Adequate Ventilation of Low-Slope Roof Systems: The Need for Better Understanding and Guidance

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IN MONTREAL, QUEBEC, low-rise residential buildings with low-slope roof systems are an important part of the city's architectural character. However, the current building code requirements and typical design and construction practices for these structures do not always provide for adequate ventilation of attic spaces. This article explains how the current code requirements were derived and uses case studies to illustrate ventilation problems and the repair strategies employed. Collaborative research efforts to address gaps in our knowledge and provide better guidance to architects and building enclosure professionals are also described. Low-slope roof systems refer to a roof system with a slope less than 1:6 and are commonly called "flat" roofs, such as throughout this article.

HISTORICAL CONTEXT

The introduction of thermal insulation for residential housing in North America in the late 1920s and early 1930s created condensation issues, most notably within wood-framed residential dwellings. Typical signs of condensation were noted in the form of peeling wall paint and water staining within upper-story ceiling finishes. Eventually, these issues were mostly controlled through the installation of vapor barriers within walls and roof systems; however, problems within some roof attic spaces persisted. Researchers in the mid- to late 1930s indicated that the installation of a vapor barrier was sometimes not sufficient to reduce the potential for condensation and that the ventilation of attics and roof cavities was necessary.[1]

However, the appropriate approach to ventilation of the roof space remained ambiguous until 1939, when Professor Frank Rowley—a professor at the University of Minnesota and the president of the American Society of Heating and Ventilating Engineers (ASHVE), which is currently known as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)—conducted roof ventilation research using specimens in the form of small-scale houses that closely resembled the size and shape of doghouses. The test specimens in the "doghouse experiments" were constructed with sloped roofs and were similarly prepared and constructed without vapor barriers. The only difference between the specimens was the amount of ventilation allowed into the attic space. The first specimen had no roof ventilation, while the other two specimens were constructed with vent ratios of 1/288 and 1/576, respectively. (A vent ratio represents the required area of openings providing exterior air into the roof cavity per horizontal roof area.) These test specimens were then subjected to interior and exterior conditions similar to residential dwellings under typical winter conditions, and at the conclusion of the test, only the house with a vent ratio of 1/288 revealed no traces of condensation or frost formation.

Rowley, Axel B. Algren, and Clarence E. Lund later completed full-scale tests yielding similar results to the doghouse experiments.[2] As part of the series of full-scale tests, a test specimen was also evaluated with a flat roof configuration.

The test conditions were an exterior temperature of -10°F (-23°C), and interior air at 70°F (21°C) and 40% relative humidity (RH). In general, various-sized ventilation openings and types were evaluated for the roof cavity under constant test conditions and the same building configuration. According to their findings, "light" frost accumulations were typically noted within the roof cavity spaces regardless of whether roof ventilation was provided by side wall or roof openings.

In 1942, the US Federal Housing Authority (FHA) published *Property Standards and Minimum Construction Requirements for Dwellings*,[3] which stated that ventilation should be provided for all roof cavities and that the minimum net ventilation area be "1/300 of horizontally projected roof area" for sloped roofs. Rowley's findings were often assumed to be the source or basis for the 1/300 vent ratio; however, the FHA provided no references or citations in their publication.[1]

Five years later, the Housing and Home Financing Agency (HHFA), which oversaw the FHA, conducted research in order to verify the 1/300 requirement. Under the supervision of Ralph Britton (HHFA principal investigator), Penn State University conducted the tests, which used six insulated flat-roof structures. A vent ratio of 1/300 was used for four of the specimens, with the other two having either no ventilation or a vent ratio of 1/100. The structure with a vent ratio of 1/100 and one of the structures with a 1/300 vent ratio were studied without the installation of a vapor barrier.

In the experiments, no visual or imminent condensation was identified in the flat-roof structures with a vapor barrier installed and a vent ratio of 1/300. In addition, structures with no installed vapor barriers, whether with a 1/300 or 1/100 vent ratio, and the structure with no ventilation all revealed imminent or some frost formations. Despite some overall encouraging initial findings, subsequent research was halted due to a lack of funding, and the 1/300 requirement was adopted by ensuing building codes.[1]

THE EVOLUTION OF ROOF VENTILATION IN THE BUILDING CODE

The continued use of the 1/300 vent ratio for sloped roofs and 1/150 vent ratio for flat roofs in North American building code requirements for ventilation of attic spaces is a somewhat arbitrary choice. Although the 1/300 vent ratio value was supported by the experiments of Rowley and colleagues and subsequently verified through additional testing for flat-roof structures by the HHFA, the data from those limited experiments is not significant enough to be considered a scientific basis for the building code requirements.

