Characterization of Air Leakage in Residential Structures—Part 1: Joint Leakage

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ABSTRACT

Air will leak through a building envelope that is not well sealed. This leakage of air decreases the comfort of a residence by allowing moisture, cold drafts, and unwanted noise to enter, and air leakage can account for up to 40% of the energy used for heating and cooling in a typical residence. With nearly a mile of exterior joints in a typical residence that can leak air, knowing which joints leak the largest quantity of air allows for the most strategic placement of sealant. This two-part paper describes an extensive investigation to quantify the leakage characteristics of various types of joints and openings in a residential structure. All in all, 17 different joints/openings were characterized through both laboratory and real-house measurements using fan pressurization. Part 1 presents the methods and results associated with the air leakage of the individual joints/openings. Part 2 adapts these individual results to the whole house, including an examination of the joint leakage interdependence in the wall cavity.

INTRODUCTION

It is well known today that a properly insulated building uses less energy for heating and cooling than the same uninsulated building. And most people know that the higher the R-values of ceiling and wall insulation, the greater the energy savings. What is less known is that the air leakage of a home is also a major factor in how much energy a building uses for heating and cooling.

Air will leak through a building envelope that is not well sealed. This leakage of air decreases the comfort of a residence by allowing moisture, cold drafts, and unwanted noise to enter and may lower indoor air quality by allowing in dust and airborne pollutants. In addition, air leakage accounts for between 25% to 40% of the energy used for heating and cooling in a typical residence (EPA 2000).

To reduce air infiltration and achieve an energy-efficient building, the builder or building owner must seal gaps in the building's thermal enclosure. Installing high-quality, tightly sealed windows and doors is a good start, but it is also important to seal joints and openings in the walls, ceiling, and flooring/foundation. To properly address the negative effects of air leakage, such as wasted energy, occupant discomfort, condensation, and so on, all of the joints and openings in the building enclosure should be air-sealed. However, some builders or building owners may only have limited funds available to devote to air-sealing. With nearly a mile of exterior joints in a typical residence that can leak air, knowing which joints leak the largest quantity of air allows for the most strategic placement of sealant. As the drawing in Figure 1 depicts, there are many leakage paths through the building enclosure. This study is an investigation to quantify the leakage characteristics of various types of joints and openings in a residential structure (Part 1) and to prioritize the joints/openings in terms of the amount of air leakage per unit cost to seal it—a kind of air leakage bang-for-your-buck ranking of the joints/openings (Part 2). The air leakage results are primarily reported at a pressure difference of 50 Pa (0.2 in. water) due to its prevalence in the pre-commission testing of residential structures in the United States.

There is an abundance of information available in the literature on the air leakage characteristics of buildings. Sherman et al. (2004) and ASHRAE (2001) provide an overview

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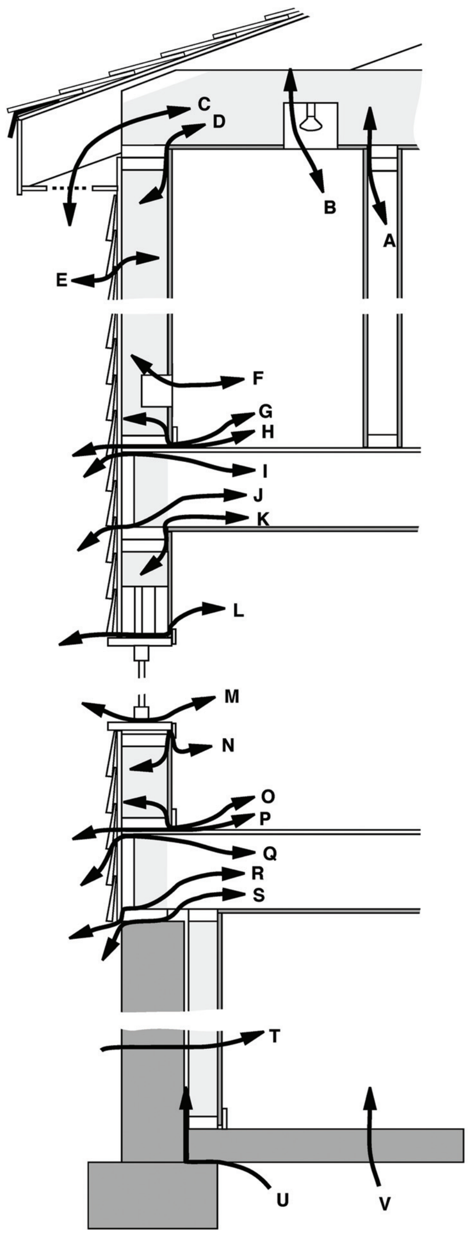

Figure 1 *Schematic of a house cross section showing the various air leakage paths.*

of many of the key papers. This information is almost all a macroview of air leakage, meaning that the information on air leakage is at the building level, not the joint level. A microview of air leakage (i.e., knowledge about the joint-level behavior) is necessary in order to understand how houses leak and where they leak from. The available literature that takes the microview is limited to a few references. But, even in those cases, only a few joints/openings have been investigated, which prevents the insightful exercise of taking the individual performance of joints/openings and integrating them into the whole-house performance (i.e., taking the microview in order to get a better appreciation for the macro view).

Onysko and Jones (1989) performed airtightness tests associated with vertical joints formed by waferboard sheathing. They investigated the effects of transitioning from green lumber to dried lumber (~15% moisture content) on air leakage. Siitonen (1982 and referenced by Relander et al. 2011) measured the airtightness of the joint between the wood bottom plate and a concrete slab floor of an actual house. The 2001 *ASHRAE Handbook—Fundamentals* also includes an extensive table of air leakage values, although most of the descriptions are either vague (e.g., drop ceiling, chimney, etc.) or obscure (e.g., aluminum double horizontal slider window with weather stripping). All of these microreferences will be reviewed in more detail later, where their results are compared to the results of this study.

EXPERIMENTAL SETUP

This study involved two forms of testing. One form was to test individual components and wall assemblies in a laboratory setting. The other form was to test these same elements in a whole-house setting. The lab setting had its advantages in that it provided well-controlled conditions, ease with isolating individual joints/openings, and ease with measuring small leakage quantities. The lab's disadvantages were that the test assemblies could inadvertently be constructed to a higher quality than is typical of site-built construction due to the equipment and environmental conditions being more ideal and that the length of joints is often restricted due to practical limitations. The whole-house setting had its advantages in that it provided field-prototypic conditions, more joint length, and typical construction quality. The whole-house challenges were that testing needed to occur amidst uncontrolled conditions (e.g., wind) and more difficulty in isolating joints. In short, one form's strength was the other form's weakness, which is why both forms of testing were pursued.

