Airtightness of Wall Sheathing as a Function of Lumber Drying

D.M. Onysko, Ph.D. S.K. Jones

ABSTRACT

Lumber shrinks as it dries out and the resulting "nail popping" tends to loosen nailed connections. This paper presents the results of airtightness tests on three full-sized walls built with green lumber and with joints in waferboard sheathing. The correlation between shrinkage, nail popping, and the air leakage characteristics of joints was studied. Also reported are the results of air leakage tests of wall sheathing as a function of the wetting of the sheathing from the inside, as happens when heavy condensation occurs. This information, in addition to providing insight into the airtightness behavior of wall sheathing, provides order-of-magnitude leakage characteristics which will allow simulation of the drying-out of walls using recently developed computer models.

INTRODUCTION

Shrinkage of framing leads to the loosening of sheathing-frame connections. Some sheathing, which is relatively impermeable to air, may become very leaky at joints. The degree to which loosening occurs depends largely on the shrinkage characteristics of the lumber framing and its moisture content at the time of assembly. Differential shrinkage between studs and sill plates can also cause openings to occur, irrespective of the nail popping that takes place.

Current code provisions require that lumber used in construction not have more than 19% moisture content by weight. It has long been recognized that much of the lumber used in construction in parts of Canada and the U.S. has a higher moisture content than specified by building regulations. Often, the climatic conditions are such that substantial drying takes place before this moisture is locked in by vapor retarders and sheathing. In other climates or construction periods, drying is poor and the excess moisture locked in during construction takes longer to dry.

Studies have shown that nail popping depends largely on the shrinkage of the wood, and that it is not dependent on the nail diameter or shape but on the embedment length (Suddarth and Angleton 1956). Fluctuating moisture contents also cause some further working out of fasteners. Others (Platts 1962) report that some fasteners, particularly ringed nails, do not work out to the same extent.

A great deal of information is available on the mean shrinkage properties of many softwood and hardwood species in North America (FPL 1988; Mullins and McKnight 1983). From the information provided, however, it is not possible to assess the range of shrinkage that can take place or what variability will be encountered. There is some correlation between the specific gravity of wood and its shrinkage. However, differences between radial and tangential shrinkage, together with the variability associated with differences in density between fast-growth (juvenile) wood and normal-growth wood, suggest that shrinkage in a piece of lumber may be difficult to characterize. The location in the cross section of the tree from which a piece

D.M. Onysko is a building systems scientist at Forintek Canada Corporation, Ottawa, ON.; S.K. Jones (formerly with Forintek Canada Corp.) is a technologist with Robert Halsall and Associates, Toronto, ON.

of lumber has been cut also plays a role, both as a result of the density of material included and the ring orientation at the edges of individual boards (see Figure 1).

The moisture content of lumber framing and the effects created when it dries and shrinks or warps are events over which builders sometimes have very little control. This may lead to systemic failure by decay if leakage paths develop (these allow moisture to collect within the walls under certain weather conditions). In order for the true impact of framing shrinkage to be studied, it is necessary to obtain representative information on some of the factors that lead to the loosening of attachment and the degree of air leakiness that develops. Given this information, it may be possible to assess the impact of leakage paths in the exterior sheathing under the influence of wind and atmospheric pumping as well as steady-state pressure differences across the wall. This may become possible using recently developed computer models, for example, WALLDRY (Ferraro et al. 1988). The ultimate goal of this work is to demonstrate how builders can achieve better performance of both residential and industrial wood-framed construction through a better understanding of the consequences of the inappropriate use of materials.

This paper examines two factors that influence airtightness of wall systems. First, nail popping caused by shrinkage of lumber framing contributes to the leakiness of wall constructions. Second, wetting of an expansive sheathing material leads to increased airtightness.

MATERIALS AND METHODS

To study the correlation of nail popping or lumber shrinkage with airtightness, it is required that one or both variables be measured in the lumber where a joint in the sheathing is located. Since the tightness of the nailed attachment is responsible for the integrity of joints and their airtightness, it was convenient to use nail popping as an appropriate measure of shrinkage effects. However, measurement of nail popping on the same side of the lumber edges to which sheathing is attached is incompatible with the simultaneous measurement of airtightness. It was decided to measure nail popping on the opposite edge of the lumber studs. This allowed measurement of nail popping at studs without compromising the airtightness of the sheathing on the other edge. This necessitated designing a separate experiment to study the correlation between nail popping on opposite edges of lumber studs. Figure 2 shows a cross section of a typical joint.

Two concurrent studies were designed to assess whether nail popping measurements were related to airtightness. The first study sought to determine whether there was a correlation between nail popping measured on one edge of a piece of lumber and that measured on the other edge. The second study was done on full-sized walls to assess if the nail popping measured on the opposite edge was correlated with air leakage. Since the findings of the first study need not necessarily agree with the findings of the second study, both were required. This second study included tests to determine the influence of wetting of sheathing from the inside on the airtightness of sheathing joints.

Nail Popping on Opposite Edges of Lumber

Materials. Five nominal 2 in. by 4 in. (38 mm by 89 mm) lumber studs 90 in. (2.286 m) long were selected to be representative of five different lumber shrinkage classes. The classes were established by studying the shrinkage of a large number of studs. This was done by examining the cross-sectional shrinkage of slices of material cut from one end of each stud when the slices were dried. Lumber in this study generally came from small trees. Many pieces contained the pith of the tree or were located close to the pith. The lumber was originally green and held at or above 60% moisture content by weight in a "green" chamber until ready for use.

The four fastener types selected for this investigation were 2-in. (52 mm) and 3-in. (78 mm) standard spiral nails, and 1-in. (26 mm) and 1 1/2 in. (31 mm) drywall screws. The fasteners were installed on the centerline of each edge. The four fastener types were spaced at approximately 2 1/2 in. (65 mm) and in the same order, so there were eight fasteners of each type on each face of each stud. The same fastener types were lined up on opposite edges and were offset to prevent the points from intersecting to minimize splitting. Each nail or screw was fastened into the lumber leaving the head protruding approximately 3/8 in. (9.5 mm), as they would be if sheathing of this thickness were attached to the studs.

