Forintek Canada Corp.
Western Division
2665 East Mall
Vancouver, BC
V6T 1W5

Confidential

Testing of Lateral Resistance of Handcrafted Log Walls Phase I and II

by

Dr. Marjan Popovski

Prepared for
International Log Builders' Association

March, 2002

Project No. 3512 / 3512A

Marjan Popovski	Bill Deacon	Erol Karacabeyli
Project Leader	Reviewer	Manager, Wood Engineering Dept.

Confidential

Summary

Under a contract with International Log Builders' Association (ILBA) and financial contribution from Forest Renewal British Columbia, under the Value-Added Technology Transfer Program, Forintek Canada Corp. has carried out a testing program to assess the lateral load capacity of handcrafted log walls. Five different configurations of handcrafted log walls were tested. A total of ten quasi-static tests were conducted: four monotonic (pushover) tests and six reverse load (cyclic) tests. Results form the tests are presented in this report along with some recommendations for potential improvement of the system, and directions for future research.

Acknowledgements

Forintek Canada Corp. wishes to acknowledge the FRBC financial contribution to the project. The project leader would like to acknowledge the contribution of all Forintek staff involved in the project, especially the contribution of Mr. Henley Fraser, Mr. Paul Symons, Mr. Len Stroh and Mr. Bill Deacon from the Wood Engineering Department, for their highly professional commitment to the work. The comments, suggestions and guidance provided by Mr. Erol Karacabeyli, the manager of the Wood Engineering Department, is greatly acknowledged.

Table of Contents

List of Tables

List of Figures

1 Objectives

A large amount of research is available on the lateral resistance of conventional wood-frame construction, the most common structural system used in residential buildings in North America. However, to the best knowledge of the author, there is virtually no research published on the response of handcrafted log houses subjected to lateral loads. For that reason, under contract with the International Log Builders' Association (ILBA), Forintek Canada Corp. has carried out an experimental research program to assess the lateral load resistance of handcrafted log walls as main lateral load resisting elements in log houses. The research program:

- Provides the load-deformation relationships of the tested configurations of handcrafted log walls when subjected to unidirectional and cyclic lateral loads;
- Provides information on strength, stiffness, deformability and failure characteristics of the tested configurations of handcrafted log walls;
- Studies the lateral load transfer mechanism in various configurations of log walls;
- Gives comments on the energy dissipation characteristics of the tested configuration of log walls.

2 Introduction

The response of timber structures to wind or earthquake loading is in general a complex issue, involving many different interacting factors that need to be understood and quantified. Although both wind and earthquake actions introduce lateral loads on the structures, they are very different natural phenomena that require different design approaches. In the case of strong winds, pulses of velocity pressure caused by the wind create lateral forces on the structure. The size of the lateral force generated by wind depends on various factors including the velocity of the wind, shape of the building, slope of the roof, and exposure of the building site. The building has to be designed to have the adequate strength to withstand the wind-induced forces, while having adequate stiffness to avoid excessive deformations.

In case of an earthquake, the ground acceleration, velocity and displacements (referred to as ground motion) when transmitted through a structure cause horizontal displacements that induce horizontal inertial forces on the structure. In some cases these horizontal forces exceed those the structure can sustain, leading to structural damage, or even partial or total structural collapse. Observations from past earthquakes supported by theoretical and experimental investigations have shown that besides the characteristics and duration of the ground motion, many other parameters such as building configuration and structural irregularities, dynamic characteristics of the building, and damping and energy dissipation mechanisms, influence the seismic response of timber buildings. The most important consideration for designing earthquake resistant structures is to provide a system that can absorb a large amount of the seismic energy and thus lower the earthquake-induced forces, while maintaining adequate stiffness to avoid excessive deformations.

Handcrafted scribe-fit log houses are unique among timber structures because of the techniques and details used during their design and construction. The interlocking joinery that is used in handcrafted log houses creates a structural system that acts differently under seismic and wind loading than the systems used in conventional wood-frame construction (Hahney 2000). Although, according to the National Association of Home Builders (NAHB 2002) there are currently more than 400,000 log homes in use in the U.S. and Canada, the lateral load resisting characteristics of this system have yet to be determined. It is expected that the results from this study will be very helpful to this industry and will lead to the further study of log homes, so that inherent advantages of this type of structures can be convincingly established. With an average price of a log house, excluding land being around $ US 150,000 (LHLI 2002), and a total industry output valued at more that one Billion $ US per year, this is long overdue. The need for study will increase as more log buildings are constructed ranging from starter homes and cozy cottages to luxury residences and retirement homes, due to the environmental advantage of building with a renewable material that creates a warm and inviting atmosphere.

3 Materials and Methods

A series of quasi-static tests was performed in Forintek's Wood Engineering Laboratory to determine the lateral resistance of handcrafted log walls. Quasi-static testing is the most common testing procedure in structural and earthquake engineering because of its relative simplicity and cost effectiveness. Much of the current knowledge on seismic performance of wood connections, components and systems was derived from quasi-static testing. The term 'quasi-static' testing indicates that the loads are applied at rates slow enough so that the material strain rate effects do not influence the results. As such, quasi-static testing refers to either pushover or cyclic tests, although it is more commonly associated to the later in the literature. Quasi-static tests allow monitoring of the components' behaviour under controlled loading conditions. The behaviour obtained from these tests, unlike interpretations from purely analytical research, contains all possible failure mechanisms whether or not the researcher has anticipated them prior to the test.

During the experimental program, two types of displacement controlled quasi-static tests were performed: pushover and cyclic. Generally, in displacement controlled pushover tests of walls, unidirectional displacement is introduced to the top of the wall at a certain rate, while the bottom of the wall is fixed to the foundation. The testing usually continues until the ultimate displacement of the wall has been reached. During a typical cyclic test, a reverse displacement pattern with increasing amplitudes is introduced at the top of the wall. This pattern is supposed to resemble the reversing displacements present in real earthquake motion, but at much lower displacement rate.

The tests were performed using the Forintek's apparatus designed for testing of the lateral resistance of wood-framed shearwalls. Some adjustments were made to accommodate the log wall specimens. According to both letters of understanding between ILBA and Forintek, a total of four tests were planned, two pushover and two cyclic, on two different wall configurations under constant vertical load. However, a total of ten tests were conducted, four pushover and six cyclic, for a total of five different wall configurations. To study the influence of the vertical load on the lateral resistance of the walls, some of the additional tests were conducted under higher vertical load than the originally agreed load of 5.34 kN (1,200 lbs) per wall. The decision to expand the testing program at no additional cost to the client was made by the project leader in consulting with the manager of the Wood Engineering Department, to further study the parameters that influence the lateral resistance of handcrafted log walls. The test matrix for the experimental program for both pushover and cyclic tests is shown in Table 1.

Table 1 List of the quasi-static tests conducted

Test Number	Wall Number	Test Type	Vertical Load		Wall Configuration
			(kN)	(lbs)	
1	I	Pushover	5.34	1,200	No wood pins, no corners
2	I		10.68	2,400	No wood pins, no corners
3	II		5.34	1,200	Hardwood pins, no corners
4	III		5.34	1,200	Corners, no wood pins
5	III-A	Cyclic	5.34	1,200	Corners, no wood pins
6	III-B		44.48	10,000	Corners, no wood pins
7	IV		5.34	1,200	Softwood pins, no corners
8	IV-A		5.34	1,200	Hardwood pins, no corners
9	V		5.34	1,200	Hardwood pins, with corners
10	V-A		44.48	10,000	Hardwood pins, with corners

The client provided Forintek with a total of five walls form two different suppliers, and a number of wood pins. A total of five wall configurations were tested: (a) log wall with no wood pins and no corners; (b) log wall with wood pins but no corners; (c) log wall with corners but no wood pins; (d) log wall with softwood pins and no corners; and (e) log wall with hardwood pins and corners. In the case of walls with hardwood pins, two round 25.4 mm (1 inch) pins were placed between each two adjacent logs of the log wall in a staggered pattern. Similarly, in the single tests with softwood pins, Douglas-fir square pins were used provided by the client.

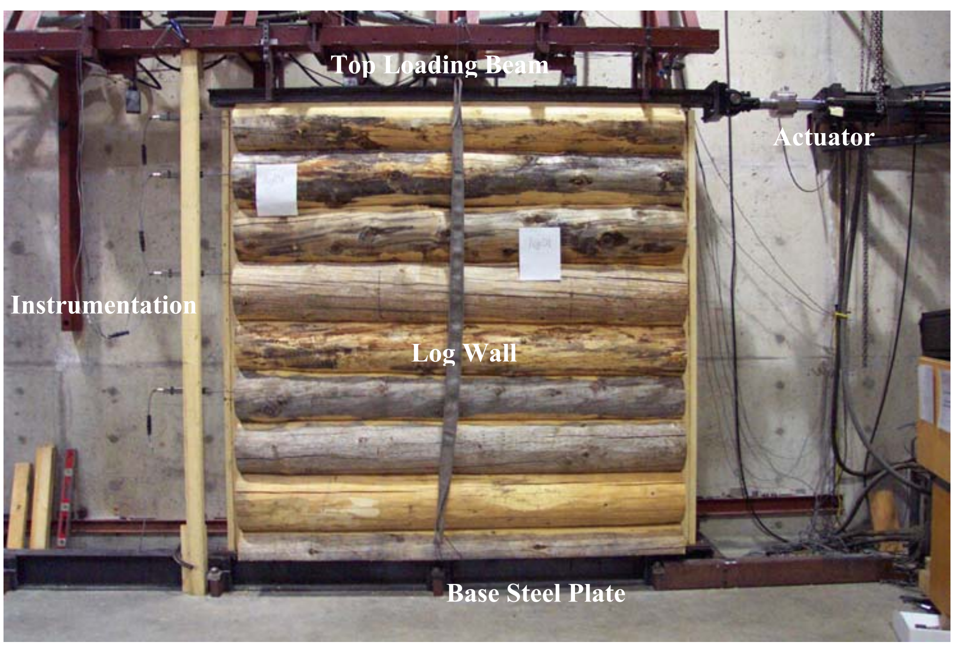


Figure 1 The lateral load testing apparatus with log wall specimen ready for testing