Component and Assembly Testing

Airtightness of a building component or assembly was determined by exposing the specimen to a steady-state pressure difference and measuring the airflow rate needed to maintain the pressure difference per ASTM E 283 (2004). Two pressure chamber designs were used; each integrated with the same pressurization and measurement system. An 8 × 8 × 2 ft (2.4 × 2.4 × 0.61 m) chamber was used for wall testing; a 4 × 4 × 2 ft (1.2 × 1.2 × 0.61 m) chamber was used to evaluate components. Figure 2 shows a photograph and sketch of the larger chamber. The chambers were constructed with silicone sealant applied to all of the joints to prevent extraneous leakage. The flange around the perimeter of the chamber opening had a gasket present to form a good seal with the mating flange of the test plug. The two flanges, one on the chamber and one on the test plug, were clamped around the perimeter with the compressible gasket sandwiched in between.

An Infiltec Duct Leakage Tester (DL1-DM4-110) with the low-flow orifice tubes was used for the testing. This system allows for testing components with low airflow rates down to

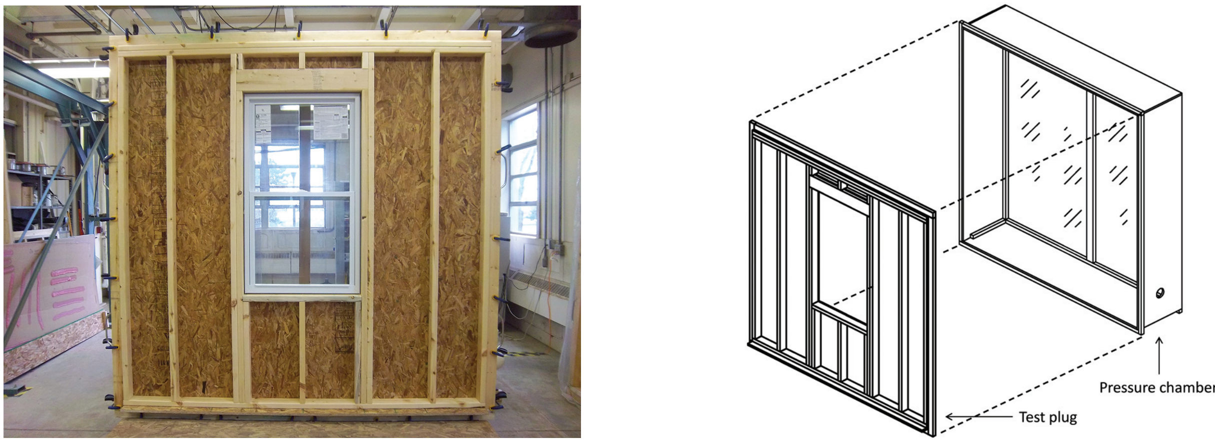

Figure 2 *(a) Photograph showing the test plug side of the larger pressure chamber. (b) Drawing showing the mating of the test plug and pressure chamber (b).*

0.33 ft^3/min (0.16 L/s), which was sufficient precision for the leakage rates that were anticipated. The Infiltec unit was used to blow air into (or out of) the test chamber and the pressure difference between the chamber and the outside was monitored and recorded along with the flow rate.

Prior to testing each assembly, a tare measurement was performed to establish the extraneous air leakage by eliminating the leakage through the test plug (typically with a plastic film). The protocol for testing the assembly involved pressurizing the chamber (mimicking infiltration) to the pressure differences of 40, 50 and 60 Pa (0.16, 0.20, and 0.24 in. water) with respect to the interior side of the wall assembly. The tare reading for each pressure was subtracted from the measurements of the test plug. The pressure-flow data were then curve-fit and interpolated to a pressure of 50 Pa (0.2 in. water) using a power-law relationship ($Q = C\Delta P^n$). A pressure difference of 50 Pa (0.2 in. water) was selected in order to relate the results to a whole-house blower door assessment, which is typically performed at 50 Pa (0.2 in. water) pressure difference (infiltration) by an energy rater on an actual house.

Test walls were constructed to represent 15 construction details of interest. The air leakage from individual joints on a test plug could be measured by sealing the other joints with removable clay. All tests were performed with the test plug mounted vertically, including ceiling assemblies, where the drywall-to-top plate joint was of interest. For the case of wall assemblies, the outer skin was 7/16 in. (11 mm) oriented strand board (OSB) (no housewrap) on 2 × 4 in. nominal wood framing (38 × 89 mm actual), and there was no interior skin (no drywall), so these laboratory measurements isolated the resistance of the joint only, excluding any upstream or downstream resistances.

Whole-House Testing

The test house was a 1400 ft^2 (130 m^2) single-story structure with a basement and crawlspace that is located on the Owens Corning Science & Technology grounds in Granville, Ohio. It was originally constructed in 1977 by a local custom home builder. During the original construction, Owens Corning personnel observed the progress and documented construction details, but did not supervise the actual construction. It was felt, therefore, that the house was of better than average quality but was still typical of many houses being built. The original sheathing on the house was 1/2 in. (12.7 mm) fiberboard. Since the predominant construction practice currently in the United States is to use 7/16 in. (11 mm) OSB, it was thought important to replace the sheathing. All of the siding and sheathing was removed from the house and replaced with 7/16 in. (11 mm) OSB and housewrap by a local contractor.

The basic measurement system consists of a computer-controlled blower door system with multichannel pressure measurement and data logging capabilities. The fan was the Minneapolis Blower Door™ System (Model 3) from The Energy Conservatory (TEC). The data logger was the Automated Performance Testing (APT) system, also from TEC, which had eight differential pressure channels with autozeroing capability and resolution of 0.1 Pa (4×10^{-4} in. water) in the range of ±400 Pa (1.6 in. water). The system is operated using software supplied by TEC (TECHLOG2). A pressure tap was located at each exterior face of the envelope – one at the base of each wall (north, south, east, and west), buried in gravel to minimize localized wind effects, and one located in the ventilated attic. Other measurements included indoor and outdoor temperatures, barometric pressure, and relative humidity. All measurements were made with the pressure difference across the house enclosure of 50 Pa (0.2 in. water). The data reduction was done per the method described in ASTM E 1827 (1996).