Measurement Techniques. An aluminum tool was fabricated to hold an electronic displacement gauge for the nail popping measurements. This gauge had a resolution of 0.0025 in. (0.001 mm). Measurements were taken by placing it over the fastener head and having the flat end of the tool bear uniformly against the face of the lumber surrounding the fastener while the plunger of the gauge rested on top of the fastener head. The electronic displacement gauge was connected to an interface module and then to a computer. A photo showing this tool in use is given in Figure 3.

Repeatable measurements on any one nail were obtainable if the tool was pressed firmly against the edge of the lumber. Repeatable readings could be obtained by different people, usually within 0.025 in. (0.01 mm).

Three pairs of insulated resistance moisture pins were installed into each edge of each stud in line with the nails and screws to monitor the drying of the studs at a depth of about 1.2 in. (30 mm). Moisture contents measured below fiber saturation are usually accurate to within 1% moisture content by weight.

The mass of each stud was obtained each time a set of nail popping measurements was made. It was intended that five sets of data be collected while the lumber dried to equilibrium. When the final set of readings was taken, the moisture content of the lumber was 10% by weight. At the conclusion of drying, 10-in.-long (250 mm) sections of each stud were cut off to determine the specific gravity based on air-dried volume and the moisture content by oven drying.

During this period, three studs became badly twisted because they were unrestrained during drying. Additional studs were selected from the same three shrinkage classes to add to the data base.

Air Leakage Through Joints in Sheathing

Materials. Three full-sized walls, approximately 8 ft. by 10 ft. (2400 mm by 3000 mm), were built for airtightness testing to fit the large chamber designed for this purpose (Onysko and George 1987). The framing details and location of joints in the waferboard sheathing are given in Figures 4 and 5.

Green framing was used for the construction of the walls. Each wall had four joints in the 7/16-in. (11.1 mm) waferboard sheathing, and studs from different shrinkage classes were used at each joint. The shrinkage classes used were 3, 5, 7, and 9. The individual shrinkage values for each stud are used in the analysis but, for convenience in this paper, they will be referred to by these numbers.

The nail spacing at joints in the sheathing was 6 in. (150 mm) using 2-in. (50 mm) standard spiral nails. Each wall was taped around the perimeter with construction tape to guard against leakage through joints other than those on the face of the wall. Three wooden straps were nailed to the opposite edges to restrain twisting as the studs dried (Figure 5).

Similar nails were installed on the opposite edges of each stud for nail popping measurements. Eight of these nails were spaced at approximately 12 in. (300 mm) from top to bottom of these studs, as shown in Figure 5. They were installed to the same depth as the nails used to attach the sheathing on the opposite edge. This was done to assess the average shrinkage of each stud on the assumption that there might be a reasonable correlation between nail popping on each edge of each stud, i.e., that nail popping would be sufficiently similar on both edges. The wooden straps installed to restrain twisting also guarded the protruding nails against damage during handling of the walls.

Three pairs of insulated pins were installed at the mid-depth of each stud to monitor the moisture content. The bottom of the wall was reinforced with a steel plate to facilitate handling when the wall was moved on rollers into a storage frame.

Airtightness Tests of Walls. Each wall was tested in the same way using an airtightness testing chamber. The wall was clamped against the chamber so that the sheathing was outermost, with the joints in the sheathing exposed. The test chamber and auxiliary equipment are shown in Figure 6. The pressure range used was $\pm$ 0.209 to 5.221 lb/ft^2 (10 to 250 Pa).

All four test joints were taped over with 3-in. (75 mm)-wide tape. An airtightness test was done to obtain the overall calibration leakage. This included leakage from around the seal of the wall with the chamber (which in previous testing had been found to be small), leakage through the waferboard material itself, and leakage around nails at locations other than joints in the sheathing. Each test series of a wall included a calibration test to correct for possible changes in conditions from one time to another, particularly if other unknown leakage paths occurred.

The airtightness test itself consisted of measurement of the airflow into the chamber using mass flow meters, doing both negative and positive pressure tests. The tests were monitored using a data acquisition system which provided median values of the pressure and flow signals over a four-minute period using 20 sets of 301 samples per set at a sampling rate of 454 readings per second. This technique was found to reliably remove the influence of pressure variations resulting from uncontrolled openings of doors, and of pressure fluctuations in and around the laboratory. Corrections for atmospheric pressure variations, relative humidity, and temperature were made to the measured leakage data. This allowed for correct comparison with leakage data from one test to another over the duration of the experiment, which lasted about three months. Ten pairs of steady-state pressure and flow were obtained over the pressure test range selected.

Each joint length was measured and the actual value used for this determination. The average joint length was 87.25 in. (2.22 m).

Each joint was uncovered in turn and the air leakage was evaluated in the same way. The tested joint was then taped and another joint tested. In this way, all four joints were tested without removing the wall from the chamber so that no change in the calibration flow resulted. The nail protrusions on the opposite edge of each stud were measured and input directly to a data file in a microcomputer. The moisture contents were also recorded.

Each wall was set aside to dry in a storage frame in the conditioned laboratory set at 65% relative humidity and 70°F (21°C). A total of three sets of airtightness tests were obtained as the framing in each wall dried from moisture contents ranging from 31% to 61% by weight to a range of 15% to 23% by weight at the time of the last airtightness test on the dried walls.

Finally, each wall was placed face down and water was poured into each cell to a depth of about 0.25 in. (6 mm) to simulate a condition where condensation of moisture led to thorough wetting of the sheathing. The walls were covered with plastic and the water was allowed to soak into the inside surface of the wall sheathing overnight. When the outer sheathing surface was dry enough so it could be taped, positive pressure leakage tests were done. The walls were tested with all joints taped and then with all joints uncovered.

RESULTS

Nail Popping at Opposite Edges of Lumber

Summaries of the nail popping measurements are provided in Table 1. On examination of the data over the whole drying period it was apparent that the nail popping readings were not always consistent. The measurements were negative on some days for some fasteners. For a few others, nails appeared to progressively enter the wood. Also, the individual values from some sets did not vary monotonically.

