Position paper for the panel discussion

Pushing the (Building) Envelope Compartmentalization in high-rise construction

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The concept of compartmentalization is typically overlooked in the design, specification, and construction of new high-rise buildings. It is crucial, however, to remember the building is a system and that controlling air flow is an important consideration in its healthy function.

Floor-to-floor air leakage strains a building's HVAC system, inflates utility bills, contributes to poor indoor air quality (IAQ), and causes occupant discomfort leading to poor tenant retention. More significantly, this leakage exacerbates life-threatening hazards such as smoke spread.

High-rise building compartmentalization is critical. All trades, especially specifiers, must understand the importance of air sealing and proper weatherization, the practice of protecting a building and its interior from the elements---particularly from sunlight, precipitation, and wind---and of modifying a building to reduce energy consumption and optimize energy efficiency. Common weatherization materials include weatherstripping (rubber seals, aluminum doorsets, fin-seals, sweeps, v-strips, foam tapes and polyurethane foam caulking), air barriers and vapour barriers to control air leakage.

Air migration paths between floors, up vertical shafts, and under doors must be considered beyond merely meeting minimum that *Building Codes* requires. Typically there are four key air barrier requirements listed (for further details see Construction Canada, March 2008 pp. 48-56):

Airtightness: …sheet and panel type materials intended to provide the principal resistance to air leakage shall have an air leakage characteristic not greater than 0.02 L/(s/m2) measured at an air pressure difference of 75 Pa." While there are many commercial air barrier materials that satisfy this requirement, these materials must be joined into a system so that the system is airtight under different indoor environmental conditions.

Continuity: The air barrier system shall be continuous (a) across construction, control and expansion joints, (b) across junctions between different building assemblies, and (c) around penetrations through the building assembly." Not only is it important that no gaps exist in the individual components that comprise the system, but also the components must be joined such that there are no gaps in the system as a whole. It is air leakage at the connections between air barrier components, and at penetrations through it, that usually determine the overall effectiveness of the system.

Structural Integrity: An air barrier system installed in an assembly subject to wind load, and other elements of the separator that will be subject to wind load, shall transfer that load to the structure." Specifically, it shall be "…designed and constructed to resist 100% of the specified wind load as determined in subsection 4.1.8." The air barrier system must be able to resist peak wind loads, stack pressure effects or sustained pressurization loads without exhibiting signs of detachment, rupturing or creep load failure.

Durability: The air barrier system must be durable, meaning it must be able to perform its intended function, be compatible with adjoining materials and resistant to the mechanisms of deterioration that can be reasonably expected given the nature, function and exposure of the materials, over the life of the building envelope.

In a nutshell requirements for air barrier systems deal with performance of a building assembly and we must also examine performance of the building system.

Theory of compartmentalization

All buildings leak. Unless a building is hermetically sealed with no doors or windows, there will be holes, gaps, and cracks within the building's interior, and through the exterior via the building envelope. Although the inclusion of air barriers, as mandated in the NBC, helps reduce air leakage, more can be done to tighten a building.

There are two terms used to describe the process of compartmentalization, although the approach and materials used to accomplish both are the same. 'Compartmentalization' specifically refers to sealing off areas in a building, such as separate units or rooms from one another, to help equalize pressure differences. The actual *separation of floors from one another* is technically called 'decoupling.' For the purpose of this note, the term 'compartmentalization' is used when referring to the overall process of air sealing to achieve compartmentalization.

Decoupling floors involves sealing junctions between walls, as well as floor-to-floor vertical penetrations such as elevator shafts, garbage chutes, and plumbing and electrical penetrations. Interior compartmentalization involves sealing units off from one another, as well as sealing service or common areas from the rest of the building.

Stack effect

Compartmentalization helps control stack effect, the primary culprit behind uncontrolled air movement in large buildings. Stack effect (also called chimney effect) is very common. It occurs when warm indoor air rises through a building (via gaps, cracks, and holes) and exfiltrates through openings in the roof and the roof/wall intersections. As air rises, it creates suction at the bottom of the building, drawing in unconditioned air through openings such as main doors and parking garages.

This phenomenon is most noticeable in winter, when cold air infiltration at the building's base causes temperatures to drop and the increased pressure of warm air at the top of the building forces temperatures to rise. Efflorescence at the building's top exterior or occupant complaints about poor temperature control are good indicators of stack effect, but diagnostic testing, such as building pressurization and smoke generators, thermographic cameras or in-situ window testing are all effective ways of measuring air flow rates. In some extreme cases, a whistling sound may be heard in the front lobby near the main entrance, or close to elevator shafts.