The whole house leakage fell within the range from 500 to 900 ft^3/min (236 to 425 L/s) at 50 Pa (0.2 in. water) throughout the sealing experiments (hereafter the unit CFM50 will be used to refer to a flow rate of ft^3/min at 50 Pa (0.2 in. water) pressure difference), which enabled orifice ring B to be used with the fan. The question that needed to be answered was whether this measurement system, using the B-ring, would provide the needed detection level for differences expected in whole house leakage, which was estimated to be 10 CFM50 (4.7 L/s). This led to the development of a means of introducing precision holes into the test house via a variable orifice plate (or VOP) concept. The VOP essentially comprised a thin metal plate with five precision holes cut in it. Using a cover plate with a single hole larger than the maximum hole size in the base plate, one could then dial in the hole size of interest, either during a test or between baseline envelope pressure checks.

The first step was to verify the system's detection abilities in the laboratory, where the variability from wind was absent. The blower door and the VOP were installed in an 8 × 8 ft (2.4 × 2.4 m) wall, which was then mated with the pressurization chamber. As Figure 3 clearly shows, differentiation down to 10 CFM50 (4.7 L/s) was easily achievable, given no wind-related variation in exterior pressures during the measurement. This led to the next step of semi-empirically establishing meteorological limitations (i.e., pressure data filters), so that the desired level of differentiation could be achieved when testing the actual house. Combining noise reduction filters and averaging techniques, a balance was derived whereby the desired precision could be attained within a practical length of time and number of repeats. Since it was already established that the blower door could effectively measure a 10 CFM50 (4.7 L/s) change in a controlled environment, it was feasible to empirically establish a data rejection protocol for the test house measurements, for $n = 5$ tests, as follows:

a. All five baseline envelope pressures within 2 Pa (8×10^{-3} in. water) of each other
b. All five baseline envelope pressures with standard deviation <1.5 Pa (< 6×10^{-3} in. water)
c. Fan pressure standard deviation less than 3 Pa (12×10^{-3} in. water)
d. Fan flow change of less than 7 CFM50 (3.3 L/s) over five one-minute averages

This resulted in an effective differentiation down to 10 CFM50 (4.7 L/s). These considerations for testing and data filtering resulted consistently in the ability to measure down to a 10 CFM50 (4.7 L/s) change in the test house venue. Figure 4 shows individual consecutive tests run in which the 1.75 in. (44 mm) orifice was alternately opened and closed, causing a 20 CFM50 (9.4 L/s) change in house leakage.

A total of 13 different joints were measured in the test house. The incremental air leakage for a given joint was the difference in whole-house leakage between the test-in and test-out measurements. What separated the test-in and test-out measurements was the act of sealing with a commercially-available air sealant.

RESULTS AND DISCUSSION

Component and Assembly Results

A total of 15 different joints were studied in this venue. Each of the joints/openings are described in this section, along with a summary of the results in Table 1 and a sketch/photograph in Figure 5. All of these leakage results are for the unconstrained condition, where restrictions to airflow on the interior (e.g., base trim, drywall, etc.) and exterior (e.g., a water-resistive barrier and cladding) are omitted. The potential effect of such constraints will be addressed later in this

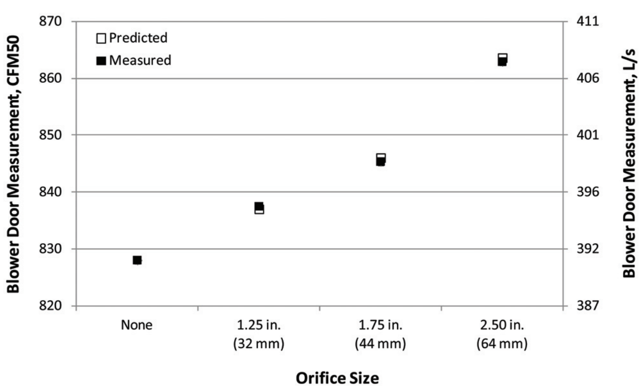

Figure 3 *Blower door results for controlled laboratory conditions and simulating the whole house leakage anticipated from the test house (828 CFM50 [391 L/s]), but where holes of a known size are introduced to determine if the measurement system is capable of differentiating the change, which this chart verifies.*

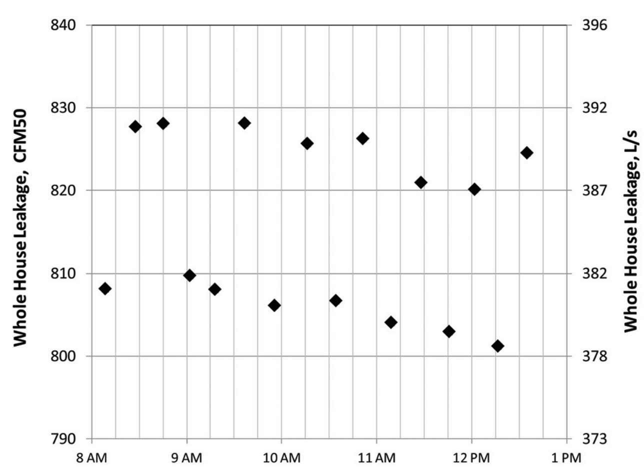

Figure 4 *Blower door results for the test house, where a 1.75 in. (44 mm) sharp-edged orifice was repeatedly opened and closed. The predicted flow through that orifice at 50 Pa (0.2 in. water) pressure difference is approximately 20 CFM50 (9.4 L/s), which is the approximate offset seen above between alternating data points.*

Table 1. Summary of Lab Leakage Data for Various Joints/Openings, Excluding Any Applicable Upstream or Downstream Flow Resistances