All log walls tested were 2.44 m (8 feet) by 2.44 m (8 feet) in size. Each wall consisted of nine logs, with diameters varying from 305 to 355 mm (12 to 14 inches). All logs were grooved along the length and notched for corners, where applicable. The logs were also marked for the order and orientation of their placement in the walls. The bottom log (log 1) was trimmed to match the testing apparatus bottom steel plate and was bolted using ten 12.7 mm (1/2 inch) bolts to the plate to provide fixture against lateral loads. The logs were then placed one by one on the top of each other, including the wood pins and corner logs where applicable, according to the marking scheme provided by the client. The top log (log 9) was trimmed to a 100 mm (4 inch) wide top to accommodate the top loading beam (horizontal spreader bar) be bolted with four 12.7 mm (1/2 inch) bolts to the top log. The top loading beam can have up to 111 kN (25,000 lbs) of lateral load applied through an actuator that is pin-connected to the right end side of the top loading beam. In addition it can also have up to 1.7 kN/m (1,200 lbs/ft) vertical load applied through several actuators with rollers at the point of loading. The test setup with a log wall ready for the test one is shown in Figure 1.

For the quasi-static pushover tests, a constant rate of loading (displacement) was used at 7.6 mm (0.3 inches) per minute. Cyclic tests were conducted using the International Organization for Standardization cyclic testing protocol, ISO-2001 (ISO/DIS 16670 2001). All tests were conducted with a total vertical load of 5.34 kN (1,200 lbs) except for the tests 3 which was conducted with a vertical load of 10.68 kN (2,400 lbs), and tests 6 and 10 with a vertical load of 44.48 kN (10,000 lbs). The cyclic testing protocol used is shown in Figure 2.

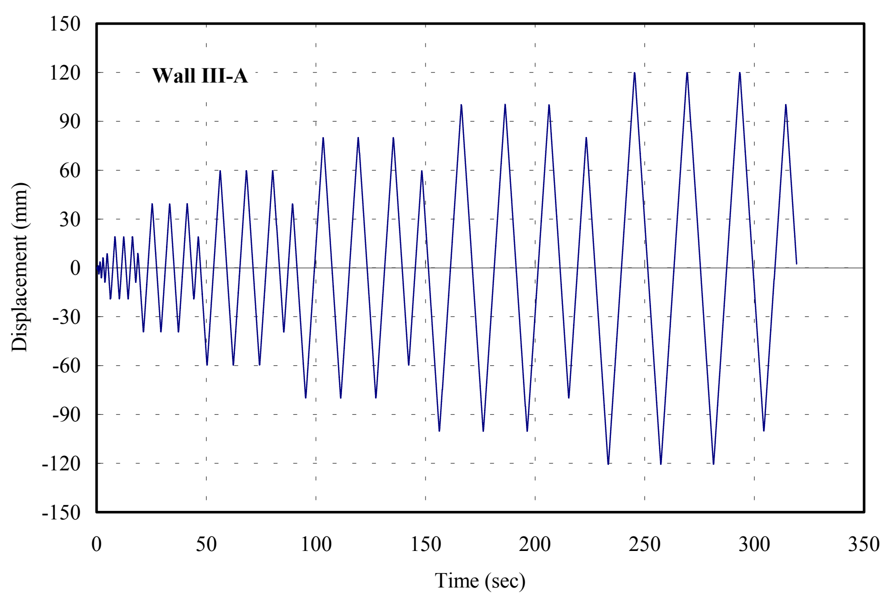


Figure 2 Cyclic testing protocol ISO-2001 used in the testing program

Eight data measurements (channels) were collected during the tests: applied lateral load, movement of the actuator head (stroke), and six deformations of the log wall. Lateral displacements of the top log (log 9), log 8, log 7, log 6, and log 4 were measured along with the vertical displacement (uplift) of the top right corner of the wall, near the place where lateral load was applied. The displacement transducers used for measuring lateral displacements had a maximum capacity of 114 mm (4.5 inches) in one direction or ± 57 mm (2.25 inches), if reversible displacements were expected. The list of all instrumentation channels is given in Table 2, while their location and channel numbering is shown in Figure 3.

Table 2 List of instruments used and their location

Channel Number	Instrument	Measurement	Direction
0	Load Cell	Lateral Load	Horizontal
1	Displacement Sensor	Stroke	Horizontal
2	Displacement Transducer	Displacement Log 4	Horizontal
3	Displacement Transducer	Displacement Log 6	Horizontal
4	Displacement Transducer	Uplift	Vertical
5	Displacement Transducer	Displacement Log 8	Horizontal
6	Displacement Transducer	Displacement Log 9	Horizontal
7	Displacement Transducer	Displacement Log 7	Horizontal

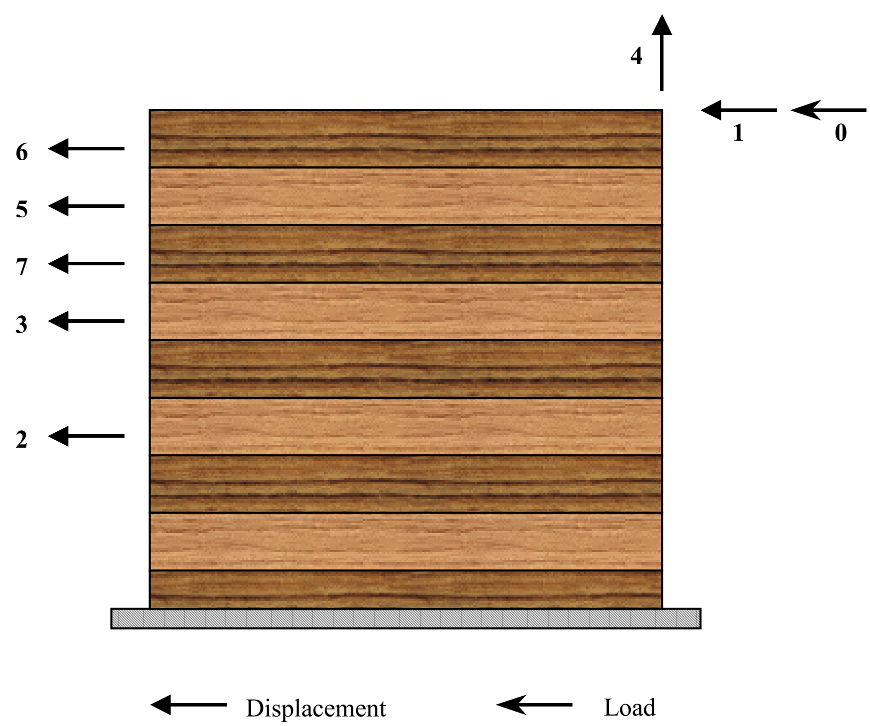


Figure 3 Location of the instrumentation points on the log wall

4 Results and Discussion

4.1 Pushover Tests

Pushover tests showed the load-displacement characteristics of the tested wall configurations when subjected to unidirectional lateral load. The load-deformation relationship obtained at the top log of the Wall 1 during test 1 is shown in the Figure 4. The displacement time histories of the top log (log 9) and log 8 are shown in Figure 5a, while the same histories for the logs 4 and 6 are shown in the Figure 5b. The time histories are not presented in one frame because of big differences in displacement values. It should be noted that all results are given in SI units. For conversion in Imperial units please note that 1 inch = 25.4 mm (1 mm = 0.03937 inches) and 1 kN = 224.81 lbs (1 lb = 4.44822 N).

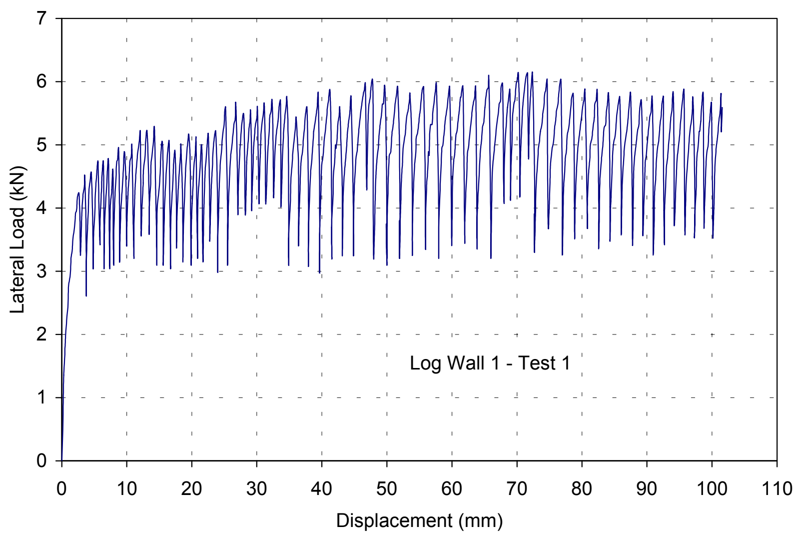


Figure 4 Load-deformation relationship at the top log level of Wall 1 - test 1

As shown in Figure 4, the load-deformation relationship of the wall is characterized by two mechanisms, friction, and wood crushing, with friction being the basic component of load transfer. After lateral load at any certain point has exceeded the friction capacity, a slip along one of the surfaces between logs occurred, resulting in sudden drop in the lateral load resistance. This was followed by rise in lateral load resistance when friction between logs increases due to wedging effect and wood crushing along the grooves between logs. This pattern was constantly observed during the test. However, as shown in Figure 4, the wall was able to sustain a deformation of over 100 mm (4 inches), and almost reaching the transducers' capacity, without showing significant reduction in strength properties. This kind of deformability is a very desirable feature for a wall component when subjected to earthquake ground motion.