How to determine the stack effect[3]:pressure difference

The following are the calculations to determine pressure difference due to stack effect between the inside and outside of walls or the roof.

1. Determine the height of the building (H) above grade.
2. Arbitrarily select a neutral pressure plane height (Hnpp) above the grade of the building, usually one or two stories above grade in a multi-level building. In a low building select grade as the neutral pressure plane (npp).
3. Select a given height above (or below) the neutral plane, such as the roof plane.

Compute the pressure difference at that plane as follows:

$\Delta Ps = dixg\ (H-Hnpp)(Ti-To)/To$

where ΔPs= stack effect pressure difference (Pa)
and di = density of indoor air, kg/m^3
and g = gravitational acceleration, 9.81 m/s^2
and H = height of plane above (or below) Npp, m
and Hnpp = height of neutral pressure plane, m
and T= absolute temperature, Kelvin
and i = indoor, o = outdoor

For a 60-m (197-ft), 20-storey building with a neutral pressure plane at about the fourth storey or 12 m (40 ft) from grade, in winter with an outdoor temperature of –20 C [-4 F] and an indoor temperature of 20 C [68 F], the stack effect at the top of the exterior wall (and roof plane) is:
$\Delta Ps = 1.2x9.81x(60-12)x[(273+20)-(273-20)]/(273-20)$
=89 Pa [1.86 psf]

Stack effect wreaks havoc on HVAC system control. The struggle to adjust temperatures and pressures for all floors contributes to building degradation. As the escaping warm, moist air meets colder, outdoor air at condensing surfaces (and vice versa, seasonally), mould and material decay occur, affecting residents' health and comfort, as well as building durability. Cold air sucked up from the parking garage is of particular concern given the toxic nature of exhaust fumes. In a fire, air migration due to stack effect also carries smoke upwards more rapidly and has been associated with deaths from smoke inhalation on upper floors.[2]

Decoupling floors is particularly important with respect to stack effect, as it stops the uncontrolled air movement between floors to create distinct compartments within the building. Without interior compartmentalization, stack effect forces air in and out of units, stairwells, rooms, and entryways. Often-overlooked areas for interior compartmentalization include the boiler room, mechanical rooms, shipping docks, high-voltage rooms, computer rooms, air-locks at the main entrance/exits, garbage chute rooms, and shafts for elevator cables and cars.

Wind

The second most influential pressure on buildings is wind. A constant presence around buildings, wind exerts varying forces on them. On the windward side, wind can infiltrate gaps, cracks, and holes in the building's façade. It will also travel upwards and around the building. On the other (leeward) side, suction is created, causing exfiltration of interior air. Uncontrolled infiltration of air carries dust, dirt, allergens and pollutants into the building, while uncontrolled exfiltration of air can cause the HVAC system to overcompensate for lost conditioned air. Moisture migration thanks to the exfiltration of conditioned air can cause efflorescence on the outside of the building. Mould can also form at sites where interior air meets exterior air of a different temperature and condensation forms.

The following formula can be used to determine wind pressures[4]:

The pressure exerted by wind striking a surface is a function of the wind speed and the density of the air. The pressure of wind stagnating on a building façade may be determined from the following equation:

Pw=1/2 x dV2

where Pw = the stagnation pressure of wind, Pa,
and d = density of air, kg/m^3 (about 1.2 kg/m^3[can we get an imperial conversion? Metric is standard for these calculations and even American professionals tend to perform these calculations using metric.]),
and V = velocity of the air, m/s.
For example, an 11.1 m/s (40 kmh or 25 mph) wind speed having an air density of 1.2 kg/m^3 may result in a stagnation pressure of:
Pw=1/2 x 1.2 x (11.1) 2
=74 Pa [1.55 psf]

Interior and building envelope compartmentalization is crucial to reduce the effects of wind infiltration and exfiltration. An insulating air barrier system is one of the best ways to increase wind resistance and ensure thermal comfort for occupants. For instance, a spray-applied polyurethane foam insulation and air barrier system provides both high-quality insulation material, redundant vapour retarder, and a monolithic, airtight seal between roof/wall, floor/wall and wall-to-wall intersections. Code does not specify that insulation and air barriers have to be one system, but it is an unbeatable combination for IAQ, energy efficiency and occupant comfort.