Joint	Length Tested, ft	Normalized Leakage Min., CFM50/ft	Normalized Leakage Max., CFM50/ft	Normalized Leakage Ave., CFM50/ft	CFM50/ft = $C\,\Delta P^n$ C, CFM50/ft·Pa^n	CFM50/ft = $C\,\Delta P^n$ n
Bottom plate-to-subfloor	104	0.016	0.306	0.113	0.00428	0.837
Plate-to-sheathing	160	0.040	0.266	0.091	0.00300	0.871
with engineered 1/8" defect	16	0.259	0.728	0.493	0.03102	0.707
Double-top plate	56	0.025	0.424	0.179	0.00700	0.829
Vertical sheathing-to-stud	64	0.046	0.380	0.129	0.00339	0.929
with engineered 1/8 in. defect	16	0.498	0.595	0.547	0.02555	0.783
Band joist-to-plate	56	0.079	0.307	0.171	0.00535	0.886
Band joist-to-subfloor	56	0.033	0.316	0.110	0.00389	0.854
Drywall-to-top plate						
top plate w/ studs, cantilever fastened	64	0.688	2.225	1.759	0.20212	0.553
top plate w/ studs, top plate fastened	64	0.340	2.187	1.168	0.09833	0.633
top plate w/ studs & hurr. clips, cantilever fastened	48	2.105	2.561	2.343	0.28394	0.539
top plate w/ studs & hurr. clips, top plate fastened	48	1.165	1.839	1.547	0.13885	0.616
Inside corner	48	0.123	0.788	0.325	0.01201	0.843
Outside corner	32	0.014	0.070	0.037	0.00147	0.822
Garage wall base	32	0.105	0.376	0.201	0.00910	0.791

Opening	Units Tested	Normalized Leakage Min., CFM50/each	Normalized Leakage Max., CFM50/each	Normalized Leakage Ave., CFM50/each	CFM50/ea = $C\,\Delta P^n$ C, CFM50/ea-Pa^n	CFM50/ea = $C\,\Delta P^n$ n
Recessed light	4	6.86	10.58	9.10	1.048	0.552
Duct boot	4	5.93	8.89	7.69	0.879	0.554
Light switch	4	0.39	3.33	1.40	0.181	0.524
Electrical outlet (interior)	7	1.63	3.87	2.62	0.249	0.601
Electrical outlet (exterior)	4	0.56	4.11	2.79	0.205	0.668

paper. The results are presented as follows for each of the joints/openings in terms of the average air leakage and corresponding 95% confidence interval associated with that average.

Bottom Plate-to-Subfloor (0.113 ± 0.051 CFM50/ft [0.175 ± 0.079 L/s·m]). The leakage is shown to range from a best case of 0.016 CFM50/ft (0.025 L/s·m) to a worst case of 0.306 CFM50/ft (0.474 L/s·m) (~19X). This variability in air leakage is likely the result of the construction tolerances that are inherent to the assembly of this joint, despite these joints being constructed in a controlled environment and by the same person.

Plate-to-Sheathing (0.091 ± 0.028 CFM50/ft [0.141 ± 0.043 L/s·m]). For this testing, top plate-to-sheathing and bottom plate-to-sheathing are nominally identical in their construction, so the results are combined. Two of these results are for joints with an engineered defect, where the center stud on an 8 ft (2.4 m) wide wall was offset from the plates by 1/8 in. (3.2 mm) toward the sheathing. In that case, the average normalized leakage is shown to increase to 0.493 CFM50/ft (0.763 L/s·m). This off-setting creates a larger gap, resulting in larger leakage. The 1/8 in. (3.2 mm) gap was not chosen arbitrarily. This is an expected tolerance on wall assemblies as specified by the Gypsum Association (2010), which represents the major drywall manufacturers.

Double Top Plate (0.179 ± 0.093 CFM50/ft [0.277 ± 0.144 L/s·m]). The double top plate joint represents the leakage through the mating surface of the two plates at the top of the wall.

Vertical Sheathing-to-Stud (0.129 ± 0.074 CFM50/ft [0.200 ± 0.115 L/s·m]). The sheathing seam was located at the stud and the sheathing gap was 1/8 in. (3.2 mm) per industry recommendations (APA – The Engineered Wood Association, 2011). Note that these leakage values apply to the combined leakage on both sides of the stud. There were two additional measurements for joints where the center stud was offset from