Another examination of the load transfer mechanism can be made using the displacement histories of different logs presented in Figure 5. During the initial phase of the test, the lateral force applied to the top log was transferred evenly through friction and wood crushing to the log 8 below. Using the same mechanism, the force is transferred down to the bottom log. During this early phase, the displacement of the log 8 closely resembles that of log 9 (Figure 5a). At approximately 40 seconds into the test, slipping occurred between the two logs, as the applied lateral force grew larger than the friction between them. However, at a later instance in the test (at approximately 60 seconds) as a result of increased friction between the logs (wood crushing along the groove), the force got transferred down to the log 8 again. Both patterns had occurred once again, approximately at 110 and 210 seconds into the test (Figure 5a). After this time, the rate of displacement increase of log 8 closely resembles that of the top log, suggesting that the slip mechanism has shifted down below the log 8. Having the displacement histories of log 4 and 6 in mind (Figure 5b) one can conclude that the major slip has occurred below log 8, but above log 6.

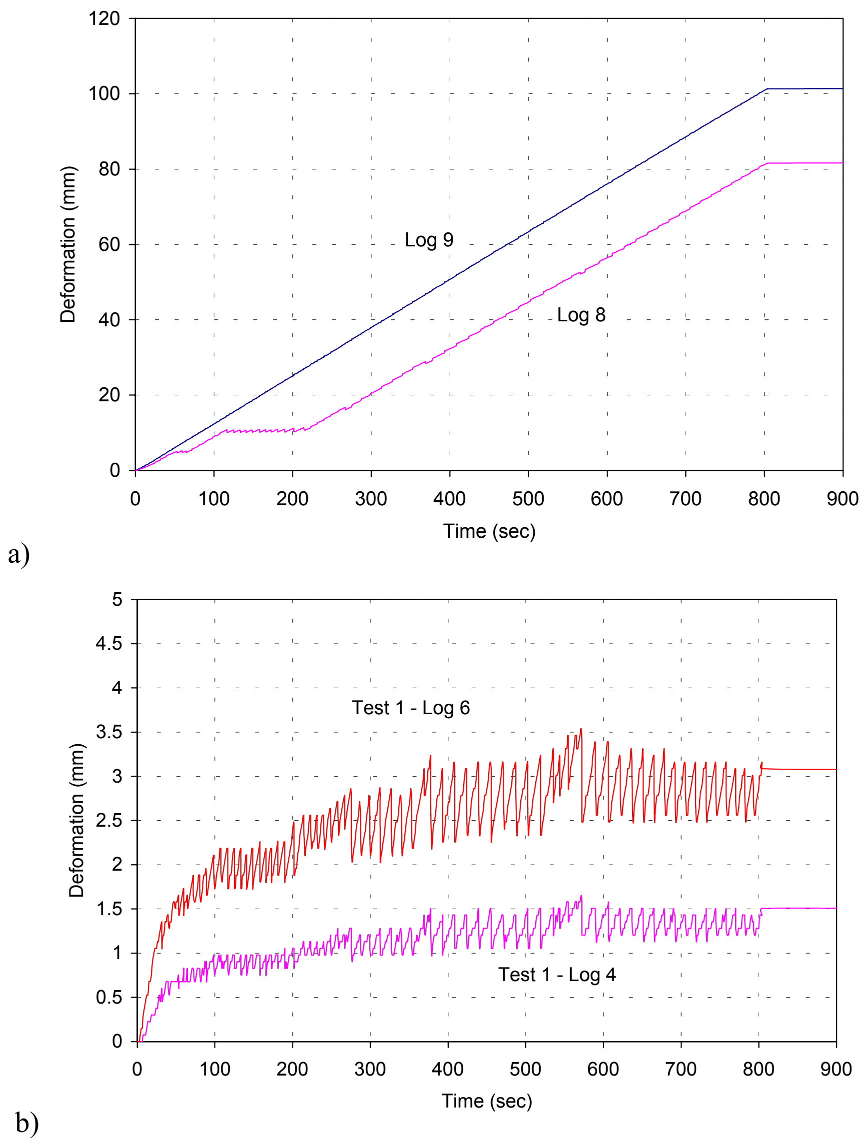


Figure 5 Displacement histories of logs obtained during test 1: (a) top log and log 8 (b) log 6 and log 4

The same observation can be made by analysing the relative displacements of the logs in the wall during the test (Figure 6). As the figure shows, the largest relative deformation occurred somewhere between logs six and eight. By visual inspection of the deformed shape of the wall after the test, we can confirm that maximum relative slip occurred between the log six and seven. The deformed shape of the wall after the test is shown in Figure 7a, while the close-up view of the left side of the wall where the maximum displacement occurred is shown in Figure 7b.

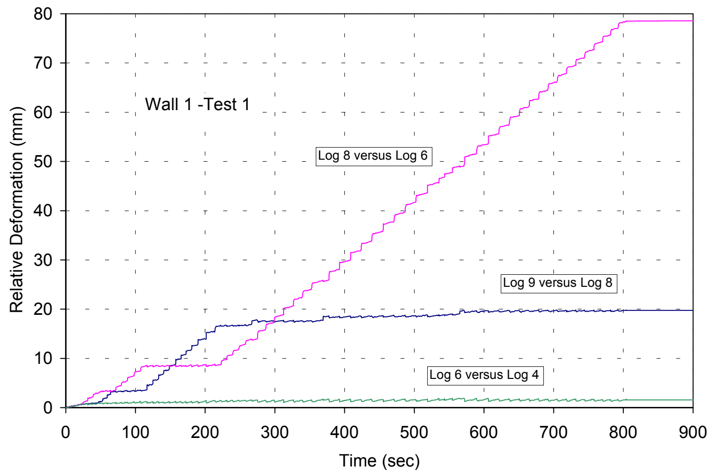


Figure 6 Relative displacement histories of logs during test 1

a)

b)

Figure 7 Deformed shape of the wall after the test 1: (a) front view; (b) Close-up view of the left side

The maximum lateral load that the wall could carry was 6.134 kN (1,379 lbs), while the initial stiffness was 2.422 kN/mm (13,831 lbs/inch). The strength and stiffness properties of this wall are also given in Table 3 along with the results from other pushover test. The initial stiffness was calculated as the slope of the straight line connecting two points on the load-displacement curve, the first at 0.1 P_{max} and the second at 0.4 P_{max}, where the P_{max} is the maximum load obtained from each test (CEN 1995). The coefficient of friction for the wall calculated as the ratio of the maximum lateral resistance versus the applied vertical load was found to be 1.149. If we take into account that the main slip occurred between logs 6 and 7, and add the weight of the top three logs into the equation (approx. 570 lbs), the friction coefficient stands at approximately 1.28. Finally, during the test the wall exhibited uplift on the side where the lateral load was applied. The maximum uplift value recorded at the end of the test was 8.5 mm (0.335 inches). The time history of the uplift recorded during the firsts test is shown in Figure 8.

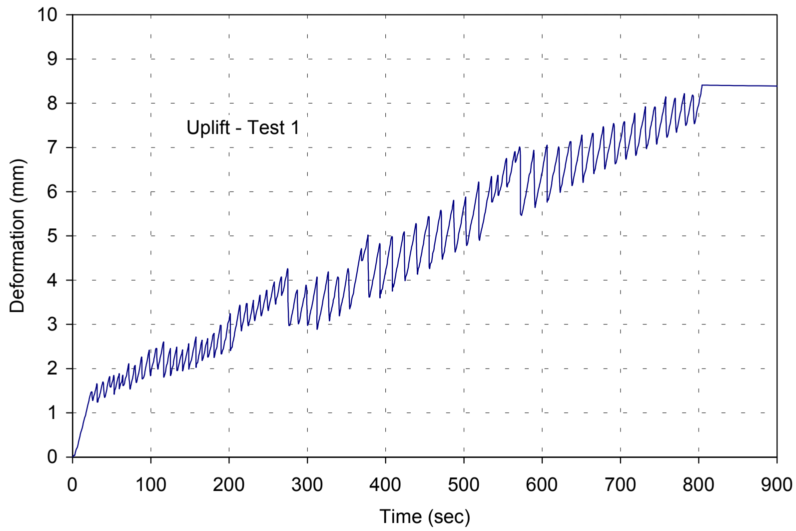


Figure 8 Time history of the vertical uplift at the top right corner of the wall during test 1

To study the effect of vertical load on this wall configuration, the second pushover test was conducted on the same wall, with vertical load now being doubled to 10.68 kN (2,400 lbs). The load displacement behaviour of the wall at the top log level is presented in Figure 9.