Some building science experts recommend compartmentalization theory in the form of rainscreen building envelope design to help combat wind infiltration. Wind pressure, experts note, is the primary cause of rain penetration through the building envelope[5], although mechanical and stack pressures can also play a role as well by creating suction and drawing water through leakage paths.

The Ontario Association of Architects offers this definition of rainscreen design:

The rain screen wall addresses the forces that move rain into the wall. The basic configuration, incorporating two layers, or wythes, separated by an air space, has variations that provide different levels of rain protection effectiveness. A distinction should be made between the drained cavity wall, the simple or open rain screen, and the pressure-equalized rain screen wall. What is usually meant by a “rain screen wall” is generally the latter: an exterior cladding, a cavity behind the cladding, drained and vented to the outside; an inner wall plane incorporating an air barrier; and a set of compartment seals limiting the cavity size. The outer “screen” layer of cladding deflects the kinetic force of the rain, while the inner wythe remains protected. The vented cavity uses gravity and flashings to drain water that penetrates the outer wall, away from vulnerable surfaces and joints. The cavity is sufficiently wide that surface tension and capillary action are not able to move water across the cavity.

Mechanical

The third significant pressure influencing airflow in a building is mechanical, created by HVAC systems and make-up air. A properly compartmentalized building sealed with an air barrier system and weatherization materials allows more effective control of these systems, as they do not struggle to overcome the negative or positive pressures associated with uncontrolled air leakage.

Make-up air is rarely needed after an air-sealing retrofit, as the HVAC system is not compromised by stack effect and can therefore condition and ventilate each floor more effectively and energy-efficiently. In fact, improving the HVAC system's efficiency, and consequently lowering building operating costs, is a primary justification for weatherization retrofit projects.

How to compartmentalize a building

Sealing and/or weatherstripping areas, in the following order, is a sound strategy for compartmentalizing a high-rise building:

Top of the building
1. Roof/wall intersections
2. Mechanical penthouse doors and walls
3. HVAC equipment—duct shafts through mechanical curbs
4. Various roof penetrations

Bottom of the building
1. Underground parking access doors
2. Exhaust and air intake vents
3. Soffits and ground floor access doors
4. Pipe, duct, cable and other service penetrations into core of the building
5. Sprinkler hanger penetrations, inspection hatches and other holes
6. Core wall to floor slab

Vertical shafts
1. Stairwell fire doors
2. Fire hose cabinets
3. Plumbing, electrical, cable, and other penetrations within service rooms
4. Elevator rooms, cable holes, door controller cable holes, bus bar openings
5. Garbage chute perimeter and access hatches
6. Hallway pressurization grille perimeters
7. Elevator shaft smoke control grille
8. Service shafts

Outside walls and openings
1. Weatherstripping on windows, doors, balcony, and patio doors
2. Window trim
3. Exhaust fans and ducting
4. All service penetrations
5. Baseboard heaters
6. Electrical receptacles

7. Baseboards

Isolation

1. Vented mechanical rooms
2. Garbage compactor room
3. Emergency generator room
4. High-voltage rooms
5. Shipping docks
6. Elevator rooms
7. Workshops

Compartmentalization in application

The materials needed to decouple floors from one another and to compartmentalize units and special-purpose rooms include[6]:

- one- and two-component polyurethane foam-insulating air sealants (air barriers);
- door and window weatherstripping; and
- air-seal/firestop system.

Each product performs a different function in decoupling and compartmentalization, and is critical to creating a high-performance air barrier system.

One-component polyurethane foam-insulating air sealant

One-component foam cures quickly when exposed to moisture in the air and is ejected from its pressurized container as a thin, sticky bead. It can be applied with accuracy, due to the gun-style applicator and small bead diameter of 6 to 50 mm (0.2 to 2 in.).
This foam is typically used for filling small gaps and cracks, and is installed at junctions between different building elements, such as crevices in walls, door and window perimeters, roof-wall connections, and around mechanical and electrical penetrations. One-component foam is used for gaps (less than 6 mm) and cracks (between 6 and 50 mm)

Two-component polyurethane foam-insulating air sealant

Two-component polyurethane foam is used for jobs that require a more substantial foam seal. Stored in separate containers, two-component foam is activated when chemicals merge at the applicator gun and cure as the foam meets air. This formulation is used for the same applications as one-component foam, but is used for openings large enough to be classified as holes (openings greater than 50 mm). Examples of applications include: voids in walls and at roof-wall connections, drill and inject applications at beams and columns, and for continuity in other insulation systems. In new construction, two-component, closed-cell, spray-applied polyurethane foam (SPF) materials are often used to create the air barrier system for the entire wall portion of the building enclosure. In Canada, section 3.1.4.6 of the *NBC* permits foam air sealants for use in non-combustible construction.