It was then decided to examine the data using only the first and last measurement sets since the small change in nail popping that took place from one measurement set to the other did not justify closer examination. Also, the larger change in readings had a smaller percentage error associated with the manner by which the operator applied the tool. The only error still likely to be significant was that associated with nail head rotation caused by non-uniform shrinkage across the edge.

Based on an analysis of variance, as expected, only the shrinkage class and fastener type proved to be significant variables, since boards had been selected on the basis of assumed different shrinkage classes and the fasteners had different lengths. The experiment was not designed to distinguish effects related to surface characteristics of the fasteners. From this analysis it was also determined that nail popping on some boards was different from that on other boards and that the longer fasteners (spiral nails) experienced significantly larger nail popping than the shorter fasteners (drywall screws). But, every shrinkage class was not distinctly different from the others.

Air Leakage Through Joints in Sheathing

The airtightness tests were evaluated and the data fitted to the following equation:

$$Q = C \cdot \delta P^{n} \qquad [1]$$

where Q is the flow rate at standard conditions per unit length of joint $ft^3/(ft \cdot s)$ $(L/(m \cdot s))$, and δP is the pressure difference (lb/ft^2) (Pa), and C and n are constants.

On finding the above coefficients by regression, the equivalent leakage area (ELA) in in^2/ft of joint length (mm^2/m) at a pressure difference of 0.20885 lb/ft^2 (10 Pa) was calculated using the following expressions:

$$ELA = 8.0505 \cdot C \cdot 0.20885^{n-0.5} \quad \text{(I-P system)} \qquad [2a]$$

$$ELA = 1269.54 \cdot C \cdot 10^{n-0.5} \quad \text{(SI system)} \qquad [2b]$$

Another expression for characterizing flow through joints is:

$$Q = A_1 \cdot \delta P^{0.5} + A_2 \cdot \delta P \qquad [3]$$

The first term is related to turbulent flow, while the second is related to laminar flow where the joints are assumed to be straight-through gaps. Better fits are generally found with this equation than with Equation 1. Here, too, the coefficients A_1 and A_2 are found by least-squares fitting.

A summary of the results is presented in Tables 2, 3, 4, and 5 by shrinkage class for the first and last air leakage tests. These tabulations are provided for the positive pressure tests, i.e., for flow from inside the chamber to the outside of the sheathing, and include the coefficients C, n, A_1, and A_2 for Equations 1 and 3 representing the best fits to the data in each case. The equivalent leakage areas calculated using Equations 2a and 2b are also provided for a pressure difference of 0.209 lb/ft^2 and 1.566 lb/ft^2 (10 Pa and 75 Pa). The results for both positive and negative pressure tests are provided in the original project report (Onysko and Jones 1989).

Corresponding nail popping measurements of nails in studs at sheathing joints are provided in Table 6.

The tests of walls where the waferboard sheathing was wetted were fitted in the same way. In addition, the base leakage through the sheathing material itself was also evaluated, with the quantities and constants summarized in Tables 7 and 8.

DISCUSSION

Nail Popping at Opposite Edges of Lumber

Most of the variability in nail popping readings was attributed to the variability in the surface against which the nail popping tool was pressed from one time to the other. Some twisting of the studs and non-uniform shrinkage across the lumber edge contributed to the rotation of some of the protruding nails. This caused the plunger of the measuring tool to ride up on the high point of the nail head, giving larger readings than the actual nail popping.

To assess the correlation of nail popping with shrinkage class, embedment length was treated as a covariate. The least-squares adjusted mean nail popping obtained by board were then plotted against the estimated specific gravity for each board. The latter value was calculated on the basis of the oven dry weights of the cut-off ends and the air-dried volume. No correlation was found.

Examination of the correlation of nail popping for the longer fasteners with estimated specific gravity showed that a positive significant correlation was found on one of the two edges. Based on the nature of the stud lumber used in this study and the inclusion of pith material, it is likely that studs having a lower bulk density possessed more juvenile wood. Inclusion of the pith region of a tree in a stud appears to lead to highly variable shrinkage properties from one edge to the other.

Finally, since each fastener had the same type of fastener located almost directly opposite it on each board, paired t-tests were performed to see whether there was any significant differences in nail popping from one side to the other. The analysis was done by fastener type and by board. Out of 32 tests of significance (four fasteners by eight boards), 10 comparisons showed significant differences. Nail popping on opposite edges was significantly different for all fasteners in only one board. The majority of cases involved only the spiral nails, as they were longer. Seven of the ten comparisons which were significantly different involved two boards that warped badly. Thus, while the nail popping on opposite edges was not significantly different for some boards, it was significantly different for others, particularly for studs that exhibited warping. The latter behavior is a sign that a different type of woody material predominated on opposite sides of these studs. Paired t-tests were also done across all boards. It was found that the difference in nail popping between edges was not significantly different from zero, given the variability in the data.

This analysis suggests that nail popping can be significantly different on opposite edges of lumber and that, if this were so for a given piece of lumber, the difference would be far greater for a longer fastener than for a shorter one. It also suggests that nail popping as measured here would not be reliable as an indicator for loosening of attachment of sheathing.

Air Leakage Through Joints in Sheathing

An analysis of variance of air leakage measurements showed that there were no significant differences between negative and positive pressure tests at the mean, whether walls were tested green or dry. Aside from this, there were significant differences between walls, even in the green state, because their joints had different degrees of airtightness to begin with.

Of greater importance are the changes caused by drying, and the potential correlation of air leakage with nail popping as measured in this study. It was found that all but one joint (shrinkage class 5 in Wall 1) became leakier from the first test to the last. The difference in airtightness was correlated with shrinkage class but was not correlated with nail popping as measured here, even when the joint noted above was omitted. The flow through joints at 0.209 lb/ft^2 (10 Pa) increased by a factor of 3 to 28 for the "outflow" positive direction and from 2.8 to 20 for the "inflow" negative direction. At the mean, "outflow" leakage was higher than "inflow" leakage. Plots showing the unit air leakage for all joints tested when the studs were green and after they dried are shown in Figures 7 and 8.