In Canada, the requirement for the 1/300 vent ratio first appeared in a 1959 revision inserted into the 1953 *National Building Code of Canada* (NBCC)[4] and the requirement (Article 3.6.2[b]) did not make any distinction between structures with flat and sloped roofs:

> All unheated attic spaces shall be vented to the outside air. The total unobstructed area of vents shall be not less than 1/300 of the insulated ceiling area. Each vent shall be at least 60 square inches in net cross-sectional area and vents shall be spaced to provide the optimum circulation and change of air."

A distinction in required vent ratios between flat- and sloped-roof structures was later introduced in the 1977 edition of the NBCC.[5] Article 9.19.1.3 states, "Where insulation is placed below the roof sheathing, and the roof slope is less than 2 in 12 or the roof incorporates no attic space, the unobstructed vent area shall be not less than 1/150 of the insulated ceiling area, uniformly distributed on all sides of the building." Only minor changes to these articles in the code have been made in later editions. In the latest version of the NBCC (2020),[6] the 1/150 vent ratio for flat roof structures remains. Article 9.19.1.2-2 states, "Where the roof slope is less than 1 in 6 or in roofs that are constructed with roof joists, the unobstructed vent area shall not be less than 1/150 of the insulated ceiling area." Article 9.19.1.2-3 adds that the vent openings are not to be concentrated to only the top or to the bottom of the roof spaces:

> Required vent types may be roof type, eave type, gable-end type or any combination thereof, and shall be distributed a) uniformly on opposite sides of the building, b) with not less than 25% of the required openings located at the top of the space, and c) with not less than 25% of the required openings located at the bottom of the space

Although the placement of item (c) appears to serve as a general statement regarding both sloped- and flat-roof structures, it is rarely applied in the actual design of structures with flat roofs.

FLAT ROOFS: A MONTREAL STAPLE

The Industrial Revolution in the late 19th and early 20th centuries resulted in a significant increase in population for the island of Montreal, from approximately 90,000 inhabitants in 1861 to roughly 724,000 60 years later. The growth of the city was prompted by the construction of the Lachine Canal and the expansion of the Port of Montreal, and residents chose to form "villages" in these popular areas. In the rapid developing riverside boroughs of Ville LaSalle, Lachine, Pointe St. Charles, and Griffintown, in addition to more inland boroughs such as Notre-Dame-de-Grace, Saint-Henri and Plateau Mont-Royal, residential dwellings were constructed in close proximity to each other. Many new dwellings in these communities were attached structures on narrowly spaced lots. With little to no space between individual properties, a flat roof design proved advantageous over a sloped roof design.[7] Flat roofs also provided a roof construction option that was more economical than sloped roofs. Consequently, dwellings with a flat roof design became a popular type of construction.[8]

As the city expanded, the construction of flat-roof structures remained popular. Dwellings constructed with a flat roof continued to provide effective use of the available land. Aerial views of Montreal today reveal the extent of residential low-rise buildings constructed with flat roofs. These buildings were typically of wood-framed construction and had a roof cavity between the roof deck and upper-story ceiling finishes. The older structures were rarely subject to condensation issues, mainly because these structures were minimally insulated and were not airtight. During the early period of residential construction, energy was relatively inexpensive and the need for insulation and airtightness was generally not required.[9]

However, with rising energy costs and revised building code requirements to design and build energy-efficient structures, the use of insulation (especially within roof attic spaces) and tighter construction evolved. New construction and existing structures subject to significant renovation were generally better insulated and were generally subject to less air leakage than older construction.

VENTILATION STRATEGIES FOR FLAT ROOFS

Cavity ventilation is essential for insulated flat-roof structures and can be achieved through passive or active means, or through a combination of both. In general, the roof structures of older residential buildings in Montreal were constructed using roof joists, whereas modern roofs are constructed using parallel-chord wood trusses. The installation of these trusses is an economical option and allows

Figure 1. *Various roof ventilation strategies employed for similar roofs in the Villeray/Parc-Extension borough of Montreal.*

for deeper roof cavities and consequently deeper layers of insulation. The open webs of the trusses also provide a possibility for cross-ventilation of the roof cavity, given that sufficient distance remains between the top of the insulation and the bottom of the truss's upper chord.[9] A typical expectation, and an NBCC requirement, is that a minimum 3 in. (75 mm) distance remain between the top of the insulation and the underside of the roof deck.