Door and window weatherstripping

Professional-grade, durable weatherstripping and installation is often overlooked as an effective way to decouple and compartmentalize a building. In this author’s 30 years of experience, door weatherstripping specification is an area with room for improvement, especially in material selection. When installed correctly, door and window weatherstripping provides an airtight barrier between two spaces. Quality door weatherstripping can reduce the exchange of air at high-traffic points such as main doors, garbage room doors and chutes, shipping doors, and dumpster storage areas. In special-purpose areas such as boiler rooms, computer/electronics rooms, electrical rooms, and other low-traffic, high-importance areas, door weatherstripping helps regulate room temperature and prevents infiltration of dust and moisture. Window weatherstripping performs the same functions, but in the author's experience, is more often specified and professionally installed than door weatherstripping; doors are where more focus needs to be applied by specifiers.

Materials include:
- aluminum doorsets;
- doorsweeps;
- thresholds;
- polyflex v-strip in door frames;
- patio door pile;
- dust plugs; and
- door and window foam tape.

Window weatherstripping:
- PolyflexV-Strip, small (11mm) or large (32mm) "V" shape
- Window Finseal Pile
- Corner Seal/Dust Plug

Door and window weatherstripping should be installed via the following protocol:

Examination:
1. Examine surfaces affected by the work and advise client/consultant in writing if substrates are unsatisfactory. (Do not proceed with work if not corrected.)

Preparation:
1. Prepare surfaces to receive weatherstripping/seals by brushing, scrubbing, scraping, or washing to remove dust, oil, grease, frost or other deleterious material. Ensure bearing surfaces are dry before proceeding.
2. Protect surrounding areas and surfaces during installation against damage resulting from work.

Installation:
1. Install work at door and/or window locations indicated in building assessment.
2. Install weatherstripping/seals strictly in accordance with manufacturer's/supplier's written instructions or installation guidelines.
3. Install weatherstripping/seals plumb, square and level, wherever possible.
4. Adjust weatherstripping for correct function and to form weathertight seal.
5. Remove excess sealant with recommended solvent.

Air-seal/ firestop system
The combination of air barrier and firestop in horizontal and vertical separations throughout a building provides the best of both worlds—a continuous plane of airtightness and specified fire rating. An air-seal/firestop system uses two-component polyurethane foam and fire-barrier mortar, and provides an airtight closure at openings

around penetrations (*i.e*. electrical), at continuous spaces, and at openings within fire separations and assemblies with a fire resistance rating. These include spaces at perimeter edge conditions, such as party walls (a common source of interior air leakage).

The order of applying firestopping materials is governed by the Underwriters' Laboratories of Canada (ULC) firestop system. Generally, these steps are taken:

1. The foam, which is typically used as a backer for the mortar, is injected using a gun-foam applicator.
2. The mortar paste is applied into the opening with a trowel, or poured into large openings from a mixer or mixing container.
3. The paste is then worked to ensure all voids are filled.

Fire safety

Fire safety is perhaps the most compelling reason to ensure proper compartmentalization and decoupling of a high-rise building. A mid-90s tragedy in Toronto at the 30-storey apartment complex at 2 Forest Laneway drew critical attention to the importance of building science in fire safety. Although the fire remained contained within its unit of origin on the fifth floor, six occupants died of smoke inhalation near the top of the building's two stairwells, illustrating the fatal hazard of smoke travel in high-rise fires.

