting with the outermost screws. Configuration 2 specimens began splitting upon installing the screws when no pre-drilling was done, contributing to screw withdrawal as the mode of failure, which was similar for the specimens with pre-drilling, although the lack of splitting in pre-drilled specimens resulted in greater ultimate connection capacity. Small splits were also observed between fasteners following installation of screws for Configuration 3 specimens without pre-

Table 3. Corbel testing configurations.

Configuration	Screws	Corbel (sample size)
1A	5.3 mm x 150 mm Type 17, 40 mm o.c.	2 @ 100 mm x 220 mm, grain parallel to loading (1)
1B	5.3 mm x 150 mm Type 17, 40 mm o.c.	2 @ 100 mm x 220 mm, grain perpendicular to loading (1)
1C	6.4 mm x 150 mm SFS 40 mm o.c.	2 @ 100 mm x 220 mm, grain parallel to loading (2)
1D	6.4 mm x 150 mm SFS 40 mm o.c.	2 @ 100 mm x 220 mm, grain perpendicular to loading (2)
2	5.3 mm x 150 mm Type 17, 50 mm o.c.	2 @ 100 mm x 290 mm, grain parallel to loading (2)
3A	5.3 mm x 100 mm Type 17 40 mm o.c.	1 @ 100 mm x 220 mm, grain parallel to loading (3)
3B	5.3 mm x 100 mm Type 17 40 mm o.c.	1 @ 100 mm x 220 mm, grain perpendicular to loading (3)
4	5.3 mm x 100 mm Type 17 40 mm o.c.	1 @ 100 mm x 220 mm, grain perpendicular to loading (2)

Note: o.c. means the screw spacing "on centres"

Table 4. LVL double shear connection testing results and comparisons with design standard values.

Configuration	Average Test Capacity with No Pre-Drilling (kN)	Average Test Capacity with Pre-Drilling (kN)	NZS 3603 Design Strength (kN)
1	12.44	12.45	4.31
1A	NA	19.70	7.58
2	8.33	11.57	3.26
3	17.78	19.46	9.17
4	NA	43.87	27.60

drilling, and both pre-drilled and non pre-drilled specimens failed as a result of a combination of withdrawal and screw breakage, although screw breakage was considered to be the primary and limiting failure mode. Configuration 4 specimens failed as a result of perpendicular to grain splitting of the LVL at the plane where the screws ended.

While the data obtained provided verification that these screwed LVL connections were sufficiently strong, experimental observations suggested that the behaviour of these double shear connections was more complex than simple withdrawal of the fasteners, but also incorporated aspects of bending as the steel plate was displaced and some amount of shear due to the lateral movement of the steel plate in connections where a notch prevented the free rotation of the plate. To design these connections it was assumed that the steel plates were rotating about the inside corner of the steel plate and that the distribution of load to the line of fasteners would be linear due to the relative stiffness of the steel plate. It is worth noting that the strength reduction factor used for determining capacities of connections was 0.7, the most stringent in NZS 3603 (SNZ, 1993) and resulted in very conservative design values. Carter Holt Harvey literature suggests designs in LVL using Type 17 screws could use a strength reduction factor of 0.8, with the assumption that these screws have similar reliability to nails. Comparisons with test capacities provided acceptable factors of safety, but decreased as the number of screws per connection was increased. Pre-drilling holes did not have a significant effect on Configuration 1, but the capacity of Configurations 2 and 3 increased by 39% and 9.5%, respectively when pre-drilled holes were used.

3.2. SCREW WITHDRAWAL TESTING RESULTS

Screw withdrawal testing from the edge of LVL was conducted as previously detailed and averages of each configuration are presented in Table 5. Failure mode for all single screw withdrawal tests was withdrawal of the screw from the LVL. Screw withdrawal continued to be a failure mode when two and three screws were installed at 50 mm spacings, but when spacings were reduced to 25 mm a type of plug shear failure was observed where a segment of timber was removed from the region between the screws as load was applied. Examples of this failure mode are shown in Figure 8. A proposal that rolling shear values be considered for designs to avoid this type of failure has not been finalised. None of the screws fractured during withdrawal testing.