A summary of nail popping measurements of 2-in. (50 mm) spiral nails at studs located at each joint (by shrinkage class) is presented in Table 6. An analysis of variance showed that shrinkage class studs 3 and 5 were different from shrinkage class studs 7 and 9 at the 0.002 probability level. In this experiment, while the studs were restrained from twisting, some of the class 3 and 5 studs exhibited negative nail popping.

On the basis of the analysis in the previous section and the finding here, it is clear that the technique for classifying studs by shrinkage class using end slices was not effective. It was confirmed by the air leakage tests that leakage which developed on one edge was not correlated with the nail popping that was measured on the opposite edge.

Air Leakage Through Wetted Joints and Sheathing

Wetting of the waferboard sheathing caused expansion of the material, which led to reduction in the airflow through joints. Based on the data summarized in Table 8, the airflow was reduced by a factor of 5.6, 2.0, and 4.0 for Walls 1 through 3, respectively, at a pressure difference of 0.209 lb/ft^2 (10 Pa). Waferboard does not tend to shrink when it dries after it swells on being wetted, so the swelling tends to overcome effects caused by drying of lumber framing.

In the case of the airtightness of the material itself, swelling produced by wetting caused some breakdown in the bond between flakes and generally resulted in a decrease in airtightness. Walls 1 and 2 became leakier by factors of 1.5 and 1.2, respectively. However, Wall 3 became slightly tighter. Wall 3 material was observed to be somewhat wetter to the touch than the other two at the time of testing. So, it is expected that, on recovery of equilibrium moisture conditions, the blocking effect caused by water within pores and interstitial spaces will be removed and the air permeability of all walls will increase.

To examine the relative importance of leakage through joints compared with leakage through the material, flow through Wall 2 was examined at a pressure difference of 10 Pa. Flow was calculated per unit height of wall assuming a full width spacing of joints, i.e., 4 ft. (1.219 m). It was found that flow through joints would represent 93% and 85% of total flow for dry and wet conditions, respectively. Wall cells immediately adjacent to joints would experience an even higher proportional effect of air leakage through joints.

CONCLUSIONS

This work provides the first test data showing the change in leakage that can be expected when stud material dries and confirms that it is significant, in keeping with commonly held preconceptions.

Both experiments have shown that nail popping is highly variable in lumber cut from smaller trees. It was confirmed that longer fasteners exhibit more nail popping than shorter nails. While no significant difference was found in nail popping on opposite edges for most studs, a difference was found for some studs. This did not translate into a correlation between nail popping and air leakage.

High variability in shrinkage of lumber caused by ring orientation and the location of the stud relative to the pith of the tree led to the conclusion that nail popping on one edge was not well correlated with nail popping on the other edge for some studs. Consequently, measurement of nail popping on one edge does not provide reliable data for correlation with airtightness of sheathing fastened to the other edge. Rather, it was suggested that overall shrinkage was likely to be a more reliable measure for this purpose.

Air leakage tests on three full-sized walls confirmed that air leakage changes as a result of lumber drying were not well correlated with nail popping measured on the opposite edge. Increases in the airflow through unit joint length ranged from factors of about 3 to 28 times for joints built with the lumber green and dried to about 15% moisture content.

Heavy wetting on the inside of the sheathing caused swelling of the material and at joints, which greatly increased their airtightness by overall factors of 2 to 5.6. The sheathing material itself became less airtight because of swelling, which caused a breakdown in some of the bonds between wafers. The air permeability of the sheathing increased by factors of 1.22 and 1.48 for two walls, while the third, which was wetter, became slightly less permeable. It is expected that the air permeability of the sheathing will increase further when the sheathing dries fully.

This work has provided a better understanding of the factors influencing air leakage through sheathing as a function of drying of the lumber framing. A larger study is now under way to increase the data available using improved techniques for measuring the lumber shrinkage that leads to loosening of the connections. The information will then be used to assess the influence of different degrees of shrinkage on the moisture thermal performance of walls using computer modeling.

ACKNOWLEDGMENTS

This work was carried out with funding provided by the Canadian Forestry Service.

REFERENCES

Ferraro, V.; Schuyler, G.D.; and Swinton, M.C. 1988. Drying characteristics in timber frame walls of low-rise residential housing: final report. Report 487-1400-1 submitted to the Research Division, Canada Mortgage and Housing Corporation, Ottawa, ON.

Forest Products Laboratory. Rev. 1987. Wood handbook: wood as an engineering material. Agricultural Handbook 72, Washington, DC: U.S. Department of Agriculture.

Mullins, E.J., and McKnight, T.S., ed. 1983. Canadian woods: their properties and uses, third edition. Toronto: University of Toronto Press.

Onysko, D.M., and George, P. 1987. Design, construction and calibration of a chamber for testing the air tightness of full-sized wall sections. Project Report 03-43-10C-016. Ottawa, ON: Forintek Canada Corp.

Onysko, D.M., and Jones, S.K. 1989. Experiments on drying of framing and air leakage of joints in wall sheathing. Project Report 03-43-10C-016. Ottawa, ON: Forintek Canada Corp.

Platts, R.E. 1962. "Nail popping: moisture is the trouble-maker." Canadian Builder, Vol.12, No.9, pp. 67-68.

Suddarth, S.K., and Angleton, H.D. 1956. "Nail popping, a result of wood shrinkage". Station Bulletin 633. Lafayette, IN: Purdue Agriculture Experiment Station.