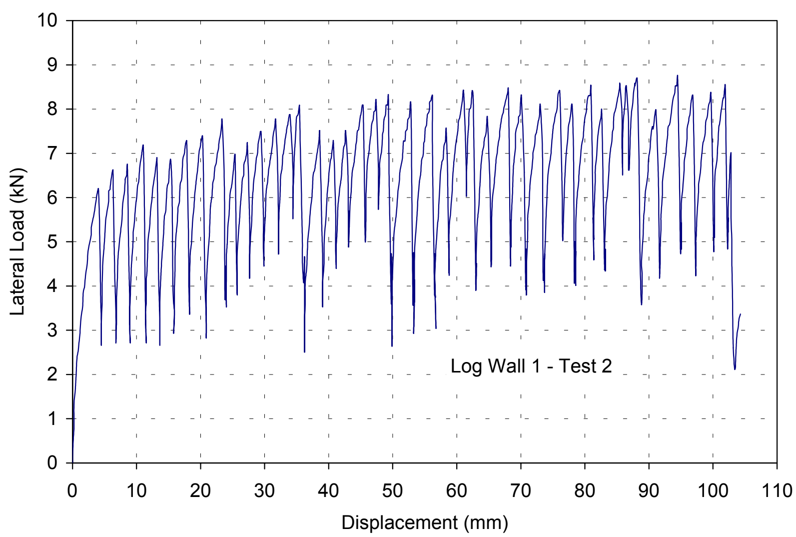


Figure 9 Load-deformation relationship at the top log of Wall 1 - Test 2

As shown in Figure 9, the wall exhibited similar behaviour to that during the first test. The load pulses, however, were now less frequent but larger in magnitude. This is a direct result of the fact that the friction surfaces (grooves) between the logs were smoothed during the first test. During the test 2, the wall was able to sustain a maximum lateral load of 8.741 kN (1,965 lbs), which is 40 % higher than the load in test 1. The higher vertical load also made the displacement distribution more proportional (following a triangular deformation shape) along the height of the wall. Displacement histories recorded at different logs during test 2 are shown in Figure 10, while a photo of the deformed shape of the wall at the end of the test is shown in Figure 11.

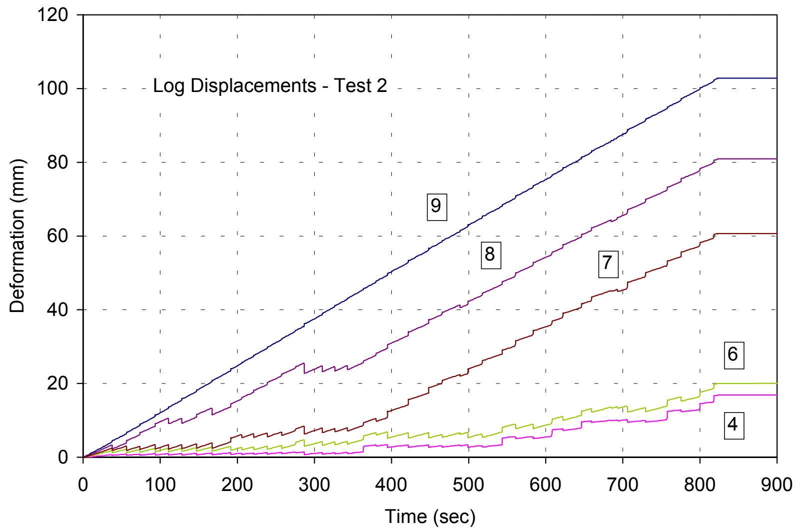


Figure 10 Displacement histories recorded at different logs during the test 2

Figure 11 Deformed shape of the wall at the end of the second test

The lateral resistance of handcrafted log walls with hardwood pins was investigated during test 3. The wall was built the same as the previous one, with an addition of two 25.4 mm (1 inch) diameter pins that were placed between each two adjacent logs. The pins were placed in one-inch diameter pre-drilled holes in each log, as provided by the client. The pins were placed along the height of the wall by alternating the distance between them. The top pins (the pins between log 9 and log 8) were placed closer to both ends of the wall, while the pins below (between log 8 and log 7) were placed closer to the centre of the log, and so on. The wall was subjected to lateral displacement (force) at its top right corner at a rate of 0.3 inches per minute, as in all pushover tests.

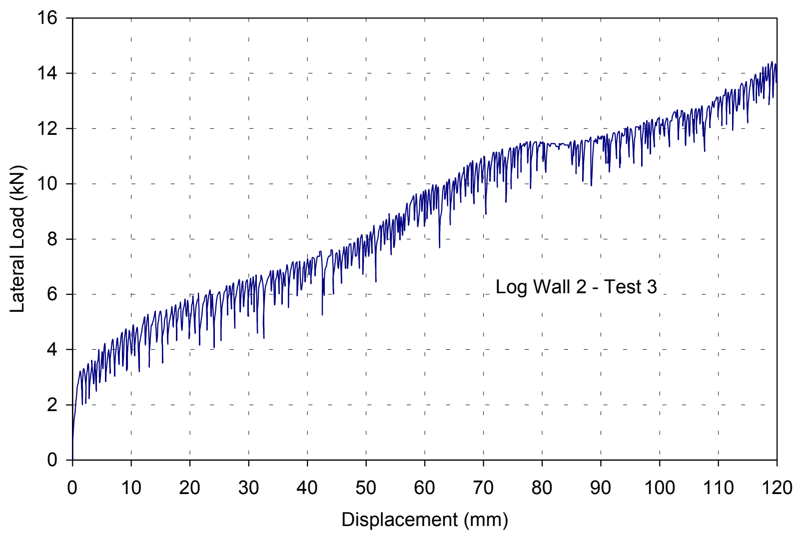


Figure 12 Load-displacement relationship at the top log level of the wall with hardwood pins

The load-displacement relationship of the wall at the top log level is shown in Figure 12. The wall behaviour has changed significantly when compared to the behaviour of walls without pins. The wall resistance is again a combination of friction and wood crushing, but in this case the wood crushing is the far more prevalent component. The pins are the primary wall components that transfer the load down to the foundation. As the lateral load increases during the test, the hardwood pins start crushing the softer wood of the logs around the holes in the direction of the load. A crushed hole with the pin in it at the end of the test is shown in Figure 13.

Figure 13 Wood crushing mechanism around a hole of a pin at the end of test 3

The maximum lateral load that the wall carried during test 3 was 14.55 kN (3,271 lbs), which is 134 % increase over the wall without pins under same vertical load. It should be noted that this is not the ultimate load for the wall, but the maximum obtained during the test, before the test was terminated after reaching the capacity of the displacement transducers. The same wall configuration was tested later in the program under the cyclic testing protocol and was able to sustain a load of 3,906 lbs, which is an increase of 179 % over the wall without pins. It should also be noted that these results, as all others presented in this report, are based on a single replicate test and should be viewed as such. The variability of results obtained from testing components in wood engineering can be as high as 30 %. In order for results to have more statistical significance at least three replicates from each configuration should be tested.

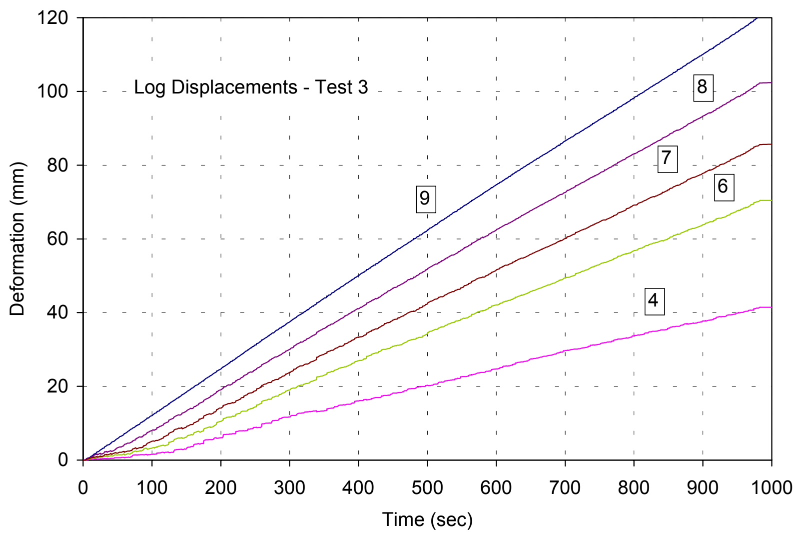


Figure 14 Displacement histories recorded at different logs during the test 3

The wall during test 3 was able to sustain a deformation of over 120 mm (4.8 inches), almost exceeding the transducer's capacity, without showing reduction in strength properties. Hardwood pins proved to be an excellent load transfer component, which resulted in very proportional displacement distribution of logs along the height of the wall. Displacement histories recorded at different logs during this test are shown in Figure 14.

While the maximum uplift of the walls during the first two tests were in the neighbourhood of 9 mm (0.35 inches), the maximum uplift of the wall with pins was 45.9 mm (1.8 inches). This uplift, which is more than five times larger than the uplift measured in previous tests, caused formation of the gap between several logs on the right side of the wall. Time history of the uplift observed during the test 3 is shown in Figure 15. A photo of the deformed shape of the wall at the end of the test is shown in Figure 16a, while the gap formed between logs due to uplift is shown in Figure 16b.