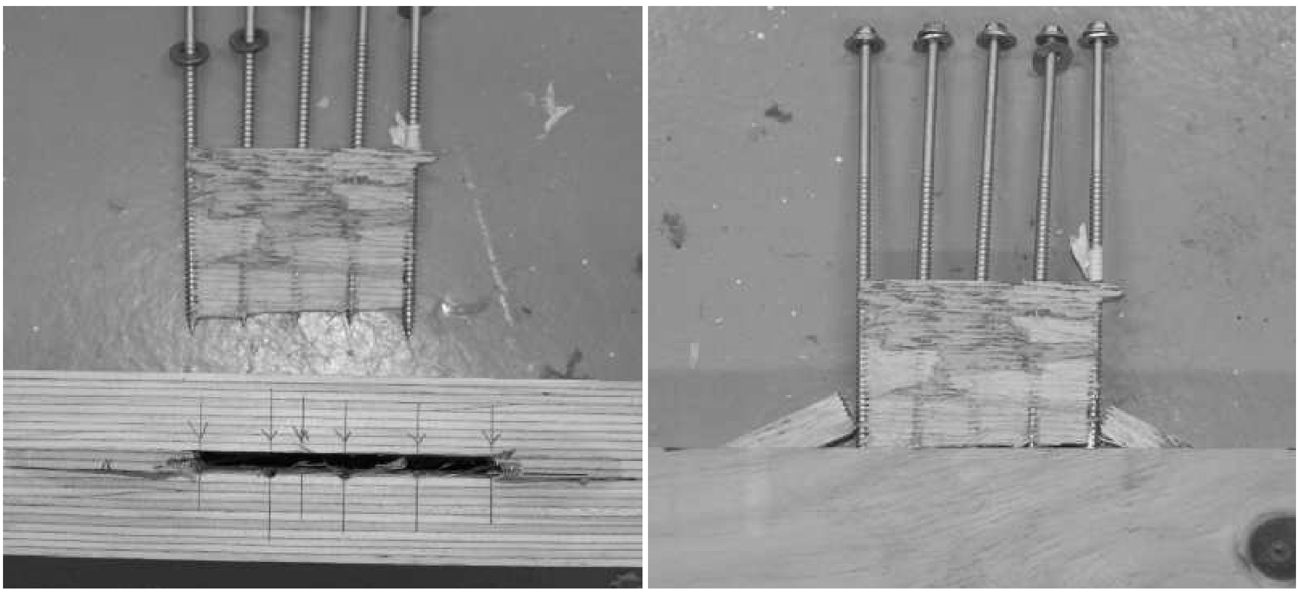

Figure 8. Shear plug failures observed during screw withdrawal tests from LVL.

Table 5. Screw withdrawal parallel to the glue line from LVL testing results and comparisons with design standard values.

Number of Screws (Sample Size)	Penetration Depth (mm)			Screw Spacing (mm)		LVL Thickness (mm)		Average (Characteristic) Testing Withdrawal Strength (kN)	Eurocode 5 Design Withdrawal Strength (kN)	NZS 3603 Design Withdrawal (kN)
	40	60	80	25	50	45	65			
1(4)	X					X		7.3 (6.7)	4.3	3.2
1(3)	X						X	6.0 (5.7)	4.3	3.2
1(3)		X				X		11.5 (11.1)	6.2	4.8
1(3)		X					X	10.6 (10.3)	6.2	4.8
1(4)			X			X		16.0 (15.9)	8.0	6.4
1(3)			X				X	13.1 (12.9)	8.0	6.4
2(3)		X		X		X		19.4 (18.9)	11.6	9.5
2(3)			X	X		X		25.8 (19.1)	14.9	12.7
2(3)		X			X	X		20.8 (19.7)	11.6	9.5
2(3)		X		X			X	15.7 (14.7)	11.6	9.5
2(2)			X	X			X	21.7 (19.9)	14.9	12.7
2(2)			X		X		X	25.1 (24.7)	14.9	12.7
2(4)		X			X		X	17.0 (15.1)	11.6	9.5
3(2)		X		X			X	21.2 (21.2)	16.7	14.3
3*(3)		X		X			X	22.2 (19.6)	16.7	14.3
3(1)			X	X			X	27.2 (27.2)	21.4	19.1
3*(6)		X			X		X	23.5 (20.9)	16.7	19.1
5(3)		X		X			X	22.2 (20.1)	26.4	23.9
5*(3)		X		X			X	25.1 (24.2)	26.4	23.9
5(3)			X	X			X	32.2 (26.6)	33.9	31.8

**Pre-drilled Specimens Tested*

Direct screw withdrawal tests in LVL provided data on behaviour of these connections subject to withdrawal loads and on the effects of connection parameters. Loads clearly increased in a very predictable fashion with increases in penetration depth. Pre-drilling resulted in slightly increased strength values and 65 mm thick LVL consistently had lower withdrawal strength values that 45 mm thick LVL. Increased fastener spacing from 25 mm to 50 mm also provided slightly increased strength. Strength gains with increased numbers of screws decreased as the number of screws went from two to three to five. Specimens having more than two screws installed 40 mm deep into 45 mm thick LVL were prone to perpendicular to grain splitting of the LVL which was attributed to the length of the specimens, therefore only 65 mm thick was used for specimens having more than two screws. Penetrations deeper than 80 mm also resulted in screw failures and were not included within these data presented.