TABLE 1
Summary of Statistics for Nail Popping by Fastener Type

Fastener[1]	N[2]	Embedded Length	Mean[3] Nail Popping	Standard Deviation	Mean[4] Difference Opposite Edges	Std. Dev. of Difference	Std. Error of Mean Difference
		(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	64	67.5	0.5046	0.1828	0.0116	0.3580	0.0448
2	62	42.2	0.3011	0.1326	0.0117	0.2424	0.0308
3	63	21.0	0.3770	0.1775	0.0039	0.1580	0.0199
4	63	15.5	0.3480	0.3910	0.1304	0.6579	0.0829
		(in)	(in)	(in)	(in)	(in)	(in)
1	64	2.66	0.0199	0.00720	0.000457	0.01409	0.00176
2	62	1.66	0.0119	0.00522	0.000461	0.00954	0.00121
3	63	0.83	0.0148	0.00699	0.000154	0.00622	0.00078
4	63	0.61	0.0137	0.00154	0.005134	0.02590	0.00326

(1) Fastener type: 1 -- 3" (75 mm) spiral nail.
2 -- 2" (50 mm) spiral nail.
3 -- 1¼" (31 mm) drywall screw.
4 -- 1" (25 mm) drywall screw.

(2) Maximum number of pairs per fastener type is 64. A lesser number resulted when a negative nail popping value was recorded or one of the values was missing.

(3) Mean across all boards and edges.

(4) Paired differences across all boards.

TABLE 2
Air Leakage Characteristics of Joints at Class 3 Studs[1]

Wall	Test	ELA @10 Pa	ELA @75 Pa	C	N	A_1	A_2
		(mm^2/m)	(mm^2/m)	(x 10^{-3})		(x 10^{-3})	(x 10^{-4})
1	green	9.9	16 9	4.282	0.7623	7.436	6.757
	dry	27.9	40.1	14.557	0.6795	25.410	8.160
2	green	2.9	3.4	1.966	0.5717	2.942	-0.134*
	dry	6.2	11.6	2.412	0.8089	5.166	5.031
3	green	1.1	2.5	0.346	0.9023	1.192	1.086
	dry	13.3	24.8	5.152	0.8085	10.095	1.124
		(in^2/ft)	(in^2/ft)	(x 10^{-3})		(x 10^{-3})	(x 10^{-4})
1	green	0.0047	0.0080	0.8798	0.7623	0.5539	0.3482
	dry	0.0132	0.0189	2.1709	0.6795	1.8926	0.4206
2	green	0.0014	0.0016	0.1933	0.5717	0.2191	-0.0069*
	dry	0.0029	0.0055	0.5936	0.8089	0.3848	0.2593
3	green	0.0005	0.0012	0.1223	0.9023	0.0888	0.0560
	dry	0.0063	0.0117	0.1266	0.8085	0.7519	0.5792

(1) All coefficients are provided based on flow per unit length of joint. Coefficients marked with an asterisk are not significant at the 0.95 probability level.

TABLE 3
Air Leakage Characteristics of Joints at Class 5 Studs[1]

Wall	Test	ELA @10 Pa	ELA @75 Pa	C	N	A_1	A_2
		(mm^2/m)	(mm^2/m)	$(x\ 10^{-3})$		$(x\ 10^{-3})$	$(x\ 10^{-4})$
1	green	4.7	7.9	2.057	0.7555	3.415	3.171
	dry	2.4	4.5	0.930	0.8099	2.739	1.255
2	green	4.9	7.1	2.506	0.6850	4.481	1.446
	dry	15.3	27.5	6.216	0.7887	12.334	11.164
3	green	1.8	2.5	0.964	0.6696	2.024	0.167*
	dry	6.9	10.7	3.344	0.7135	6.344	2.718
		(in^2/ft)	(in^2/ft)	$(x\ 10^{-3})$		$(x\ 10^{-3})$	$(x\ 10^{-4})$
1	green	0.0022	0.0037	0.4117	0.7555	0.2543	1.6344
	dry	0.0011	0.0021	0.2296	0.8099	0.2040	0.6470
2	green	0.0023	0.0034	0.3818	0.6850	0.3338	0.7450
	dry	0.0072	0.0130	1.4146	0.7887	0.9187	5.7537
3	green	0.0009	0.0012	0.1384	0.6696	0.1508	0.0860*
	dry	0.0033	0.0051	0.5690	0.7135	0.4725	1.4007

(1) All coefficients are provided based on flow per unit length of joint. Coefficients marked with an asterisk are not significant at the 0.95 probability level.

TABLE 4

Air Leakage Characteristics of Joints at Class 7 Studs[1]

Wall	Test	ELA @10 Pa	ELA @75 Pa	C	N	A_1	A_2
		(mm^2/m)	(mm^2/m)	($x\ 10^{-3}$)		($x\ 10^{-3}$)	($x\ 10^{-4}$)
1	green	8.0	12.9	3.689	0.7338	5.790	4.901
	dry	21.3	30.4	11.177	0.6766	20.218	5.434
2	green	10.7	12.8	6.858	0.5892	9.966	0.551*
	dry	37.9	51.6	20.944	0.6538	33.115	9.354
3	green	3.7	5.7	1.837	0.7060	3.596	1.214
	dry	18.1	28.8	8.378	0.7308	16.129	8.331
		(in^2/ft)	(in^2/ft)	($x\ 10^{-3}$)		($x\ 10^{-3}$)	($x\ 10^{-4}$)
1	green	0.0048	0.0061	0.6789	0.7338	0.4313	2.526
	dry	0.0101	0.0144	1.6487	0.6766	1.5059	2.800
2	green	0.0051	0.0060	0.7213	0.5892	0.7423	0.284*
	dry	0.0179	0.0244	2.8280	0.6538	2.4665	4.821
3	green	0.0017	0.0027	0.3036	0.7060	0.2678	0.626
	dry	0.0086	0.0136	1.5238	0.7308	1.2013	4.294

(1) All coefficients are provided based on flow per unit length of joint. Coefficients marked with an asterisk are not significant at the 0.95 probability level.

