Evaluating the Long-term Performance of Air Barrier Systems in Modern Buildings

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ABSTRACT

The durability of air barrier systems is a topic that is rarely discussed during the design phase of most projects. An unfortunate amount of effort is spent on drawing details and specifying products with the sole intention of meeting energy code requirements, with much less thought being given to how those systems actually will be constructed and possibly worse – how those systems will fare over time.

Air barrier systems are very complex and involve a wide variety of components. Windows, doors, walls, foundations, and roofs all need to work together, since even small breaches in the building air barrier can significantly reduce performance. But with so many different systems, all of which are composed of different types of materials, the risk of both physical and chemical incompatibilities between air barrier materials or poor weatherability is high. Unfortunately, many of these problems only will manifest after construction of the building is complete. The point of failure is likely to go unnoticed, as membranes lose adhesion, sealants fail, or expanding foam shrinks away from its substrate within walls that are concealed by interior finishes and exterior cladding or at small joints or concealed in assemblies.

This paper reviews previous research related to the long-term durability of air barrier systems, focusing on wall membranes and fenestration systems. It also discusses energy modelling of a typical large building at varied air leakage rates to show the associated potential impacts to building energy use. These results show that, as an industry, current energy code requirements are both reasonable and achievable with modern materials and industry knowledge. Instead of energy losses, deterioration of the building materials due to a poorly performing air barrier may be of greater concern.

KEYWORDS

Air barriers, Air leakage, Energy performance, Fenestration

1 INTRODUCTION

An "air barrier" as defined by the energy conservation building codes in the United States of America (energy codes) is a continuous membrane or combination of different interconnected membranes that have been tested according to different industry standards (depending on the type of material or system) as having very low air permeability or leakage when subjected to differential pressure across the membrane (we use the term "membrane" loosely in this sentence to mean a continuous planar component within the exterior walls or roofs). The current energy codes require a continuous air barrier around the building's thermal enclosure to limit energy loss from air leakage through the walls and roofs, the reason being that indoor conditioned air leaking out or unconditioned outdoor air leaking in both increase the amount of energy that the mechanical systems must use to maintain interior setpoints. While the need for an air barrier may seem logical as a way to improve buildings' energy efficiency and knowledge of the importance of an air barrier within the enclosure dates back several decades, at least as far as the 1930s (Beals, 2016), most US energy codes did not require a continuous air barrier as part of the building enclosure until 2010 (ASHRAE, 2010) and 2012 (ICC, 2011), although the Canadian building code first required an air barrier in 1985 (NRCC, 1985). Around this time, the United States Department of Energy published data showing that it estimated that air infiltration in buildings accounted for approximately 7% of total building energy use (DOE, 2014) but did not differentiate by building type or use.

While required by the energy codes (presumably for energy conservation reasons), a continuous air barrier also is an important component to help manage water vapor flow through the building enclosure. In fact, much of the older historical literature that discusses the importance of a continuous air barrier does so in the context of mitigating condensation, frost, efflorescence, biological growth, etc., with brief mention of it also being important for energy efficiency (Quirouette, 1985; Peterson & Hendricks, 1988 are examples). However, some historical authors do discuss building air leakage in the context of energy loss, noting that it can contribute as much as 40% of the total heat loss in single-family detached houses (Tamura, 1975) and that air leakage through the building enclosure must be considered when designing mechanical systems (Handegord, 1979). Using energy modelling, Sherman and Matson estimate that relying on “loose” air infiltration to provide ventilation to single-family homes, rather than mechanical ventilation or “controlled” infiltration according to ASHRAE standards, resulted in $2.4 billion in energy costs annually for the United States as a whole in 1997, but did not estimate the effect on individual buildings (Sherman & Matson, 1997). We did not find much other data (either from field measurements or energy models) that estimates or quantifies the energy loss associated with air leakage through building enclosures in our review of the literature, despite most studies stating that air leakage increases energy consumption as a given.