Confidential

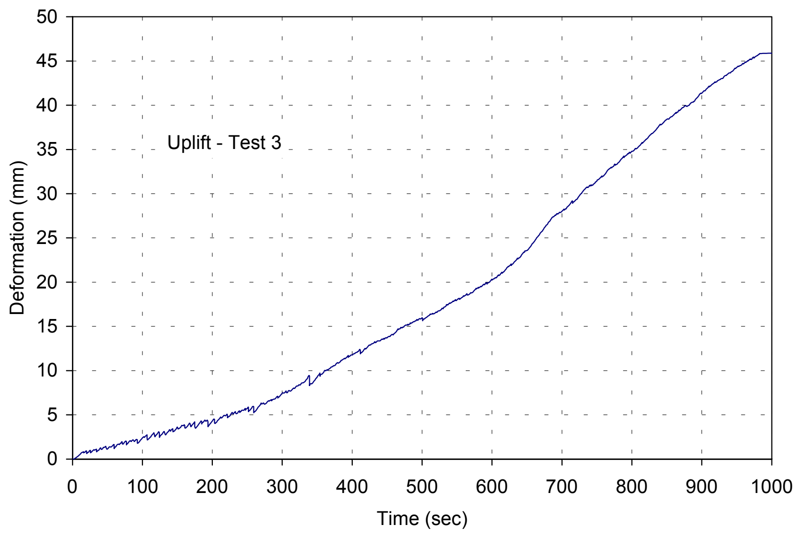
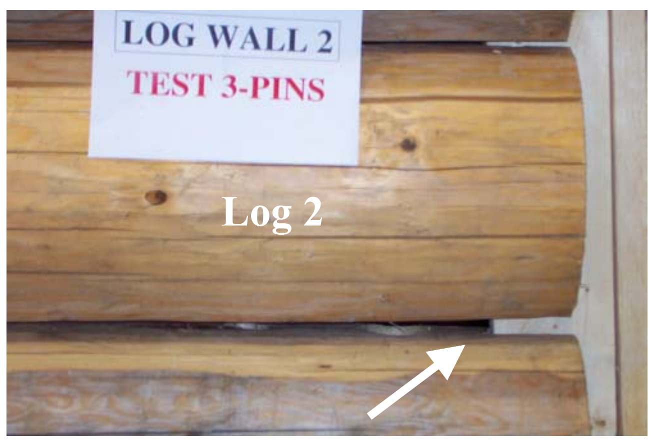


Figure 15 Time history of the vertical uplift at the top right corner of the wall during test 3

a)



b)

Figure 16 Photos of the wall at the end of test 3 (a) Deformed shape; (b) Gap between logs due to uplift

Confidential

The fourth and last test from the pushover part of the testing program was to determine the lateral load resistance properties of handcrafted log walls with corners. The wall was built according to the instructions from the client who supplied the logs. A photos of the wall with corners placed in the testing apparatus is shown in Figure 17.

Figure 17 Handcrafted log wall with corners - setup for the test 4

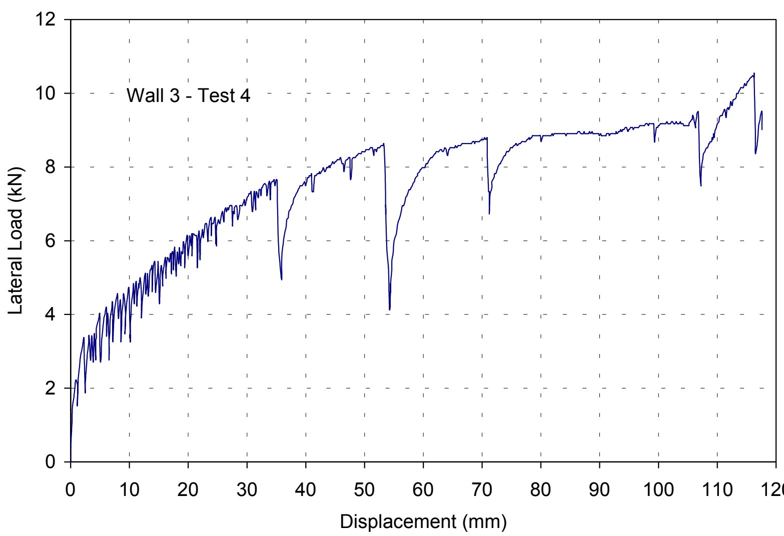


Figure 18 Load-displacement relationship at the top log level of the wall with corners- test 4

The load-displacement relationship of the wall at the top log level is shown in Figure 18. The wall behaviour was again found to be different than in any other configuration previously tested. The wall resistance is combination of friction between the wall logs and wood crushing between the wall and the corner logs. The corner logs were able to transfer the load down to the foundation in more efficient way than the wall with no corners (test 1). As the lateral load increased during the test, the crushing between logs and corner logs intensified. However, at certain point of time when the lateral load build-up was larger than the friction resistance between certain components of the wall at that time, a slipping occurred. Four large events of slipping were recorded during the test. These episodes are visible as significant load reduction peaks in Figure 18.

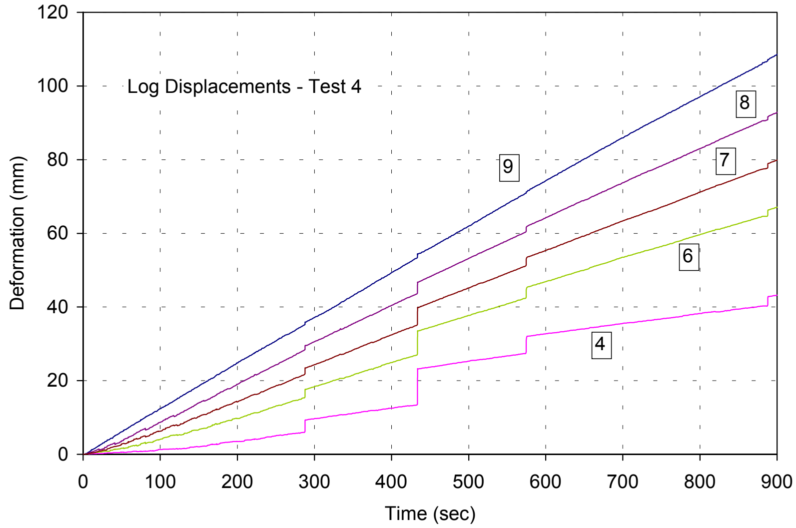
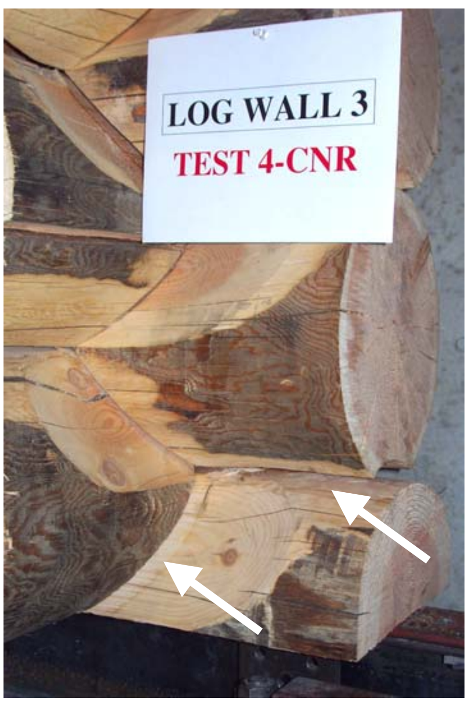
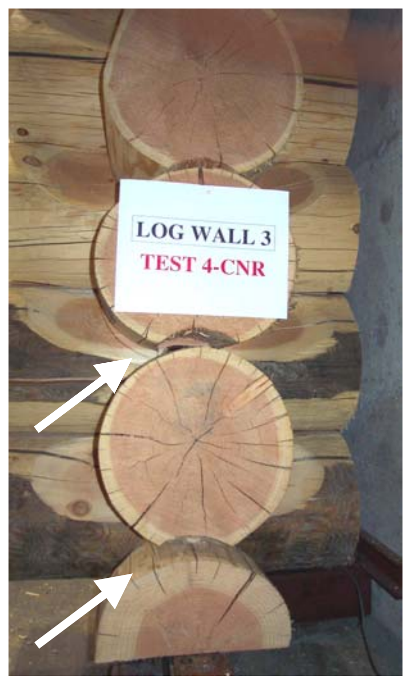


Figure 19 Displacement histories recorded at different logs during the test 4



a)



b)

Figure 20 (a) and (b) Gap formation in log wall with corners due to uplift exhibited during the test 4

The maximum lateral load that the wall carried during the test was 10.53 kN (2,368 lbs), which is 70 % increase over the wall without corners under same vertical load (test 1). However, this lateral resistance was still 27.6 % lower than the resistance obtained in the wall with wood pins, for the same vertical load, and same lateral displacement level. The wall was able to sustain a deformation just below 120 mm (4.8 inches) without showing reduction in strength properties. Improved load transfer resulted in very proportional displacement distribution along the height of the wall. Displacement histories recorded at different logs during test 4 are shown in Figure 19. Figure 19, also captures well the four big slip events during the test. As in test 3, the ultimate (failure) load for the wall in test 4 was not reached. However, it should be noted that in both cases the maximum loads were obtained at large displacement levels, levels that give a story drift of 5% of the wall height. In most seismic design codes the maximum allowable storey drift (a ratio of the maximum storey deformation versus storey height) is around 2 to 2.5%. Excessive storey drifts are not allowed because they cause second-order (P-)) effects on the building as well as damage to the non-structural elements. However for collapse prevention, the ability of a system to deform to 5% storey drift is an excellent feature.