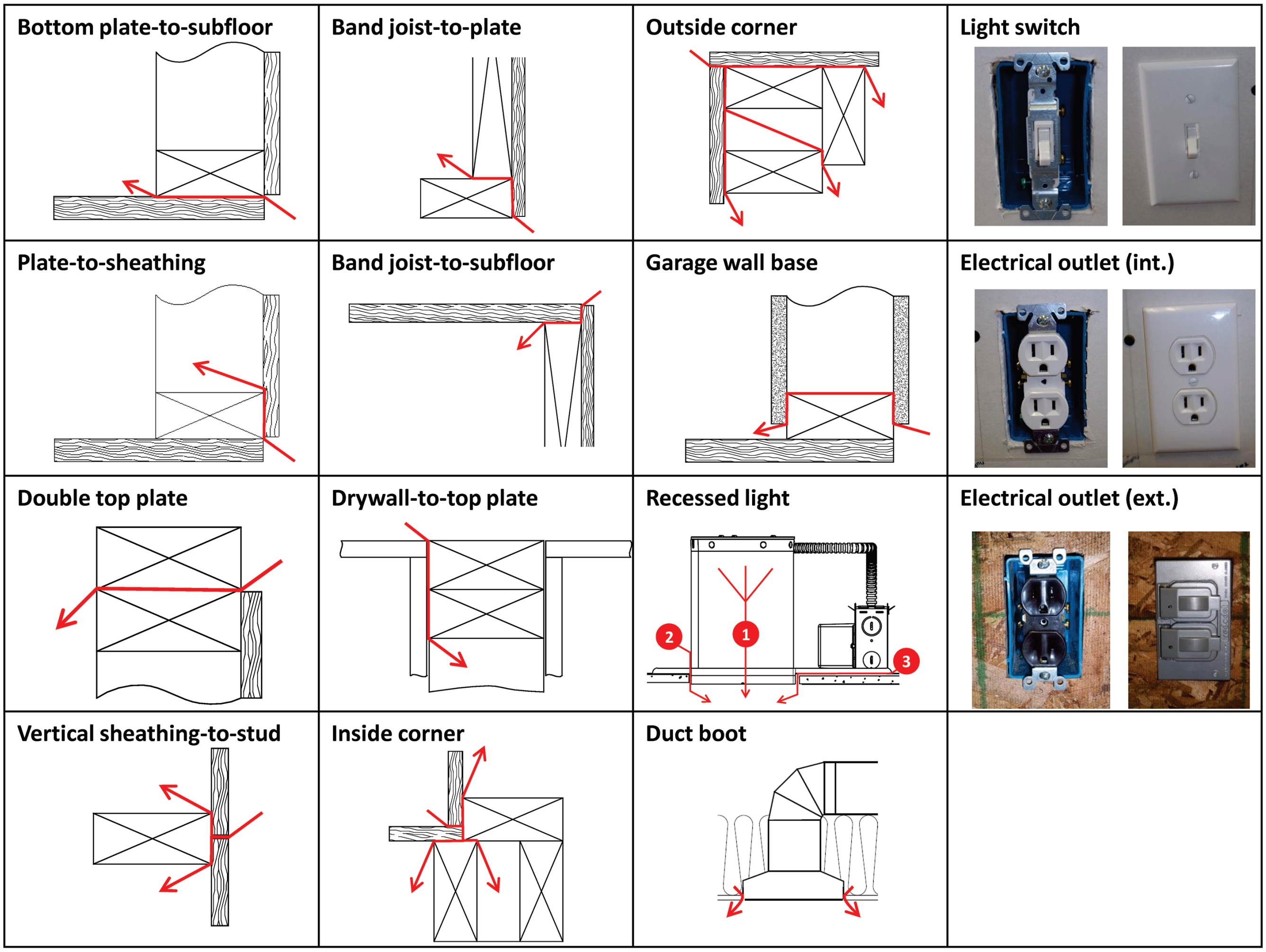

Figure 5 *Drawings/photographs of the various joints/openings studied in the laboratory testing.*

the plates by 1/8 in. (3.2 mm) toward the sheathing to simulate a construction defect, where the average normalized leakage is shown to increase to 0.547 CFM50/ft (0.857 L/s·m).

Band Joist-to-Plate (0.171 ± 0.058 CFM50/ft [0.265 ± 0.090 L/s·m]).

Band Joist-to-Subfloor (0.110 ± 0.072 CFM50/ft [0.170 ± 0.111 L/s·m]).

Drywall-to-Top Plate. Various conditions of the drywall-to-plate joint were studied, which included fastening location and the presence of hurricane clips. According to the Gypsum Association (2010), fasteners can be held back 8 in. (203 mm) from the top of the wall (i.e., the uppermost fastener is 8 in. down from the top of the wall) “to minimize the effects of truss uplift and the possibility of fastener popping in areas adjacent to wall and ceiling intersections.” This is called “floating interior angles” by the Gypsum Association. For the purpose of this testing, the drywall was either top plate fastened, which meant that fasteners were placed in the top plate on 16 in. (406 mm) centers (i.e., uppermost fastener is within 2 in. of the top of the wall), or cantilever fastened, which meant that fasteners were held back 8 in. (203 mm) from the top of the wall and placed into the studs (i.e., uppermost fastener is within 8 inches of the top of the wall), mimicking the Gypsum Association recommendation. The average normalized leakage for the condition of cantilever fastening was 1.759 ± 0.711 CFM50/ft (2.73 ± 1.10 L/s·m), whereas the condition of top plate fastening was 1.168 ± 0.748 CFM50/ft (1.81 ± 1.16 L/s·m). Hurricane ties are often used to attach the roof framing to exterior wall framing. The combination of the thickness of the tie and the thickness of the nail head can create a localized offset of 3/16 in. (5 mm) between the drywall and the plates. In all cases, there were three hurricane ties used every 8 ft (2.4 m) of top plate. The average normalized leakage for the condition of cantilever fastening with hurricane clips was 2.343 ± 0.259 CFM50/ft (3.62 ± 0.40 L/s·m), whereas the condition of top plate fastening with hurricane clips was 1.547 ± 0.392 CFM50/ft (2.40 ± 0.60 L/s·m). Notable is that both of these conditions are leakier than the case where the hurricane ties were absent, which would be expected due to the larger gaps between the drywall and top plate that are created locally at the hurricane ties. All of these drywall-to-top-plate results are for the case where there is no downstream restriction once the air is inside the wall cavity, such as the drywall-to-bottom plate connection. This downstream restriction will be addressed in Part 2 of this paper.

Inside Corner (0.325 ± 0.212 CFM50/ft [0.503 ± 0.328 L/s·m]) and Outside Corner (0.037 ± 0.023 CFM50/ft [0.057 ± 0.036 L/s·m]). An inside corner is one that points toward the interior of a building and vice versa for an outside corner. It is notable that the leakage for an outside corner is roughly one-tenth the leakage for an inside corner. A possible explanation is the tortuousity of the flow path. Figure 6 shows the possible flow paths for an outside corner. Note that Joint A, which is at the sheathing intersection, would not be expected to be tight, because these two pieces of sheathing are not nailed to one another and the sheathing edges, which form this joint, are likely to be field-cut and not precise. The flow then bifurcates at Joint B and Joint C, both of which are comprised by the mating of nailed sheathing and framing. Such joints tend to be tight due to the intimate contact, and since they are the only means of leakage across the assembly, the entire joint tends to be tight, significantly retarding flow paths 1, 2, and 3. Figure 7 shows the possible flow paths for an internal corner. Joint A, which is at the sheathing intersection, would not be expected to be tight for the same reason as mentioned above for a sheathing-to-sheathing joint. Joint B similarly would not be expected to be tight, because it also is likely to be field-cut and not precise. Joint C is the mating of a 1/2 in. (13 mm) wide surface of two framing members that are not nailed to one another, which is another joint that is very vulnerable to air leakage. Collectively, the joints of the inside corner assembly would not be expected to be very restrictive to airflow path 1 in the figure.

Garage Wall Base (0.201 ± 0.124 CFM50/ft [0.311 ± 0.192 L/s·m]). This wall is unique in that it is an exterior wall (i.e., separates the conditioned living space from the unconditioned garage space) that is sheathed on the exterior side with drywall, as opposed to some form of structural sheathing, like OSB or plywood. This is significant in that drywall has far less stiffness than OSB/plywood, which adversely affects the airtightness of the joint that is formed between the drywall and the framing members. The above result is the leakage past both sheets of drywall (interior and exterior) as depicted in Figure 5.