This tragedy, along with other Canadian high-rise residential fires, formed the basis for the Ontario Association of Architects (OAA)/CMHC-sponsored study, *Fire Safety in High-Rise Apartment Buildings*[7]. The report's findings in relation to the Forest Laneway fire include:

- unsuppressed fires in high-rise buildings generate large quantities of smoke that can spread vertically or horizontally through the building, even if the fire is contained within one room or apartment. A contained but not extinguished fire can also generate significant smoke;
- vertical smoke spread is exacerbated by wind and stack effect that occurs when the building's temperature inside is greater than outside. Thus, in Canadian winters, bottom floor fires tend to have the greatest extent of smoke spread to upper floors.
- despite the type of structure (steel or reinforced concrete), most damage, deaths, and injuries result from the spread of smoke;
- in multiple-death fires in residential high-rise buildings, many fatalities occur in egress routes (*i.e.* stairways and corridors) due to smoke from a fire elsewhere in the building; and
- in apartment fires with doors left open or burned-through, smoke will spread to the corridors, shafts, and upper levels.

A large-scale renovation of the complex took place in 1995[8], after the fire. Building-wide compartmentalization was used to correct the extreme stack effect identified in the building. The following actions were taken:

- mechanical room doors were weatherstripped;
- penetrations were firestopped;
- elevator shaft cable holes were reduced at the top of the building;
- parking areas, lower-level doors, and cable conduits were sealed and weatherstripped; and
- vertical shafts, where doors with 51-mm (2-in.) gaps underneath were prevalent, were weatherstripped.

These steps successfully decoupled floors and reduced air movement within the building.
In addition to the life-safety improvements, compartmentalization and a major HVAC upgrade resulted in significant savings—surpassing the annual goal of $200,000 in the first year—and reduced the expected payback period for the project.

The effects of uncontrolled air leakage and the impact air barriers have in reducing it were studied in 2006 CMHC Technical Series paper. The study compared two suites on different floors in a high-rise residential building, measuring them for before-and-after air leakage flow rates.[9] The units were sealed and compartmentalized and retested to determine the effects of air sealing.

The report concluded the air leakage found (via smoke pencil testing) primarily resulted from the common corridor, floor-to-floor penetrations, and minor imperfections in the air barrier on exterior walls. According to the report, this finding suggests the development and implementation of air sealing details on interior partitions still presents a challenge to the consistent and effective compartmentalization of individual suites. It recommends air leakage control training and design guidance be necessary for architects and contractors if individual suites are to be compartmentalized efficiently and cost-effectively.

This conclusion is in line with the author's experience over the last 30 years—gaps, cracks and holes are not considered as grave a threat to building performance as they should be. Occupant health, safety and comfort depend on these considerations. As the authors of this study noted, greater awareness should be raised among design professionals, specifiers, and trades about the importance of compartmentalization and best practices in installation.

The main challenge in achieving this goal is teamwork and understanding between trades. Compartmentalization needs to be specified at the design phase and continuity needs to be ensured throughout the building process. For example, a perfectly weatherstripped window in a condominium unit only functions to its full potential if the rest of the unit is properly sealed as well—if there are large gaps behind the baseboards and baseboard heater the building's performance is compromised. The same principle extends to the working life of the building as well, as renovations and the effects of time diminish even the best building practises. Understanding the role of compartmentalization, controlling air flow, and the function of the 'building as a system' by all trades and professions is key to working towards buildings that are safer, more comfortable and more energy efficient through improved design.

Notes

[1] See Kevin D. Knight, Bryan J. Boyle's "Guidelines For Effective Air Barrier Systems," Ontario Association of Architects (OAA)/CMHC.

[2] See Jacques Rousseau, R.L. Quirouette, M.Z. Rousseau, G.O. Handegord and G.F. Poirier's "Questions and Answers", which can be found on the National Research Council of Canada website http://irc.nrc-cnrc.gc.ca/pubs/bsi/83-QA_e.html

[3] See R. Quirouette's "Air Pressure and the Building Envelope," Canada Mortgage Housing Corporation (CMHC) 2004.

[4] See R. Quirouette's "Air Pressure and the Building Envelope," CMHC 2004, as cited by "ASHRAE Fund 97."

[5] See R.Quirouette's "A study of the rainscreen concept applied to cladding systems on wood frame walls," Technical Series 96-214, CMHC Research Highlights, 1999.

[6] For detailed product and application specifications visit www.zerodraft.com/specs.
[7] See note 2.
[8] See Jim Bunting's "Stop Air Movement and Smoke Spread – and improve energy efficiency and comfort too!" *Building Envelope News*, November 2004.
[9] See "Evaluation of air leakage control measures to compartmentalize newly constructed suites in a high-rise residential building," Technical Series 06-102, CMHC Research Highlights, 2006.

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