With the introduction of the 1/150 vent ratio, the NBCC 1977[5] also introduced the idea of installing 2 by 2 in. (50 by 50 mm) purlins in the perpendicular direction of the roof joists to promote cross-ventilation and the dissipation of humid air to the exterior. Sufficient cross-ventilation within the roof cavity is important to minimize the risk of condensation regardless of the employed ventilation strategies.

Ventilation of flat-roof structures can be passive or active. In general, the means for passive ventilation of flat-roof systems are limited to goosenecks, soffit vents, and longitudinal roof vents. However, soffit vents are rarely designed and incorporated into new low-rise structures, as architects are opting for designs that do not have projections near roof level and the cladding is extended all the way to the parapet.

Longitudinal vents are a relatively recent feature; they are continuous vents situated within the roof basin (area) and raised from the roof deck to exhaust the air within the cavity. Even when the height of the roof assembly is limited, longitudinal vents can maximize stack action when used in combination with soffit vents. However, it seems that longitudinal vents are not often used because active ventilation provides a more cost-effective solution.

Active ventilation is often achieved through the installation of roof ventilators. Roof ventilators are available in single-blade and multiblade formats; multiblade units draw more air from the roof cavity.

The use of roof ventilators is the predominant ventilation strategy for modern-day low-rise structures with flat roofs. These devices effectively draw air from the roof cavity; however, with insufficient outside air intake, humid air from the interior spaces can be aspirated into the roof cavity and may aggravate the formation of frost, condensation, and subsequent mold growth. Excessive depressurization of the roof cavity, relative to the occupied space, may create a significant pressure differential such that the humid interior air finds a way into the roof cavity.[9]

As shown in **Fig. 1–3**, the sides of many buildings on the island of Montreal are attached to other properties. In many cases, the adjacent properties use different ventilation strategies. Given these differences, it is important that common walls are well constructed to isolate the individual roof cavities. Although an 18th-century city ordinance governing the construction of common walls was intended to limit the spread of fire, the isolation of roof cavities is also important to ensure that the ventilation of one roof does not affect the ventilation of others.[7] The first case study presented in the next section illustrates this issue.

CASE STUDIES

Recently, greater attention has been paid to condensation problems and issues of mold growth within roof cavity spaces in new or newly renovated buildings. Unfortunately, many designers and builders place great faith in the building code with regard to flat-roof ventilation requirements without giving due consideration to basic ventilation fundamentals. In addition, given that current code requirements for roof ventilation are based on very limited research, it is no surprise that problematic situations arise.

In the following sections, we describe some projects in which our firm was called to assess issues of condensation or mold within attic spaces.

Laverdure

In April 2017, our firm was requested to investigate a recent accumulation of moisture within the shared roof cavity of attached, two-story

Figure 2. *Various roof ventilation strategies are employed for similar roofs in the Notre-Dame-de-Grace borough of Montreal.*

Figure 3. *Various roof ventilation strategies employed for similar roofs in the Ahuntsic-Cartierville borough of Montreal.*

residential townhouses in the Ahuntsic borough of Montreal. The construction of the buildings was completed the year before our investigation, and damages to the second-floor-level finishes were reported in spring 2017. An initial investigation of the roof cavity via the removal of top-mounted roof ventilators revealed dampened roof insulation and darkened wood surfaces on the underside of the roof deck and the framing members.

The shared roof cavity for the six properties contained 12 top-mounted six-blade roof ventilators located at quarter-points from the end walls of each property. No side inlet ports or other means of introducing fresh air into the roof cavity were noted. Exhaust ducts for mechanical ventilation systems (bathroom fans, hoods, etc.) were evacuated through the masonry walls.

In May 2017, smoke tracer investigations were undertaken at the second-floor level of one of the townhouses, with the goal of identifying potential moisture sources into the roof cavity. These investigations revealed minor deficiencies at the junctions of the fan casings with ducting and the polyethylene vapor barriers within the master bathroom. However, the lack of sealed ducts for the return-air-handling system was the major reason for moisture migration into the roof cavity. This lack of sealed ducts allowed humid air to enter the wall cavities and bypass the vapor barrier at the head of wall partitions. In addition, the use of only top-mounted roof ventilators for the cavity ventilation created negative pressurization within the roof cavity under normal conditions, which consequently drew humid air from the interior space.