Recessed Lights (9.10 ± 1.56 CFM50/unit [4.29 ± 0.74 L/s-unit]). Four recessed light fixtures (Juno, 6 in., IC-22 with Air-Loc® sealed housing) were tested with a standard trim piece (Juno, 24W-WH). This recessed light, like many others, has three main air leakage paths, which are shown in Figure 8. Even so-called airtight recessed lights, which are required by many building codes, can leak an appreciable amount of air at the juncture between the light housing and the mounting flange (red arrow 2 in Figure 8), as well as the mounting flange and the drywall (red arrow 3 in Figure 8). Leakage through the

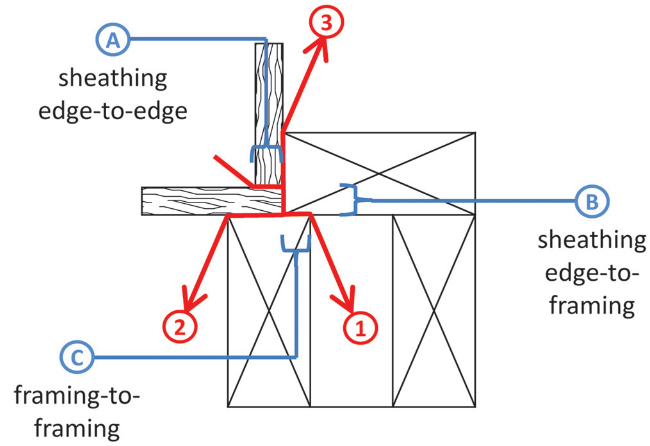

Figure 7 *Possible leakage paths at an inside corner.*

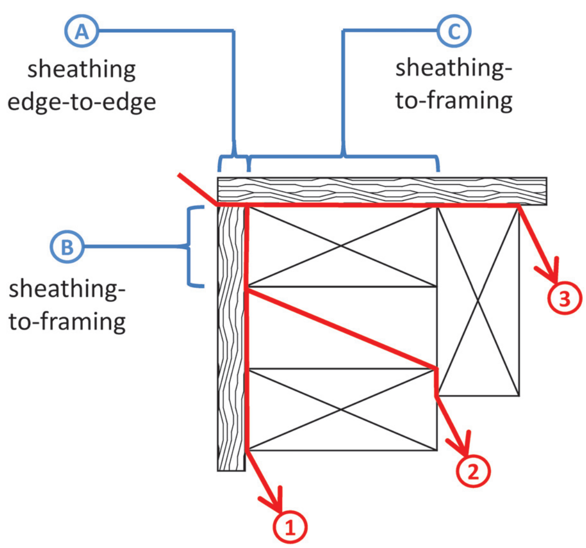

Figure 6 *Possible leakage paths at an outside corner.*

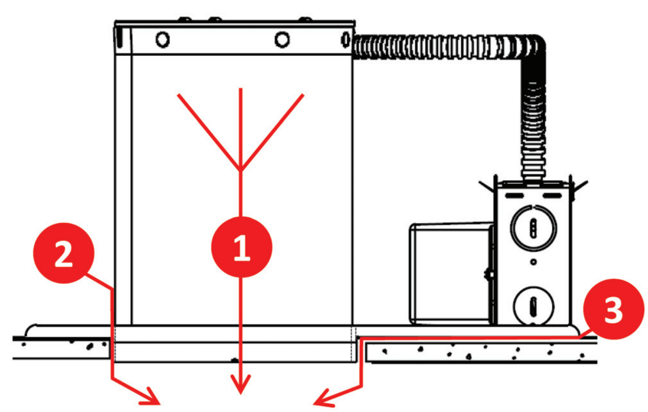

Figure 8 *Possible leakage paths associated with a recessed light: (1) leakage from the light housing, (2) leakage between the flange and housing, and (3) leakage between the flange and drywall.*

light housing (red arrow 1 in Figure 8) is fairly tight, as is required by many U.S. building codes.

Duct Boots (7.69 ± 1.31 CFM50/unit [3.63 ± 0.62 L/s-unit]). For cases where HVAC ducting is located in an unconditioned attic, the duct boots are at the ceiling and penetrate through the drywall, resulting in an air leakage path at the junction between the drywall and the perimeter of the boot. Four 6 × 10 in. (152 × 254 mm) boots, suspended from hanger brackets and mated to the drywall, were tested. The normal inlet to the boot was capped, and all of the joints on the boot itself were sealed with a silicone sealant. This was to isolate the leakage to the joint between the boot and the drywall.

Light Switch (1.40 ± 1.34 CFM50/unit [0.66 ± 0.63 L/s-unit]). Electrical light switches, positioned on the interior side of the wall cavity and penetrating the drywall, were tested with the switch cover plate installed.

Electrical Outlet, Interior (2.62 ± 0.73 CFM50/unit [1.24 ± 0.34 L/s-unit]). Electrical outlets, positioned on the interior side of the wall cavity and penetrating the drywall, were tested with the outlet cover plate installed.

Electrical Outlet, Exterior (2.79 ± 1.56 CFM50/unit [1.32 ± 0.74 L/s-unit]). Electrical outlets, positioned on the exterior side of the wall cavity and penetrating the sheathing, were tested with the manufacturer-supplied cover and gasket installed (Thomas & Betts, Red-Dot, part no. CCD).

Whole-House Results

A total of 13 different joints were studied in this venue through the incremental sealing of the joints with a spray-applied air sealant. The results from the sealing process are shown in Table 2.

Table 2. Summary of Test House Leakage Data for Various Joints/Openings, Excluding Any Applicable Upstream or Downstream Flow Resistances

Joint	Test House Leakage		
	CFM50	ft	CFM50/ft
Bottom of band joist	98	179	0.55
Top plate-to-sheathing	80	146	0.55
Outside corner	27	40	0.68
Bottom plate-to-sheathing	55	143	0.39
Top of band joist	32	184	0.17
Bottom plate-to-subfloor	7	143	0.05
Vertical sheathing seam	21	152	0.14
Sill plate-to-foundation	0	170	0.00
Inside corner	0	16	0.00
Window/Door framing-to-sheathing	32	98	0.32
Between top plates	27	155	0.17
Garage wall	18	30	0.60
Top plate-to-drywall at attic			
Bottom of drywall and 50 outlets unsealed	217	318	0.68
Bottom of drywall sealed and 50 outlets unsealed	93	318	0.29

Within this data set there are a few aberrant results that resulted from unique construction details of this test house, which couldn't be altered. The effect of the inside corner was too small to detect. Based on the laboratory results, which showed the inside corner to be quite leaky, this undetectable result with the test house was likely the result of a low occurrence for this joint type (16 ft [4.9 m]). The sill plate-to-foundation joint was also undetectable, which was to be expected since the house was constructed with a sill gasket between the sill plate and the foundation wall, which would be expected to cause flow resistance. The top of the band joist had a very small amount of leakage (0.17 CFM50/ft [0.26 L/s·m]), which was also to be expected since the subfloor was adhered to the joist members at the time of original construction, thereby forming a seal.