The maximum uplift measured during this test was 49.4 mm (1.9 inches). This uplift was the highest recorded for any configuration tested so far and caused lifting of several logs from the wall and the corners on the right side of the wall. Photos of the gap formed between logs due to uplift are shown in Figure 20 (a) and (b). As mentioned before, a summary of the strength and stiffness characteristics of the four walls tested during the pushover part of the program are presented in Table 3. Stiffness of the walls during tests 3 and 4 was not calculated as required by the CEN Standard, because that would result in non-realistic values.

Table 3 Wall strength and stiffness characteristics obtained from pushover tests

Test	Wall	Maximum Load P_{max}		Initial Stiffness		Vertical Load		Wall Configuration
		(kN)	(lbs)	(kN/mm)	(lbs/in)	(kN)	(lbs)	
1	I	6.134	1,379	2.422	13,831	5.34	1,200	No wood pins, no corners
2	I	8.741	1,965	2.005	11,447	10.68	2,400	No wood pins, no corners
3	II	14.550	3,271^{+}	1.856*	10,596*	5.34	1,200	Hardwood pins, no corners
4	III	10.533	2,368^{+}	2.047*	11,675*	5.34	1,200	Corners, no wood pins

* Stiffness was calculated using 0.2 P_{max} and 0.1 P_{max} ; $^{+}$ Failure load was not reached during the test.

4.2 Cyclic Tests

In the second phase of the experimental program six cyclic (reverse load) tests were conducted to examine the seismic behaviour of different configurations of handcrafted log walls. During cyclic tests, a reverse displacement pattern with increasing amplitudes is introduced at the top of the wall. This pattern is supposed to resemble the reversing displacements present in a real earthquake but at much lower velocity. The configuration of log walls tested under a cyclic protocol (tests 5 to 10) is given in Table 1. The main result that can be obtained from a typical cyclic test is the hysteretic load-deformation curves of the tested element. In timber structures, components or connections, the hysteresis curves are mildly to severely pinched. A typical hysteresis curve obtained from cyclic tests on a timber connection is shown in Figure 21.

The pinching effect results in thinner hysteresis loops in the middle of the loop than near the ends. In wood connections this phenomenon is caused by the loss of stiffness at small joint slips, where a cavity around the fastener is formed by crushing of the wood. The fastener shank, without wood support within the deformation level of the slip, provides the sole resistance to the applied load. The stiffness of the connection again increases gradually as the fastener makes contacts with the surrounding wood at higher deformations.

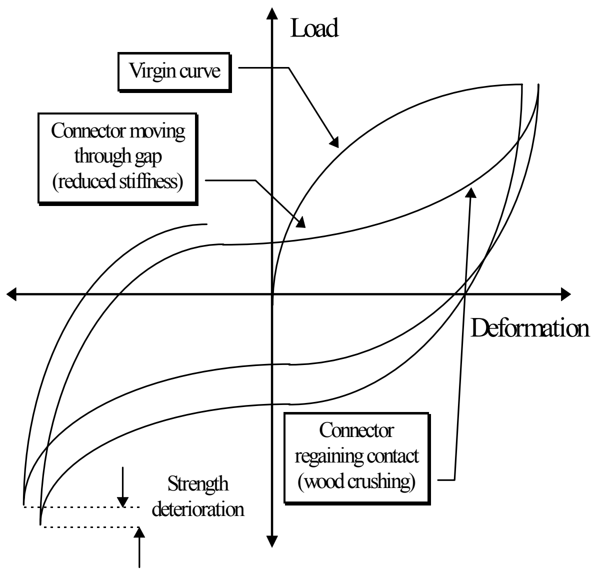


Figure 21 Typical hysteretic behavior of a timber structure component.

Considering that the area inside the hysteresis loop for each cycle represents the amount of energy dissipated during that cycle, the pinching effect reduces the hysteretic damping of the structure. Some recent test results have shown, however, that besides the shape of the hysteresis curve (pinching), the ability of timber structures to sustain large deformations without significant strength deterioration is also very significant. A progressive reduction of stiffness in each loading cycle (stiffness degradation) and reduction of strength when cyclically loaded to the same displacement level (strength degradation) are very common in timber structures under repetitive cyclic loads.

In tests 5 and 6 the seismic resistance of log walls with corners was investigated. For both tests the same wall configuration from test 4 was used, so it should be noted that the results do not represent a wall with its initial strength and stiffness properties. The hysteresis load-displacement curve at the level of the top log obtained from test 5 is shown in Figure 22. As shown in Figure 22, the response is again a combination of wood crushing and friction components. This combination of resistance mechanisms produced a hysteresis curve that is different from the typical ones obtained for conventional timber structures. The curve shows a certain level of stiffness degradation, but shows no strength degradation. In addition, the hysteresis loops are thicker in the middle than near the ends, which is exactly the opposite of the behaviour obtained from conventional wood components. This phenomenon is believed to be largely due to constant changes of the amount of friction and wood crushing components in the total lateral resistance of the wall at any particular time, and any lateral deformation level. The wall was able to sustain a maximum lateral load of 12.22 kN (2,747 lbs). During the test a significant uplift of the wall was observed, with the maximum value of 58.1 mm (2.29 inches) at the end of the test. The uplift caused lifting of several logs from the wall and the corners on the right side of the wall. Significant amount of uplift is not desirable in seismic response of timber structures. The time history of the uplift measured at the top right corner during the test is shown in Figure 23.

Confidential

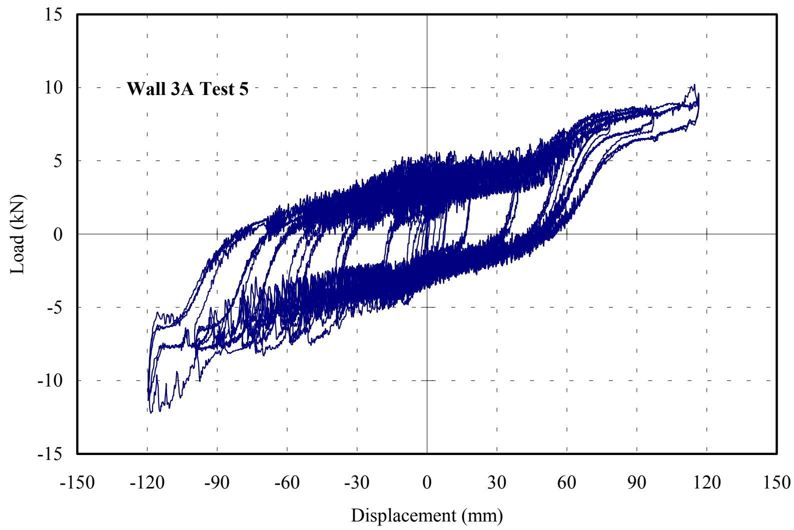


Figure 22 Load displacement hysteresis loop for wall with corners obtained during test 5

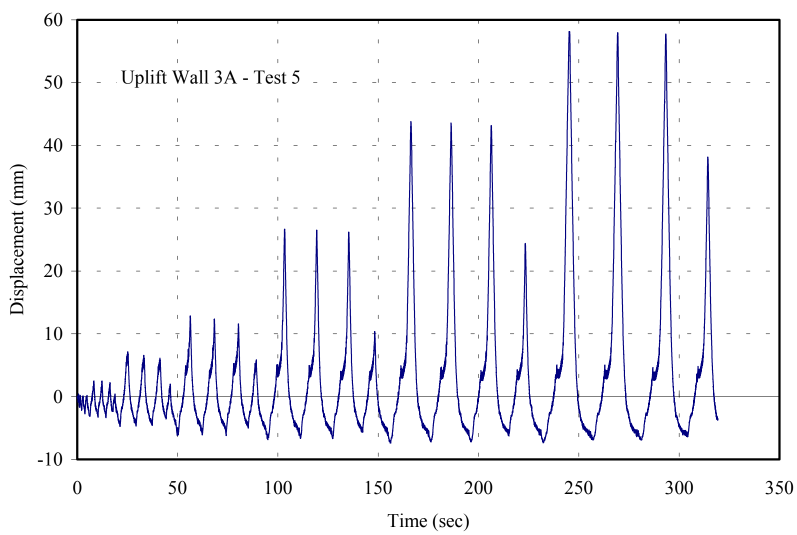


Figure 23 Time history of the uplift during test 5

To study the effect of vertical load on the load-deformation response of a wall with corners, a vertical load of 44.48 kN (10,000 lbs) was applied to the same wall during the test 6. The increased vertical load enabled the wall to carry a maximum horizontal force of 29.4 kN (6,604 lbs). The hystersis loop obtained during test 6 (Figure 24) has an increased and almost uniform thickness, with much more energy dissipated (larger area inside the loop) than the curve in test 5. The increased vertical load also helped reduce the uplift of the wall. Although the time history of the uplift during the test 6 has the same shape as the one shown in Figure 23, the maximum uplift value was reduced to 26.2 mm (1.03 inches).