In our review of the literature, most historical studies focused on small/single-family construction, with less attention paid to the air leakage performance of commercial or larger multi-family construction. More recent research has evaluated the airtightness of mid-rise and high-rise construction and found that it typically meets or exceeds energy code requirements (Sherman & Chan, 2004). Sherman and Chan state that research by others found that 42% of air leakage through high-rise building enclosures is through windows, 26% is through doors, and 6% through opaque walls and roofs, with the remainder through vertical shafts, but again, no estimate of air leakage’s effect on energy consumption (Sherman & Chan, 2004).

A study of whole-building air leakage testing of 276 new buildings of different construction types, heights, and uses built between 2009 and 2019 in the United States found that, on average, the buildings were below the maximum allowable air leakage in the energy codes (2.0 L/sm^2 at 75 Pa pressure differential). However, the study also found that, on average, buildings of a “mixed-use” type (commercial plus residential) showed air leakage approximately 40% greater than allowed by code and some individual buildings showed air leakage from 50% to more than double that allowed by code (Marceau & Shrode, 2019). This study did not analyse the energy loss due to air leakage, but it does show that even new buildings built under energy codes that require a continuous air barrier still may not meet the code-prescribed maximum air leakage. Reviewing data from whole-building air leakage testing of 267 buildings (some older, some new), one study found air leakage rates as high as over 10 L/sm^2 at a pressure differential of 50 Pa, but again, these authors did not analyse the energy loss due to air leakage. Citing research by others, the authors do state that the ratio of air infiltration to mechanical air exchange can vary greatly, ranging from almost mothing to

0.8 (Price et al, 2006). Another study in 2005 investigated air leakage in commercial buildings and found the average air leakage to be 7.9 L/sm^2 (Emmerich & Persily, 2005).

Buildings are built at a point in time, but they must provide good performance over their entire service life. A material or system that provides good resistance to air leakage at the time of construction must continue to do so over the building's lifetime for the building to still be an air barrier. Recognising the importance of air barrier durability, two French research projects, Durabilit'air and Durabilit'air2 attempted to evaluate and develop testing protocols for the long-term durability and performance of air barriers based on a review of the literature, experiments, and field data (Leprince et al, 2017; Litvak, 2022). One study of building air leakage in recently constructed single-family houses in France with different types of air barriers that was part of the Durabilit'air project found that air leakage generally increases over the first two years of service then generally stabilises (Moujalled et al, 2019). A study of single-family homes in the United States found that air leakage increased by approximately 25% twelve to thirteen years after construction, and that houses that had undergone air-sealing retrofits showed an increase in air leakage of approximately 12% six to seven years after implementing the retrofits (Chan et al, 2015).

However, it is not just the individual materials that comprise the air barrier that must continue to perform, it also is the transitions between these materials that must provide long-term performance. For example, both the wall and the roof on a building may be in good condition and airtight, but an open joint between the two due to poor installation or materials with poor weatherability can result in significant air leakage over time.

2 AIR BARRIER SYSTEMS

Many different types of materials and systems can be part of the building's air barrier. The energy codes list prescriptive materials and systems that these codes consider an air barrier, which are in the following general categories:

- Sheet or fluid-applied membranes.
- Fenestration systems.
- Foam insulation (board or spray-applied).
- Mass assemblies (e.g., concrete, fully-grouted concrete masonry).
- Rigid board materials (e.g., plywood, gypsum wallboard).

Note that the energy codes accept materials that are installed on the interior side and on the exterior side of the wall or roof deck as part of the building's air barrier. The energy codes allow other materials to be used as an air barrier if they have test results from an accredited agency showing that the materials have air permeance of 0.02 L/sm^2 under a pressure differential of 75 Pa when tested according to ASTM E2178 – Standard Test Method for Determining Air Leakage Rate and Calculation of Air Permeance of Building Materials. The energy codes do not have any requirements for long-term performance testing of the air barrier materials or air leakage of the building, so an air barrier product that fails within a few years of installation does not violate the energy code.