For top plate-to-drywall connection at the attic, there is just one entrance into the wall cavity, which is the top plate-to-drywall connection, but there are two exits from the wall cavity, which is at the termination of the drywall (bottom of the wall) and the penetrations of the drywall (mainly electrical outlets and switches). Table 2 lists two entries for this joint type. One indicates the case where the bottom of the drywall and all 50 penetrations/outlets were unsealed. The other indicates the case where only the 50 penetrations/outlets were unsealed. The latter obviously has less leakage associated with it because the predominant path at the bottom of the wall is still sealed. This can be a realistic condition in cases where all of the trim in a house is well caulked, including caulking of the trim to a tile floor.

Comparison to Other Data in the Literature

Onysko and Jones (1989) performed airtightness tests associated with vertical joints formed by waferboard sheathing. They investigated the effects of transitioning from green lumber to dried lumber (~15% moisture content) on air leakage. Figure 9 shows their results (gray and black columns), along with the individual results obtained in this study (red columns), which shows very good overall similarity.

Siitonen (1982 and referenced by Relander et al., 2011) measured the airtightness of the joint between the wood bottom plate and a concrete slab floor of an actual house. The results were reported for a 10 Pa pressure difference. By assuming that the pressure difference exponent is 0.65, the reported leakage rate at 50 Pa (0.2 in. water) is estimated to be 0.057 CFM50/ft (0.088 L/s·m at 50 Pa) with a standard deviation of 0.046 (0.071). This compares to leakage rates obtained in this study for the bottom plate-to-subfloor that ranged from 0.016 CFM50/ft (0.025 L/s·m) to 0.306 CFM50/ft (0.474 L/s·m) with an average of 0.113 ± 0.051 CFM50/ft (0.175 ± 0.079 L/s·m), which is reasonable agreement.

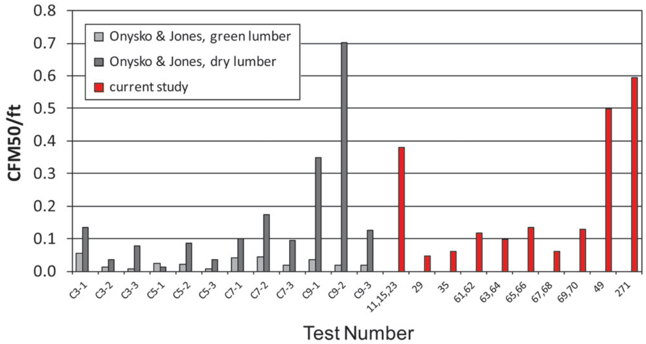

Figure 9 *Comparison of vertical sheathing joint leakage to that of Onysko and Jones (1989).*

As a part of an earlier Owens Corning study, Gavin (1985) investigated the leakage characteristics of joints located around the band joist area. Three of those joints were directly applicable to this study and are shown in Table 3, along with the results of Gavin and this present study. All of the results are expressed in terms of the effective leakage area, which was Gavin's figure-of-merit. With the exception of the band joist-to-plate connection, the agreement between the two studies is pretty good. Gavin's result for the band joist-to-plate connection is an order of magnitude larger than what was found in this study. There is no commentary by Gavin on why this joint was so much leakier than the others he studied. It is noteworthy that Gavin had no sheathing on the exterior side of the band joist when the result below was generated, whereas there was a piece of sheathing on the exterior side of the band joist in this study, which overlapped the joint in question. When Gavin added such a piece of sheathing, comparably placed to this study, the effective leakage area decreased by roughly a factor of three, which is better agreement to the present study, but still much higher.

There were several joints/openings in the 2001 *ASHRAE Handbook—Fundamentals* that were seemingly similar to this study. A comparison of some results for openings and joints is shown in Tables 4 and 5, respectively. The agreement between those data and the present data are good, with the exception of the bottom plate-to-subfloor joint, where the HoF value is one to two orders of magnitude higher.

Minimum, Maximum, and Best Estimate of Leakage Severity

Table 6 contains a summary of all the data presented here within, including both from the laboratory and test house. To the right of these measured values are columns that denote the recommended leakage values, which are broken down into a minimum, maximum and best estimate of the leakage severity, similar to how multiple measured results were handled in a previous study on the air leakage of building components (2001 *ASHRAE Handbook—Fundamentals*).

The minimum value is intended to represent the leakage severity associated with a well constructed joint. This is clearly a subjective term, but is intended to describe a condition where the construction equipment and environmental conditions are ideal, thereby enabling better-than-normal construction tolerances to be maintained. For the purposes of this testing, such conditions were routinely achieved with the assemblies tested in the laboratory, because they were constructed by highly skilled craftsmen, with precision tools, in a conditioned environment. Consequently, most of the minimum values listed in the table came from the average lab result. The lowest measured lab result (as opposed to the average lab result) was not used because it was not reproducible, even under ideal conditions.

Table 3. Comparison of Various Joint Leakages to that of Gavin (1985)

Joint	Effective Leakage Area, ft²/ft × 10⁵		
	Gavin (1985)	Present Study	
		Lab	House
Bottom plate-to-subfloor	5.4	3.0 ± 1.6	1.2
Band joist-to-subfloor	3.8	2.5 ± 1.6	4.0
Band joist-to-plate	120	3.7 ± 1.5	11

Table 4. Comparison of Various Opening Leakages to that of the 2001 *ASHRAE Handbook—Fundamentals*

Opening	Effective Leakage Area, in² per unit			
	ASHRAE (2001)			Present Study Lab
	Min.	Best Est.	Max.	
Recessed lights	0.23	1.6	3.3	0.64 ± 0.11
Electrical outlets (no gaskets)	0.08	0.38	0.96	0.16 ± 0.05
Electrical outlets (with gaskets)	0.012	0.023	0.54	0.098 ± 0.034

Table 5. Comparison of Various Joint Leakages to that of the 2001 *ASHRAE Handbook—Fundamentals*

Joint	Effective Leakage Area, in²/ft				
	ASHRAE (2001)			Present Study	
	Min.	Best Est.	Max.	Lab	House
Ceiling-wall	0.0075	0.070	0.12	0.033 ± 0.025	0.039
Sole plate, floor/wall, uncaulked	0.018	0.2	0.26	0.0043 ± 0.0023	0.0017
Top plate, band joist	0.0035	0.005	0.018	0.0054 ± 0.0022	0.017

Table 6. Summary of All Air Leakage Results with Best Estimate, Minimum and Maximum Values, Excluding Any Applicable Upstream or Downstream Flow Resistances, Unless Otherwise Noted.