TABLE 5
Air Leakage Characteristics of Joints at Class 9 Studs[1]

Wall	Test	ELA @10 Pa	ELA @75 Pa	C	N	A_1	A_2
		(mm^2/m)	(mm^2/m)	($\times 10^{-3}$)		($\times 10^{-3}$)	($\times 10^{-4}$)
1	green	7.0	11.3	3.149	0.7402	5.486	3.950
	dry	74.4	103.7	40.153	0.6644	65.252	19.737
2	green	4.1	5.5	2.305	0.6447	4.257	0.347*
	dry	181.8	198.1	129.909	0.5424	152.399	5.647*
3	green	2.8	6.1	0.940	0.8765	1.808	3.516
	dry	21.0	40.3	7.848	0.8239	16.417	18.499
		(in^2/ft)	(in^2/ft)	($\times 10^{-3}$)		($\times 10^{-3}$)	($\times 10^{-4}$)
1	green	0.0033	0.0053	0.5940	0.7402	0.4089	2.036
	dry	0.0351	0.0490	5.6486	0.6644	4.8601	10.172
2	green	0.0019	0.0026	0.3005	0.6447	0.3171	0.179*
	dry	0.0859	0.0936	11.4003	0.5424	11.3509	2.910*
3	green	0.0013	0.0029	0.3005	0.8765	0.1346	1.812
	dry	0.0099	0.0190	2.0464	0.8239	1.2228	9.534

(1) All coefficients are provided based on flow per unit length of joint. Coefficients marked with an asterisk are not significant at the 0.95 probability level.

TABLE 6
Summary of Nail Popping Measurements on Studs at Joints in Sheathing

Wall No.	Stud Class	Initial Moisture Content	Final Moisture Content	Number of Fasteners[1]	Mean Total Nail Popping	Standard Deviation	Minimum Nail Popping	Maximum Nail Popping
		(%)	(%)		(mm)	(mm)	(mm)	(mm)
1	3	40	15	8	0.386	0.237	0.178	0.877
	5	43	14	8	0.302	0.085	0.161	0.437
	7	39	14	8	0.577	0.190	0.377	1.006
	9	31	14	8	0.904	0.137	0.687	1.094
2	3	59	16	2	0.199	0.236	0.032	0.366
	5	60	15	4	0.275	0.299	0.063	0.710
	7	37	14	7	0.078	0.048	0.007	0.144
	9	34	15	8	0.165	0.078	0.010	0.256
3	3	61	16	8	0.273	0.098	0.073	0.363
	5	47	16	8	0.256	0.060	0.155	0.343
	7	37	15	8	0.809	0.153	0.512	1.024
	9	36	14	8	0.611	0.195	0.376	0.902
		(%)	(%)		(in)	(in)	(in)	(in)
1	3	40	15	8	0.0152	0.00933	0.00700	0.0345
	5	43	14	8	0.0119	0.00335	0.00634	0.0172
	7	39	14	8	0.0227	0.00748	0.01484	0.0396
	9	31	14	8	0.0356	0.00539	0.02704	0.0431
2	3	59	16	2	0.0078	0.00929	0.00126	0.0144
	5	60	15	4	0.0108	0.01177	0.00248	0.0280
	7	37	14	7	0.0031	0.00189	0.00028	0.0567
	9	34	15	8	0.0650	0.00307	0.00039	0.0101
3	3	61	16	8	0.0107	0.00386	0.00287	0.0143
	5	47	16	8	0.0101	0.00236	0.00610	0.0135
	7	37	15	8	0.0319	0.00602	0.02016	0.0403
	9	36	14	8	0.0241	0.00768	0.01480	0.0355

(1) 2-inch (50 mm) spiral nails.

TABLE 7
Air Leakage Through Dry and Wet Waferboard

Wall	Condition	ELA @10 Pa	ELA @75 Pa	C	N	A_1	A_2
		(mm^2/m^2)	(mm^2/m^2)	(x 10^{-3})		(x 10^{-3})	(x 10^{-4})
1	dry	3.1	6.9	0.968	0.8993	1.3431	4.7006
	wet	4.6	10.5	1.437	0.9052	2.6160	6.7396
2	dry	3.9	8.4	1.287	0.8797	1.3753	5.9168
	wet	4.7	10.4	1.508	0.8925	1.6817	7.4025
3	dry	4.6	9.1	1.647	0.8410	2.8212	5.0283
	wet	4.1	9.2	1.289	0.8997	2.2761	5.9011
		(in^2/ft^2)	(in^2/ft^2)	(x 10^{-3})		(x 10^{-3})	(x 10^{-4})
1	dry	0.000446	0.000994	0.1030	0.8993	0.0305	0.738
	wet	0.000662	0.001512	0.1564	0.9052	0.0594	1.059
2	dry	0.000562	0.001210	0.1270	0.8797	0.0312	0.929
	wet	0.000677	0.001498	0.1563	0.8925	0.0382	1.163
3	dry	0.000662	0.001310	0.1399	0.8410	0.0640	0.790
	wet	0.000590	0.001325	0.1376	0.8997	0.0517	0.927

(1) All coefficients are provided based on flow per square area of material.
(2) Direction of airflow was from the inside to the outside of the wall.

TABLE 8
Air Leakage Through Dry and Wet Waferboard Joints

Wall	Condition	ELA @10 Pa	ELA @75 Pa	C	N	A_1	A_2
		(mm^2/m)	(mm^2/m)	(10^{-3})		(10^{-3})	(10^{-4})
1	dry	29.5	40.6	16.092	0.6593	25.2738	8.1257
	wet	5.3	6.3	3.353	0.5918	4.9840	0.2270*
2	dry	62.1	70.3	42.437	0.5616	51.1766	5.1419
	wet	27.8	37.0	15.749	0.6426	24.9308	5.6497
3	dry	14.4	24.7	6.125	0.7676	11.4133	9.4794
	wet	3.6	5.2	1.817	0.6886	3.4730	0.9290
		(in^2/ft)	(in^2/ft)	(10^{-3})		(10^{-3})	(10^{-4})
1	dry	0.0139	0.0192	2.220	0.6593	1.8824	4.1878
	wet	0.0025	0.0030	0.356	0.5918	0.3712	1.0587*
2	dry	0.0293	0.0332	4.011	0.5616	3.8117	2.6500
	wet	0.0131	0.0175	2.036	0.6426	1.8569	2.9117
3	dry	0.0068	0.0117	1.284	0.7676	0.8501	4.8855
	wet	0.0017	0.0025	0.281	0.6886	0.2587	0.4790

(1) All coefficients are provided based on flow per unit length of joint.
(2) Direction of airflow was from the inside to the outside of the wall.
(3) An asterisk indicates that the coefficient was not significant at the 95% probability level.