Screw withdrawal test data comparisons with design values obtained from Eurocode 5 (EC5, 2004) and NZS 3603 (SNZ, 1993) suggest that there are some connection predictions which are unconservative. Some Eurocode 5 predictions were greater than experimental test values. This over estimation of connection capacity was observed for the connections using 5 screws, as can be seen in Table 5. The same trend is seen in design predictions from NZS 3603, but most of the values in this case tend to be less than the experimental strengths and for single screws a reasonable factor of safety is achieved. Five screw withdraw strength predictions from NZS 3603 are nearly equal to the experimental strengths but without much margin of safety beyond that which is included in the design load factors.

3.3. CORBEL TESTING RESULTS

Average strengths of the two connections are presented in Table 6 for each configuration along with predicted failure loads using the Johansen methods for predicting single shear connection capacities as found in Eurocode 5 (1994).

Table 6. Averaged corbel testing results.

Configuration	Maximum Load per Connection (kN)	COV (%)	Predicted Design Load (kN)
1A	51.8	NA	54.8
1B	66.0	NA	55.1
1C	61.1	8.1	63.2
1D	88.5	1.0	63.2
2	69.3	5.9	54.8
3A	47.3	10.3	45.7
3B	64.8	3.6	45.7
4	61.7	3.6	55.8

3.3.1. Corbels Attached Using Type 17 Screws

Failure modes of the fasteners for all configurations were well predicted by Eurocode 5 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. Attempts were made to remove corbels and screws following testing for all configurations and it was apparent that not all 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 100 mm wide in order to simulate the conditions in the previously described test building. Figure 9 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 throughout testing.

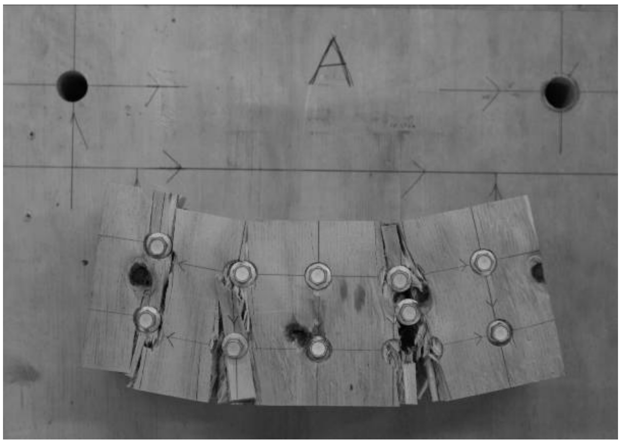

Figure 9. Corbel damage after testing of a Configuration 1A specimen with the applied load parallel to the grain of the corbel.

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. 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 45 mm thick LVL for the corbel. For Configuration 4 columns were orientated with glue lines parallel to the screws and corbels were made from 63 mm thick LVL. 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.

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. Deflections obtained for corbel to column connections were more than adequate at the design loads required for each of the configurations tested. In general corbel connections were very stiff and little displacement was observed during early loading stages. Significant displacements were not induced until design loads had been achieved.

3.3.2. Corbels Attached Using SFS Screws

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 larger diameter 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. The SFS screwed corbels were stiffer than the Type 17 connections and exhibited reduced translation of the corbels as in Figure 10.

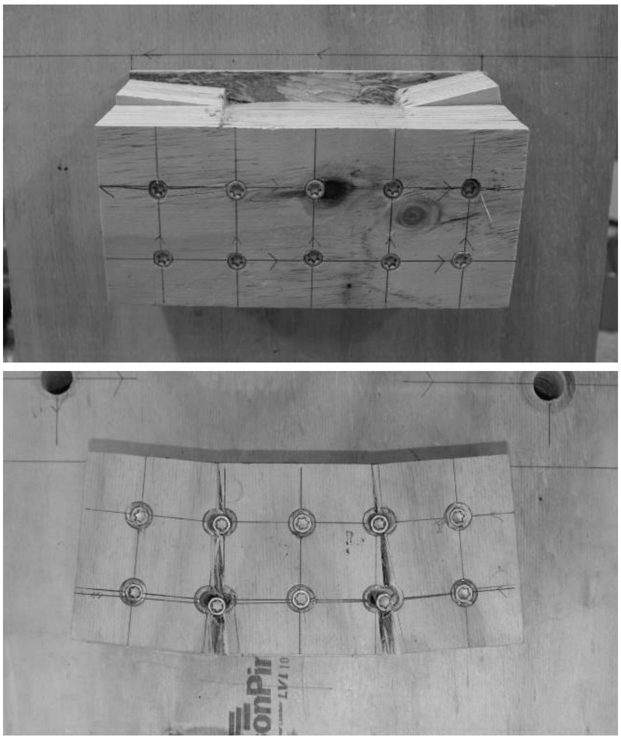

Figure 10. Corbels following testing using SFS screws for Configuration 1C (Bottom) and 1D (Top) specimens.