Confidential

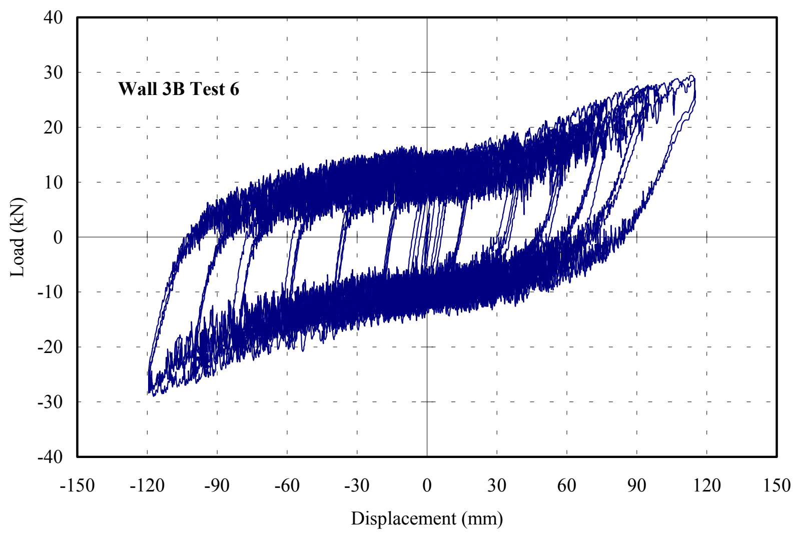


Figure 24 Load displacement hysteresis loop for wall with corners obtained during test 6

In test 7 the lateral resistance of handcrafted log walls with softwood pins was investigated. Two Douglas Fir pins were inserted in pre-drilled holes between each two adjacent logs of the wall. The vertical load applied was 5.34 kN (1,200 lbs).

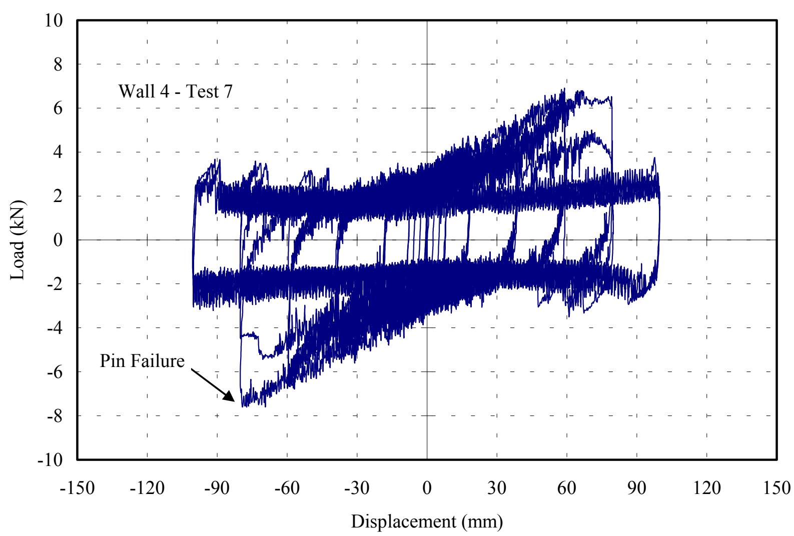


Figure 25 Load displacement hysteresis loop of wall with softwood pins obtained during test 7

As shown in Figure 25, the wall exhibited relatively thin hysteresis loops with no significant potential for energy dissipation. The wall was able to carry a maximum lateral force of 7.6 kN (1,709 lbs), after which the softwood pins at the top of the wall (between log 8 and 9) broke. The breaking of the pins was abrupt and resulted in sudden drop of the lateral load capacity of the wall. After this, the top log was simply sliding on the top of the other logs with no significant lateral resistance. This type of brittle failure is the least desired failure mode in seismic design of structures and should be avoided. A photo of the wall after the pins were broken is shown in Figure 26.

Figure 26. The failure mechanism of the wall with softwood pins - sliding of the top log

After test 7, the wall was disassembled but the same logs were used to assemble the wall for the test 8. To study the effect of pin hardness on the wall response, maple hardwood pins were used between the logs this time. Although test 8 is not using a wall with its initial properties, it can be assumed as such, since the previous test had very little effect on the wall resistance since the sliding during test 7 mainly occurred at the top log level.

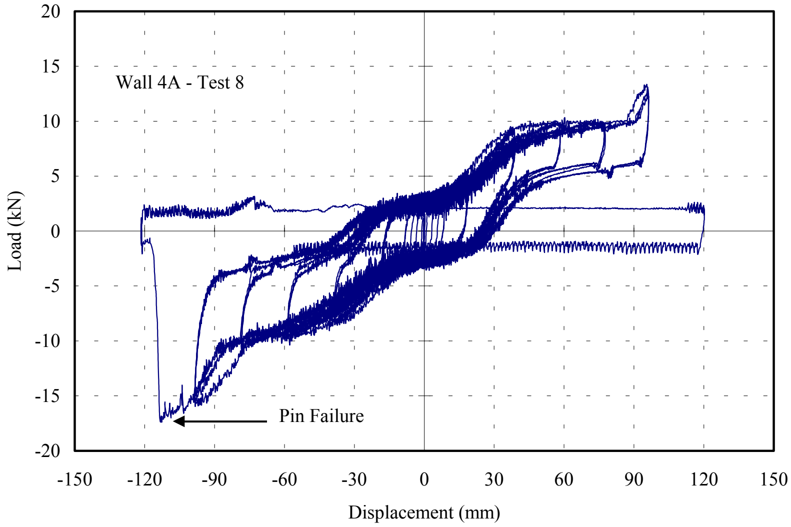


Figure 27 Load displacement hysteresis loop of wall with hardwood pins - test 8

The load-displacement hysteresis curve obtained from test 8 is shown in Figure 27. The combination of friction and wood crushing around the hardwood dowels resulted in hysteresis loops with relatively uniform thickness. The load increased until it reached 17.4 kN (3,906 lbs). At that point both hardwood pins at the top of the wall (between log 8 and 9) broke. Pin failure was abrupt and again resulted in sudden drop of the lateral load capacity of the wall (Figure 27). After the pin failure the wall has lost almost all of its lateral resistance and the top log simply kept sliding on the top of the other logs. Although the log wall with hardwood pins was able to carry 128% more load than the same wall with softwood pins, they experienced the same brittle failure modes. This type of abrupt failure mode is not desired in seismic design of timber structures and should be avoided. A photo of one of the broken pins between logs 8 and 9 is shown in Figure 28.

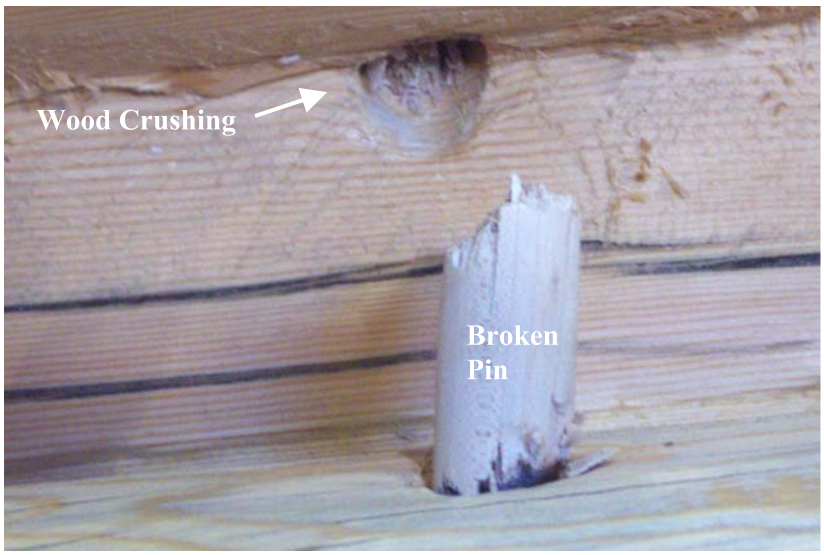


Figure 28 Close-up view of the broken pin between logs 8 and 9 during test 8

As shown in Figure 28, the hardwood pins caused extensive wood crushing around the holes in the softwood logs before they broke. Wood crushing is desirable ductile mechanism of energy dissipation in the seismic design of timber structures. During the test, the wall with hardwood pins exhibited an uplift pattern similar to the walls previously tested. The maximum uplift value at failure was 52.9 mm (2.08 inches).

In tests 9 and 10 the lateral resistance of log walls with hardwood pins and corners was investigated. A vertical load of 5.34 kN (1,200 lbs) was used in test 9, while the same wall was subjected to a vertical load of 44.48 kN (10,000 lbs) during the test 10. Three members of the International Log Builders' Association, Mr. Tom Hahney, Mr. Dave Gardner and Mr. John Boys, observed these tests. A photo of the wall specimen prepared for test 9 and guests from the ILBA is shown in the Figure 29.

The load-deformation hysteresis loop obtained from test 9 is shown in Figure 30. The presence of corner logs helped increase the wood crushing component of the resistance. This resulted in a 44% increase of the total lateral load resistance of the wall compared to the wall without corners (test 7), for the same displacement level. The maximum load obtained during the test was 25.03 kN (5,627 lbs). Significant vertical uplift was again noted during the testing with the maximum uplift exhibited during the test being 53.5 mm (2.1 inches).