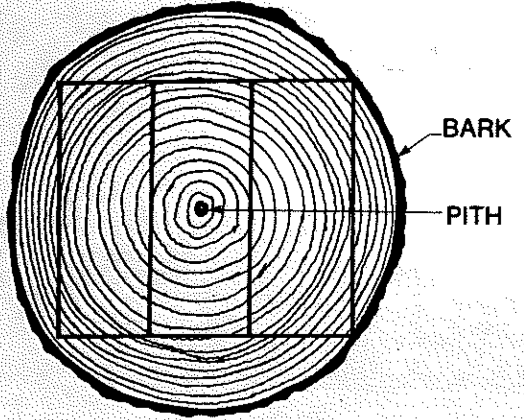

Figure 1. Cross section of tree showing where lumber might be cut relative to growth rings and the pith

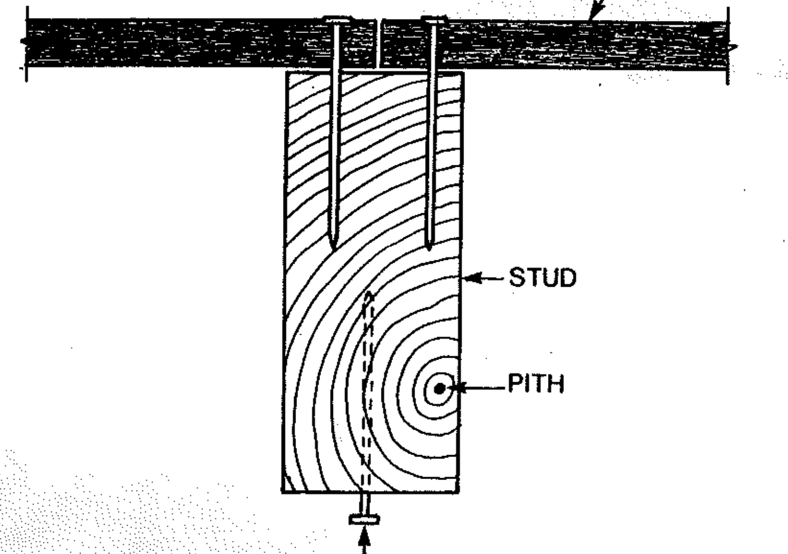

Figure 2. Cross section of wall stud at joint in sheathing

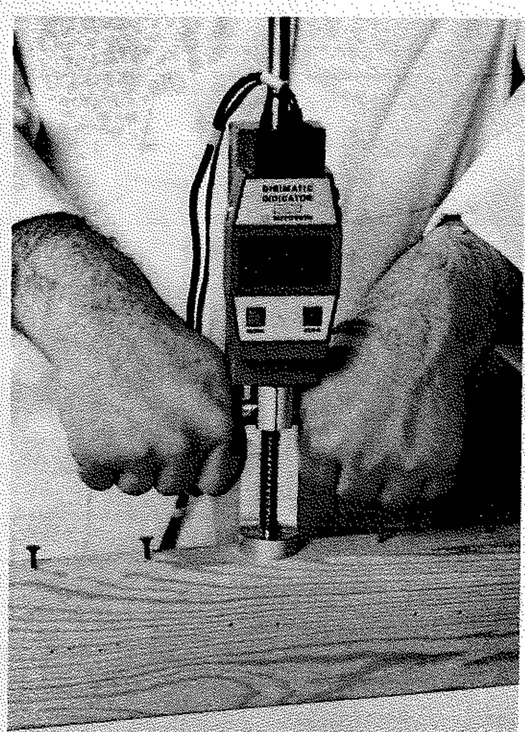

Figure 3. Measurement of nail popping using a tool built for this purpose

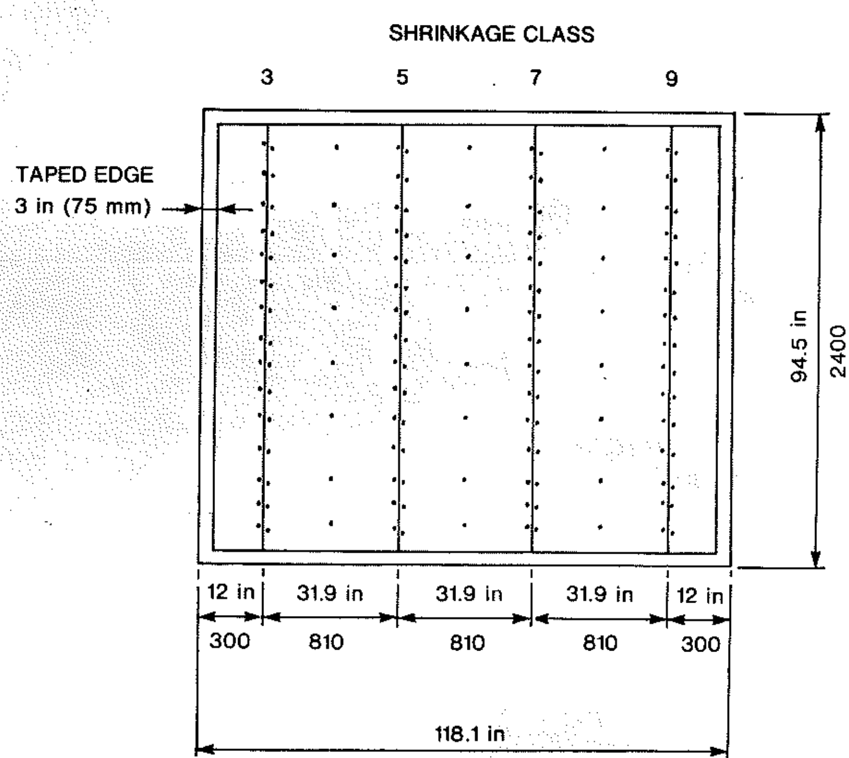

Figure 4. Elevation of a typical test wall showing nailing and joint details

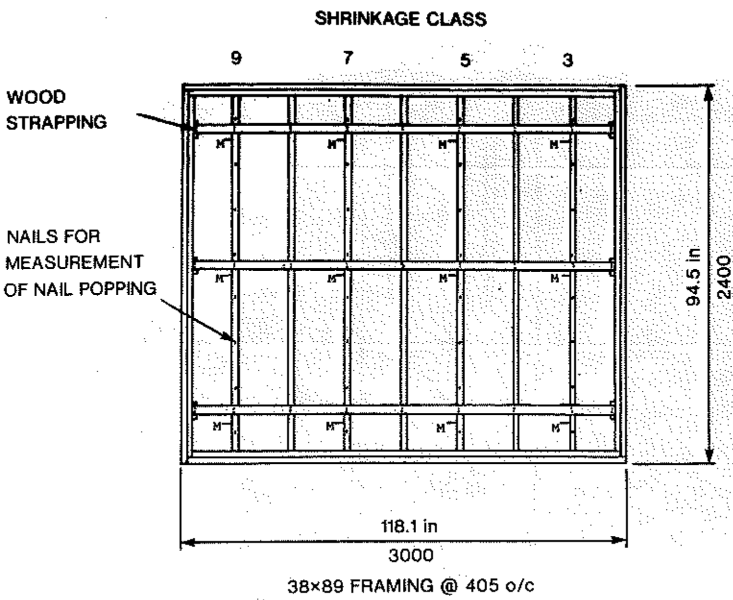