Based on these observations and analysis, the investigative team recommended localized repairs at the master bathroom fan, as well as the installation of sealed ducts for the return-air-handling system to limit interior humid air from bypassing the vapor barrier. Side inlet ports below the parapet level were recommended to introduce outside air into the roof cavity and resolve the issue of depressurization.

Prince-Arthur

In May 2017, our firm investigated the recent accumulation of moisture within the roof cavity of a three-story condominium building near downtown Montreal. The building was originally constructed in the early 20th century and had been retrofitted in 2010. Similar to the Laverdure project, damage to the interior finishes was reported at the upper-floor level (in this case, the third floor). An initial investigation of the roof cavity found darkening of the underside of the roof deck and on the framing members.

During the initial visit, the investigative team removed the capping of roof-mounted ducting enclosures to gain access to the roof cavity and found an air space of only 3 in. (75 mm). The roof ventilation was limited to two single-blade, roof-mounted ventilators.

During our investigations, we noted that a disconnected duct at one of the bathroom fan exhausts contributed largely to the moisture accumulation within the roof cavity. Once moisture was in the roof cavity, it could not be evacuated effectively.

Therefore, the main solutions proposed for this project were to conduct localized repairs at the deficient bathroom fan, introduce fresh air into the roof cavity via side inlet ports placed within the masonry, and increase the cavity depth by raising the roof deck.

Belvedere

In August 2017, our firm investigated recent moisture accumulation within the upper roof cavity of a newly remodeled residence in the Westmount borough of Montreal. During an initial site visit, high humidity levels were measured at the upper-floor level (57% to 58% RH), and investigators observed darkening of the wood framing and deck underside within the roof cavity. Also, the ducts for bathroom fan exhausts were not equipped with backdraft dampers and were improperly terminated, and the polyethylene vapor barrier was not sealed at the recessed lighting fixture boxes. During subsequent investigations, the team noted that the top-floor mechanical system was oversized and cycled excessively, not allowing sufficient time for the dehumidification of the interior air during cooling.

The characteristics of the roof were such that the thickness of the air space varied between 7 and 10 in. (175 and 250 mm), and the roof ventilation was limited to four well-distributed, single-blade roof ventilators. As part of the strategy to address the problems, side inlet ports were incorporated within the masonry wall to introduce outside air into the roof cavity and avoid depressurization during normal operating conditions. In addition, many modifications regarding the mechanical systems were recommended; these recommendations included modification of the HVAC system (to reduce cycling and minimize internal pressurization), repairs to the bathroom exhaust fan ducts, and repairs to the discontinuous vapor barrier installations.

THE NEED FOR FURTHER RESEARCH

With the goal of developing clear guidelines for effective roof ventilation, our team is collaborating with other construction and engineering professionals and university researchers to further investigate ventilation requirements for buildings with flat roofs. The intent is to undertake full-scale tests to determine adequate ventilation strategies for flat-roof wood construction.

An exterior test structure is being designed to the size of a small, one-story, wood-framed house with the goal of studying the impacts of various ventilation strategies and conditions. The structure with a 32 by 24 ft (9.8 by 7.3 m) footprint is designed to optimize the use of construction materials and to facilitate the evaluation of various roof ventilation schemes. In addition, the impact of various roof cavity configurations (that is, the depth and placement of insulation) and parapet heights will also be evaluated.

An initial phase of monitoring and data collection within the roof cavity is planned for winter 2024-2025. An understanding of the various ventilation factors and their effects on the roof cavity behavior will be obtained during this phase. If weather conditions permit, basic ventilation configurations will also be analyzed. Additional configurations will be analyzed in depth during the following winters.

Our investigations have identified that problems exist with the ventilation of flat roofs and that research is required to establish effective ventilation strategies. The goal of our research is to provide practical information that can be implemented within the housing industry.

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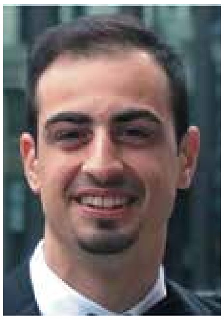

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