3.3.3. Corbel Orientation

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 (1994) 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 corbel grain oriented parallel to the applied loads were greater than design predictions. The amount that design procedures over-predicted 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 average connection test values should exceed predicted design values by 150% in order to provide a reasonable factor of safety according to some model code requirements (ICC, 2003). 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 corbels so that fasteners did not in the end have enough supporting timber around them to resist loads at the higher end of the load range.

All connections achieved maximum loads without failures that would be considered brittle. Significant amounts of energy were required to fail these joints avoiding large drops in load resistance. This indicated that the connections were ductile and were configured to maximise the ductility capacity of metal fasteners. This suggests that these 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, which are 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. RECOMMENDATIONS AND FUTURE RESEARCH

Results from testing screwed connections in LVL provided valuable information on the behaviour of these connections which are being used for rocking timber systems for multi-storey and long span structures. Due to the lack of design information on these types of connections in LVL it was necessary to test structural connections to verify the strength experimentally. Design values obtained using NZS 3603 were considered adequate and allowed for factors of safety between 1.6 and 3.5 for top hung connections. While these connections have been shown to be effective for this application, it is recommended that different connections with screws in LVL be similarly investigated.

Predicted screw withdrawal values from Eurocode 5 and NZS 3603 were unconservative when more than 3 screws were used. Because increased fastener spacing resulted in only minimal strength increases, it is recommended that designers exercise caution when predicting the strength of screwed connections subject to withdrawal loads parallel to glue lines using multiple fasteners. Spacing between multiple fasteners needs to be researched further in order to understand the plug shear failure mode described previously and to determine at what spacing this will no longer be a consideration. Screw placement should also be manipulated and tested, such as staggering rather than installing fasteners in a continuous line, as a means of avoiding this failure mode, which reduced direct withdrawal capacity.

It is recommended that investigations on the differences between solid timber, glulam and LVL be conducted for inclusion of appropriate factors for adjusting design capacities to account for the structural behaviour of LVL as a building material. Timber does not exhibit the plug shear failures observed in LVL, possibly due to rolling shear failure of laminations within LVL once the screws have been installed and this requires further research. It is also known that peeler checking during LVL manufacture and veneer thickness can affect rolling shear values, and these vary among manufacturers. Similarly, the effects of using different thicknesses of LVL should be investigated as current codes do not differentiate between them, even though withdrawal tests indicated that thicker LVL had lower withdrawal capacities.

Connections are being developed currently which will have screws installed into the end grain of the LVL, parallel to the glue lines and the longitudinal axis of the member. Corbel connections and the effects of different spacing, screw configuration on splitting at the time of installation are also under investigation at the time of writing this paper. Screws installed diagonally to the face of installation will also be tested and analysed for future connection studies.

5. CONCLUSIONS

Experimental testing of screwed connections in LVL designed for rocking timber building systems has shown that design methods in NZS 3603 (SNZ, 1993) provide acceptable 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 lateral load behaviour of the screwed connections and provided data for the design of these structures. NZS 3603 provided conservative values for these connections due to inherent uncertainty of the fastening method reflected in the standard as well as assumptions that designers make in order to predict the behaviour of connections that have never been tested or used in practice. The strength of connections has proven to be dictated more by joist or gravity beam hanger connections rather than the corbel to column connections. Therefore, while the connections provide a safe attachment of corbels for the intended use, there remain some issues to be addressed. As long as the design of these connections is contingent on 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. Development of connections similar to these and also for gravity resisting systems that do not require the ability to rock, are currently underway and will be presented in future papers.

Direct withdrawal testing of self-drilling 14 gauge Type 17 screws installed in the edge of LVL members parallel to the glue lines provided data indicating that Eurocode 5 (EC5, 1994) and NZS 3603 (SNZ, 1993) predictions of withdrawal strength tended to be unconservative particularly when more than a single screw was installed in a row along the length of the LVL. It was observed that a possible failure mode where a plug of timber between the screws was removed as withdrawal loads were applied, is a concern for designers and needs to be investigated because the spacing requirements from both model building codes did not keep this from occurring. Designers should exercise caution when designing these types of connections unless very conservative assumptions are used for the distribution of forces to screws.

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