3 DURABILITY OF MEMBRANE AIR BARRIERS

We focus our discussion of air barrier durability in this paper on two of the primary air barrier types for wall assemblies in modern buildings – membrane air barriers and fenestration systems. We use the term "durability" as including both a material's or system's chemical and UV stability and its reliability to perform as intended. For example, a mechanically-fastened membrane air barrier that falls off of its substrate within a wall cavity may be intact and chemically stable, but it no longer functions reliably as an air barrier.

3.1 Membrane Air Barriers

Membrane air barriers can be loose sheets of polyethene or spunbonded polyethylene fibres (taped at seams and terminations), adhered sheets, or fluid-applied products. The adhered sheet and fluid applied products can have low water vapor permeability or high water vapor permeability. Adhered sheet products with low water vapor permeability have the longest track record of reliable field performance; water vapor-permeable adhered sheet products and fluid-applied products with both low and high water vapor permeability have a shorter track record of field service (approximately 10 to 15 yrs).

Citing research by others, Sherman and Chan state that spunbonded polyethylene air barriers can fail at joints when exposed to high service temperatures (Sherman & Chan, 2004). Wissink et al (colleagues of these authors) describe observed in-service failures of recently installed fluid-applied air barriers, including blistering, loss of adhesion, dissolution, tearing, and network cracking. The authors performed laboratory testing of both low and high vapor-permeable fluid-applied air barrier products from different manufacturers, subjecting samples to adhesion, elongation, and water immersion testing both in an unconditioned state and after conditioning the samples with UV and condensation cycling and freeze/thaw cycling. They found that most tested products met the industry standard for adhesion and elongation (200%) both before and after conditioning, but most samples absorbed significant amounts of water during immersion testing (higher values showing an increase in weight of 20% to over 200%) or deteriorated during immersion (broke apart, dissolved, etc.). The authors note that prolonged exposure to water should be expected for air barriers (which often also are the wall's waterproofing membrane), so deterioration after water immersion is a particular concern for these products. They also note that the products that showed worse results after water immersion in their testing correlated to products that they observed to have greater incidence of failure (e.g., blistering, reverting to a fluid-like state, debonding from the substrate) in service (Wissink et al, 2012; Wissink et al, 2014). Their field observations and laboratory testing both showed that materials that may perform well upon initial installation or meet energy code requirements for laboratory-certified performance can quickly lose their air-resistive properties and have reduced function as an air barrier.

Quirouette describes a mechanically-fastened polyethylene sheet wall air barrier that had pulled away from its substrate and collapsed within the wall cavity due to cyclical positive and negative wind pressure causing it to pull off of the wall, an example of the membrane itself being durable but deficiencies in its installation causing it to fail in service (Quirouette, 1989). Lux and Brown describe open seams and transitions to other systems in the air barrier on a building that allowed significant air leakage, another example of the air barrier material itself not degrading but poor detailing significantly impairing its function (Lux & Brown, 1989).

In contrast to the failures and issues described above, GCP Applied Technologies, Inc. (a waterproofing and air/vapor barrier membrane manufacturer) tested samples of their self-adhered rubberized asphalt below-grade waterproofing membrane (which is very similar in composition to their sheet-applied air barrier systems) that had been in service for at least fifteen years and found that the material still met or exceed all published performance data. Given that a below-grade application likely is more severe than an above-grade application (prolonged exposure to hydrostatic head pressure or chemicals), this study shows that materials with a longer record of successful in-service performance can be more reliable than newer materials (GCP Applied Technologies, Inc., 2023).

3.2 Fenestration Systems

Because the glass in fenestration systems has negligible air permeability, air leakage through fenestration systems typically occurs in the joints between the glass and the sash or frame, joints between the sash and frame, joints within the sash and frame, or the joint between the fenestration and the surrounding wall system. Fenestration products must be tested by an accredited testing agency to show that their products meet energy code air leakage requirements, but that test is performed in a laboratory on a representative window sample, not on each window that a manufacturer produces. The energy codes typically do not have requirements for field testing of installed fenestration systems to confirm that the installed condition meets the code requirements for air leakage, but AAMA's voluntary test standards for field testing of installed fenestration allows the air leakage of the installed system to exceed its rated performance by 50%. These standards also only require newly-installed fenestration systems to meet this performance for the first six months of service (AAMA, 2014; FGIA 2021).