Figure 29 ILBA members with the log wall specimen placed in the testing apparatus for test 9

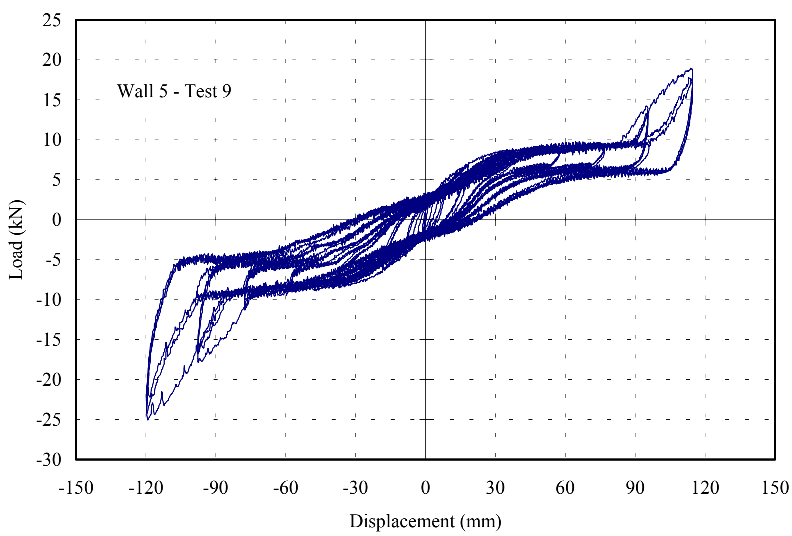


Figure 30 Load displacement hysteresis loop for wall with hardwood pins and corners - test 9

By increasing the vertical load to 44.48 kN (10,000 lbs) on the same wall configuration during the test 10, a maximum load of 35.3 kN (7,935 lbs) was reached (Figure 31). The higher level of vertical load resulted in thicker hysteresis loops and higher energy dissipation characteristics of the wall, by increasing both, the friction and wood crushing part of the resistance. The maximum value of the uplift recorded was 54.2 mm (2.13 inches), which is very similar to the value obtained during the test 9. A photo of the gap that was developing between the first and the second log due to uplift forces during test 10 is shown in Figure 32.

Confidential

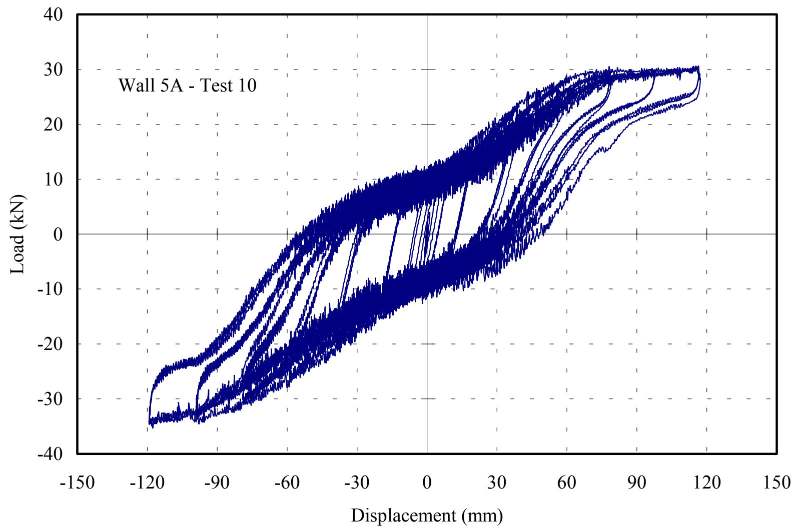


Figure 31 Load displacement hysteresis loop for wall with hardwood pins and corners - test 10

Figure 32 Gap formation between logs as a result of the uplift forces during test 10

When disassembling the wall after the test, it was observed that both pins between the fifth and the sixth log had failed during the test. However, due to the large amount of vertical load and the presence of the corner logs, this did not become apparent during the test. The pin failure event is also very difficult to capture from the load-displacement curve shown in Figure 31. The fact that the broken pins were located in the middle of the wall and not at the top, suggests that this wall system has unique load transfer properties. In addition the wall showed superior strength and ductility, as well as the largest amount of energy dissipation, based on the area within the loops, than any other configuration tested. For comparison, previous Forintek test data show that a conventional 8 by 8 foot wood-frame wall, sheathed on one side with vertical 9.5 mm plywood, with 100 mm (4 inches) nail spacing and no vertical load, has a lateral resistance of about 31.5 kN (7,081 lbs). A summary of some of the log wall properties from the cyclic testing program is shown in Table 4.

Table 4 Log wall properties obtained during the cyclic testing program

Test	Wall	Maximum Load		Maximum Uplift		Vertical Load		Wall Configuration
		(kN)	(lbs)	(mm)	(in)	(kN)	(lbs)	
5	III-A	12.2	2,747	58.1	2.29	5.3	1,200	Corners, no pins
6	III-B	29.4	6,604	26.2	1.03	44.5	10,000	Corners, no pins
7	IV	7.6	1,709	2.5	0.1	5.3	1,200	Softwood pins, no corners
8	IV-A	17.7	3,906	52.9	2.08	5.3	1,200	Hardwood pins, no corners
9	V	25.0	5,627	53.5	2.1	5.3	1,200	Hardwood pins, and corners
10	V-A	35.3	7,935	54.2	2.13	44.5	10,000	Hardwood pins, and corners

5 Concluding Remarks and Recommendations

5.1 Conclusions

Based on the test results and observations presented in this report some conclusions about the lateral load resistance of log walls can be made. It should be noted that these conclusions are based solely on the limited number of tests conducted for each configuration in the program.

- Handcrafted log walls possess unique lateral load resistance characteristics and lateral load transfer mechanisms, markedly different from the characteristics of conventional wood-frame systems;
- Log walls are very deformable systems. All walls sustained high levels of lateral loads at high deformation levels of 100 mm (4 inches) or more, corresponding to 4% or more of inter-storey drift;
- Log walls have good energy dissipation characteristics that can reduce the seismic input energy in an earthquake. However, the amount of energy dissipation, which is related to the thickness of the hysteresis load-displacement loop, varies among different wall configurations;
- The energy dissipation is also dependent on the amount of vertical load. Higher vertical loads improved the energy dissipation characteristics of the walls;
- Higher vertical loads also helped achieve more proportional lateral load transfer among the logs along the height of the wall, resulting in different lateral displacement values of the logs;
- In the case of log walls with neither wood pins nor corners, the friction between logs is the sole source of lateral load resistance. The amount of vertical load on the wall is a key contributor for the lateral resistance of the wall. These walls showed the lowest amount of lateral resistance of all the wall configurations tested at a given vertical load level;

- In the case of log walls with wood pins, the lateral resistance is based on a combination of friction between the logs and wood crushing around the pins. These walls are able to carry more lateral load per unit length than the walls without pins;
- Log walls with softwood pins showed lower lateral resistance and energy dissipation than walls with hardwood pins. The hardwood pins were able to provide more wood crushing around the holes in the logs and thus dissipate more of the seismic input energy;
- Walls with either softwood or hardwood pins, however, exhibited a brittle failure when reaching the maximum load. The sudden failure of both pins at the top log caused an immediate reduction of the lateral load resistance down to pure friction. An abrupt failure mechanism such as this is not desirable in seismic response and design of timber structures;
- The walls with corners only, showed lower lateral resistance for the same vertical load level and same lateral deflection than the walls with hardwood pins only;
- All wall configurations showed significant vertical uplift at the top right corner. Such significant uplifts are not desirable in seismic design and should be prevented. The use of internal steel rods fitted with a shrinkage adjustment mechanism, anchored to the foundation and running vertically to the top of the wall is an example of a solution that has a potential for investigation;
- In all configurations tested, the walls with corners only showed the largest amount of vertical uplift per single unit of lateral load resistance under a given vertical load;
- The amount of uplift on all walls was reduced when the walls were subjected to higher vertical loads;
- Log walls with hardwood pins and corners showed the highest lateral load capacity of all configurations tested. In addition, they showed the smallest amount of uplift per unit of the lateral load observed. They also showed the highest amount of hysteretic energy dissipation based on the estimate of the inner loop area. Finally, they were the only walls from all configurations that exhibited a ductile failure mode that consisted of a combination of pin breaking and wood crushing along the pin holes and between the logs of the walls and the corners.

5.2 Recommendations for Further Research

This project represents an initial step towards determining the lateral load resisting characteristics of handcrafted log homes. Test results showed that by placing simple shear-force transfer devices such as pins, the lateral resistance of log walls can be tremendously increased without significant increase in cost. Further research, however, is needed to study the behaviour of different configurations of this unique structural system under lateral seismic and wind loads. This research should include:

- Testing more than one replicate for each wall configuration in monotonic pushover and cyclic tests. Having at least three replicates tested of a same configuration will add statistical significance to the results and may help codify the results in the future.
- Conducting quasi-static tests on various wall configurations with steel pins or other shear transfer devices. It will be useful to investigate the use of steel pins between logs and see if they can improve the ductility of the system and eliminate the brittle pin failure modes.
- Conducting quasi-static tests on various wall configurations with internal steel rods with shrinkage takers to determine the influence of the rods on seismic and wind uplift.

- Studying and testing other solutions that will reduce and possibly eliminate the seismic uplift, including some innovative solutions such as cable systems.
- Conducting shaking table tests on a house model to determine the vibration, damping and other dynamic response characteristics of a log house subjected to a strong earthquake.
- Developing design guidelines for log buildings under lateral loads.

6 References

CEN 1995. Comite' Europeen de Normalisation. Timber structures test methods - cyclic testing of joints with mechanical fasteners. EN TC 124.117, European Committee for Standardization. Brussels, Belgium.

Hahney T. 2000. How Log Buildings Resist Lateral Loads. Log Building News No. 32. A journal of the Canadian and American Log Builders Association.

ISO/DIS 16670. 2001. Timber structures – Joints made with mechanical fasteners – Quasi-static reversed-cyclic test method. ISO TC 165 Technical committee on timber structures. International Organization for Standardization.

LHLI 2002. Log Home Living Institute Web Site: www.loghomeliving.com.

NAHB 2002. National Association of Home Builders Web Site: www.nahb.com/consumers/systems.