Figure 5. Elevation of a typical test wall showing framing layout and location of nails for nail popping measurements

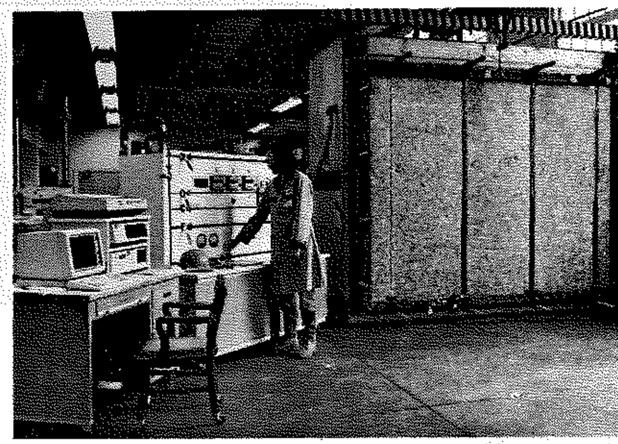

Figure 6. Air leakage test facility for walls

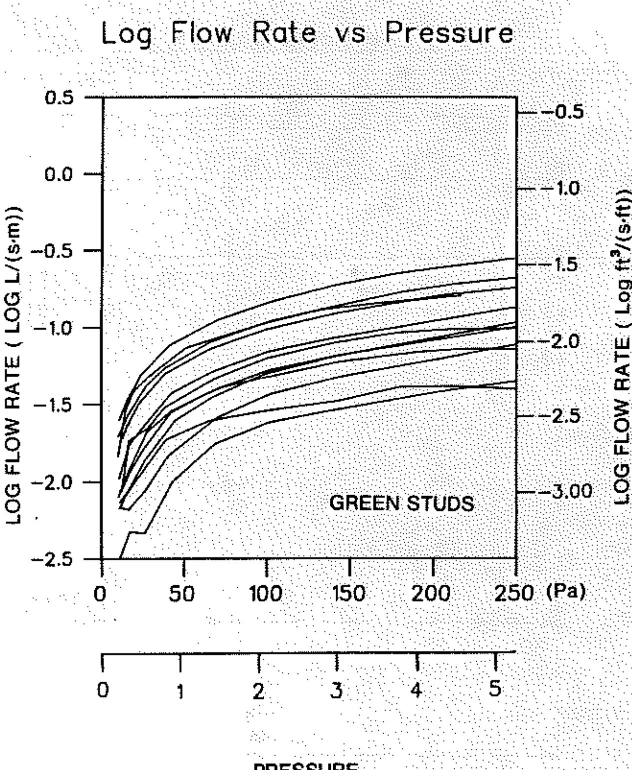

Figure 7. Air leakage through joints in three walls tested under positive pressure with studs in the green condition

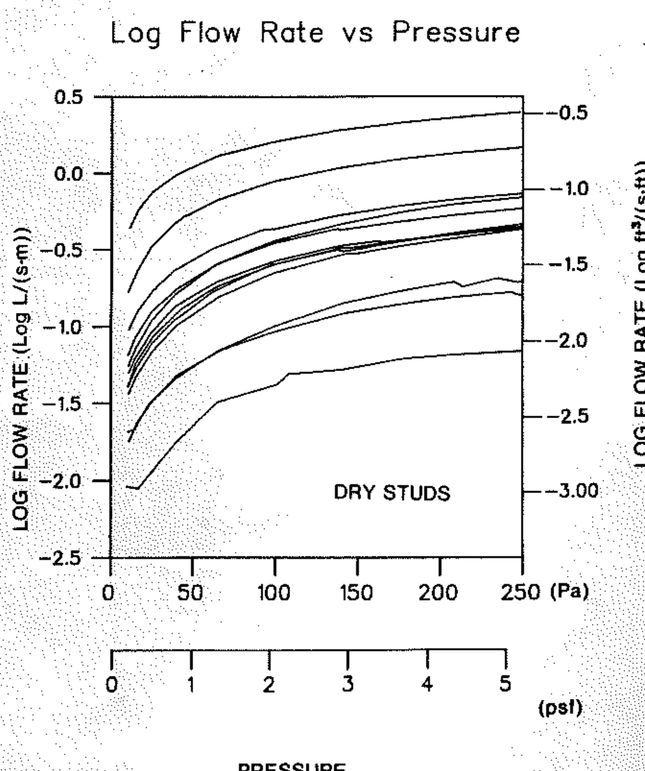

Figure 8. Air leakage through joints in three walls tested under positive pressure with studs in the dry condition