A study in 1980 tested 192 newly-installed residential windows in the field found that 40% of the windows had air leakage that exceeded their rating by as much as a factor of almost two and that, on average, window air leakage resistance decreased by 29% in the time between manufacture and installation (Weidt & Weidt, 1980). A study in 1985 subjected newly-manufactured windows to accelerated weathering in a laboratory and found that the air leakage could increase by a factor of almost two over time (Kerhli, 1985). We have not found other, more recent published information on the long-term performance of fenestration systems, but the general conclusions of these previous studies stand today – that fenestration systems' resistance to air leakage can decrease over time as gaskets and seals shrink, expand, harden, or debond, as frame and sash joints open (again due to cyclical thermal expansion and contraction), due to "wear and tear" from general use and weathering, or due to issues with their original manufacture and installation.

In addition to the windows themselves, their integration with the surrounding wall systems must also be detailed and installed to limit air leakage. One study found that air leakage due to poor sealing around the window perimeter in resulted in air leakage that was two times or greater that the air leakage through the window itself (Louis & Nelson, 1995). Another study of air leakage through window perimeter joints found leakage rates of approximately 0.32 to 0.61 L/s per meter of joint length (Weidt & Weidt, 1980).

4 ENERGY MODELLING

We performed energy modelling of a large (approximately 55,000 m^2) building using the eQUEST v3.65 building energy simulation tool. For our models, we used an idealize typical multifamily residential building, complying with the 2018 International Energy Conservation Code (IECC) and varied the air leakage rate through the enclosure based upon the previous research discussed above (ICC, 2018).

While air leakage rates for buildings and materials are typically given at a pressure differential of approximately 75 Pa, roughly equivalent to the stalling pressure of an 11.2 m/s wind speed, in reality the typical pressure differential across a building enclosure will be much lower. To account for this, we adjusted leakage rates down to a wind speed of 4.5 m/s using the methodology in ASHRAE Standard 90.1-2016, Normative Appendix G (ASHRAE, 2016). This provides a more reasonable air leakage rate for a typical building than the typical test pressures. Actual air leakage rates will vary based on the specific construction, wind speeds and exposures, but for the purposes of this analysis the ASHRAE-modified leakage rate is sufficient for comparison purposes (as we are not attempting to predict the actual energy use of a specific, real-world building, only analyse the energy effects of varying air leakage through the building enclosure).

We found that when the air leakage rate in the modelled building is doubled from the typical U.S. and ICC code-prescribed rate (maximum 2.0 L/sm^2), the corresponding increase in annual building energy use is still relatively small, in the range of 2-3%. This doubling is consistent with our above-mentioned literature review which found published research showing a doubling of air leakage in many windows over time, albeit very conservative. Going beyond that and increasing 5fold produces larger changes in energy use, around 6%, but this level of leakage would require complete failure of fenestration systems or near-total loss of airtightness in membrane air barriers. We ran a similar case considering the difference between a building built to Passive House standards (0.6 air changes per hour) and an IECC-compliant building as described above and found similar results – only about a 3% increase in space conditioning energy use. These results are relatively consistent with industry findings that, years ago when air leakage was not even considered in the energy codes, energy losses due to air leakage were extremely high so even moderate changes to leakage rates produces significant savings. Decades of research, building science education, and improvements to the energy codes have reduced the air leakage for typical new construction and produced good reductions in energy use. The results presented here show that the industry now is approaching the point of diminishing returns on air leakage, where even a factor of two on an “airtight” building might mean a leakage rate of 2 L/sm^2 instead of 1 L/sm^2. High in multiplier but still low in overall magnitude, as opposed to going from a poorly constructed building with a leakage rate of 10 L/sm^2 down to something closer to current energy code norms.