Joint	Lab Leakage			Test House Leakage			Recommended Leakage Values			Rationale for Best Estimate of Leakage Value
	Low, CFM50/ft	Ave., CFM50/ft	High, CFM50/ft	CFM50	ft	CFM50/ft	Best Est., CFM50/ft	Min., CFM50/ft	Max., CFM50/ft	
Bottom of band joist	0.08	0.17	0.31	98	179	0.55	0.55	0.17	0.55	1
Top plate-to-sheathing	0.04	0.09	0.73	80	146	0.55	0.55	0.09	0.73	1
Outside corner	0.01	0.04	0.07	27	40	0.68	0.68	0.04	0.68	1
Bottom plate-to-sheathing	0.04	0.09	0.73	55	143	0.39	0.39	0.09	0.73	1
Top of band joist	0.03	0.11	0.32	32	184	0.17	0.32	0.11	0.32	2
Bottom plate-to-subfloor	0.02	0.11	0.31	7	143	0.05	0.11	0.11	0.31	3
Vertical sheathing seam	0.05	0.13	0.60	21	152	0.14	0.14	0.13	0.60	4
Sill plate-to-foundation		Did not test.		0	170	0.00	0.00	0.00	0.00	5
Inside corner	0.12	0.33	0.79	0	16	0.00	0.33	0.33	0.79	6
Window/Door framing-to-sheathing		Did not test.		32	98	0.32	0.32	0.32	0.32	7
Between top plates	0.03	0.18	0.42	27	155	0.17	0.17	0.17	0.42	1
Garage wall	0.11	0.20	0.38	18	30	0.60	0.60	0.20	0.60	1
Top plate-to-drywall at attic	0.28[8]	0.53[8]	0.61[8]	217	318	0.68	0.68	0.538	0.68	1

Opening	Lab Leakage			Test House Leakage	Recommended Leakage Values			Rationale for Best Estimate of Leakage Value
	Low, CFM50/ea	Ave., CFM50/ea	High, CFM50/ea		Best Est., CFM50/ea	Min., CFM50/ea	Max., CFM50/ea	
Recessed light	6.86	9.10	10.58	Did not test.	9.10	9.10	10.58	9
Duct boot	5.93	7.69	8.89	Did not test.	7.69	7.69	8.89	9
Light switch	0.39	1.40	3.33	Did not test.	1.40	1.40	3.33	9
Electical outlet (interior)	1.63	2.62	3.87	Did not test.	2.62	2.62	3.87	9
Electrical outlet (exterior)	0.56	2.79	4.11	Did not test.	2.79	2.79	4.11	9

1 The test house value is generally considered to be more representative of typical construction tolerances than the laboratory value.
2 The band joist-to-subfloor connection in the test house had adhesive placed in the joint during the original construction. Since this is not a common building practice, the recommended value is taken from the laboratory data. Arguably, the actual value could be even higher than this, since laboratory results have generally been lower than experienced in an actual house. Also, one would expect the bottom of the band joist to have comparable leakage to the top of the band joist, which is the case for the recommended value (0.32 for the top vs. 0.55 for the bottom).
3 The average laboratory lab result is used, rather than the test house result, because the test house had 2 × 6 in. nominal (38 × 140 mm actual) framing, which would impart a greater resistance to air flow than the more typical 2 × 4 in. nominal (38 × 89 mm actual) framing, which was used in the laboratory testing. The laboratory lab assembly also used OSB for the subfloor, which is more typical of current construction than the plywood encountered in the test house.
4 The recommended value is from the test house, which had no gap between the sheathing seams, because this is perceived to be the more common situation. A potential upside of 0.60 CFM50/ft can still be realized for cases where a 1/8 in. gap is present.
5 A properly installed sill plate gasket on a nominally flat foundation should result in no leakage, which is what was experienced with the test house.
6 The quantity of inside corners in the test house was small, so resolving the effect on air leakage was difficult.
7 Only one set of results were obtained for this joint, which came from the test house. However, this joint is geometrically similar to the bottom plate-to-sheathing joint (0.39 CFM50/ft) and the top plate-to-sheathing joint (0.55 CFM50/ft), so the comparable results among all of these joints makes sense.
8 The lab leakage results for the top plate-to-drywall joint include the downstream constraint of the bottom-plate-to-drywall joint as well. This downstream resistance was inferred from the laboratory-based garage wall measurements described here within. The garage wall leakage includes two drywall-to-plate joints, one on the interior and one on the exterior. An estimate of the individual joint contribution (i.e., one drywall-to-plate joint) can be made by assuming that the interior and exterior joints leak the same, which implies an intermediate wall cavity pressure difference of 25 Pa (0.1 in. water). The flow rate associated with the overall pressure difference of 50 Pa (0.2 in. water), which includes the flow through both the interior and exterior joints, is the same as the flow through one of the joints with the pressure difference of 25 Pa (0.1 in. water), all of which are predicted by the same empirical relationship ($Q = C\,\Delta P^n$), so C can be inferred for the one drywall-to-plate joint. Also, the worst-case garage wall leakage was used in this calculation (see max normalized leakage in Table 1), rather than the average, based on the premise that lab-built wall assemblies generally have tighter tolerances than site-built construction.
9 Average results from the laboratory.

The maximum value is intended to represent the leakage severity associated with a "typically constructed joint". This is also a subjective term, but is intended to describe a condition where the construction equipment and/or environmental conditions are not ideal. Rough-cut (i.e., nonprecise) lumber and/or poor weather (e.g., cold, rain, snow) would be examples of such nonideal conditions, many of which can be found on a residential construction site. For the purposes of this testing, such conditions were routinely achieved with the test house, because it was site constructed with nonprecision tools and mixed weather. Consequently, most of the maximum values listed in the table came from the test house results.

The best estimate is the value that is believed to best represent what could be expected for typical site-built houses. It is not a measure of central tendency (i.e., not a mean or median). Rather, it is a value extracted from the overall test results, based on the judgment of the authors. The final column in the table lists the rationale for why the best estimate value was chosen.

CONCLUSION

This study was an extensive investigation to quantify the air leakage characteristics of 17 different joints/openings through both laboratory and real-house measurements using fan pressurization. This information is of greatest value when it can be applied to assessing the impact of joint leakage on actual houses and comprehending the effect of upstream and/or downstream restrictions in the wall cavity, such as drywall on the interior and cladding on the exterior. This will be addressed in Part 2 of this two-part manuscript.

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