Our analysis and findings show that a reduction in air barrier performance over time (barring significant deterioration or loss of performance) may not result in a significant energy penalty since the change in overall air leakage magnitude is relatively small It also helps to validate the current U.S. energy code leakage rates as reasonable targets for air leakage, as the difficulty of improving on current standards is simply not justified by the resulting energy savings.

5 OTHER ISSUES WITH POOR AIR BARRIER DURABILITY

In addition to the potential energy losses associated with deterioration of the air barrier, a deteriorated air barrier can lead to other, more readily apparent damage. Given that some deterioration of the air barrier may not result in significant energy loss (as described above), the potential for this damage may be the primary concern when considering air barrier deterioration. These products often also function as the waterproofing membrane and vapor retarder on the walls, so deficiencies in the air barrier can lead to damage from water leakage or water vapor diffusion. Leaking air also carries humidity, so air leakage can lead to condensation on or within wall or roof assemblies. Figures 1 through 6 show examples of deficiencies in installed air barriers and the types of damage that can result from air or water leakage through the air barrier that the authors and their colleagues have observed firsthand on newly-built buildings.

Figure 1: Breach in fluid-applied air barrier

Figure 2: Breach in fluid-applied air barrier

Figure 3: Corrosion on metal framing due to air leakage causing condensation

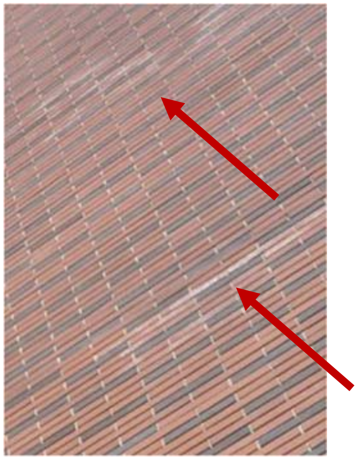

Figure 4: Efflorescence on brick masonry due to air leakage

Figure 5: Mold growth on interior wall and damaged carpet due to air and water leakage

Figure 6: Mold growth on wall due to air and water leakage

6 CONCLUSIONS

Designers and builders have a great variety of air barrier products, materials, and systems from which to select when designing and constructing a building. As with other building components, an established record of durable and reliable performance should be one of the first considerations when selecting the air barrier, because it must be able to function for the entire service life of the building. Materials that are newer to the market may be more cost-effective initially or advertise stellar performance but carry more risk without a record of performance.

Our research and energy modelling show that a complete lack of an air barrier (or an air barrier that is deteriorated to the point of no longer functioning) or lack of continuity between the different air barrier components on a building can result in modest air leakage t and resulting energy losses for larger multi-family commercial-type construction. With improvements to design and construction standards for air barrier materials and their installation and the energy codes now requiring a continuous air barrier, research by others and our energy modelling results show that the current energy code requirement of maximum 2.0 L/sm^2 both is achievable and reasonable in terms of energy performance. Attempting to lower this standard can have diminishing returns and must be considered in the context of other environmental concerns that it may cause (e.g., more raw materials, embodied energy, carbon production, etc.) from the research and development, production, and shipping of higher-performing materials or waste from installed systems that cannot meet a more stringent standard and must be removed and replaced. As building enclosure and mechanical systems develop, it will no doubt become easier to achieve lower (e.g., Passive House) levels of air leakage and realize additional savings. But for a typical modern building, dramatic reductions in air leakage alone (in the absence of improvements to the thermal envelope, ventilation, and mechanical systems) is not the most productive pathway to energy savings and must be considered in terms of costs (both monetary and environmental) versus benefit.

Given that the industry may have reached a point of balance between permitted air leakage and energy performance, a greater concern for air barrier durability may be damage to the building that could result from their deterioration or improper detailing. Air leakage, water leakage, and vapor diffusion through a deteriorated or poorly installed air barrier (which also often is the waterproofing and vapor retarder on the building) can cause significant damage to other building components. Again, in the context of the environment, damaged materials must be removed and replaced, all of which require raw materials and energy to manufacture, ship, and install the replacement materials. When we consider the environmental impacts of air barrier durability, these considerations must have equal or possibly greater weight to energy loss due to air leakage.

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