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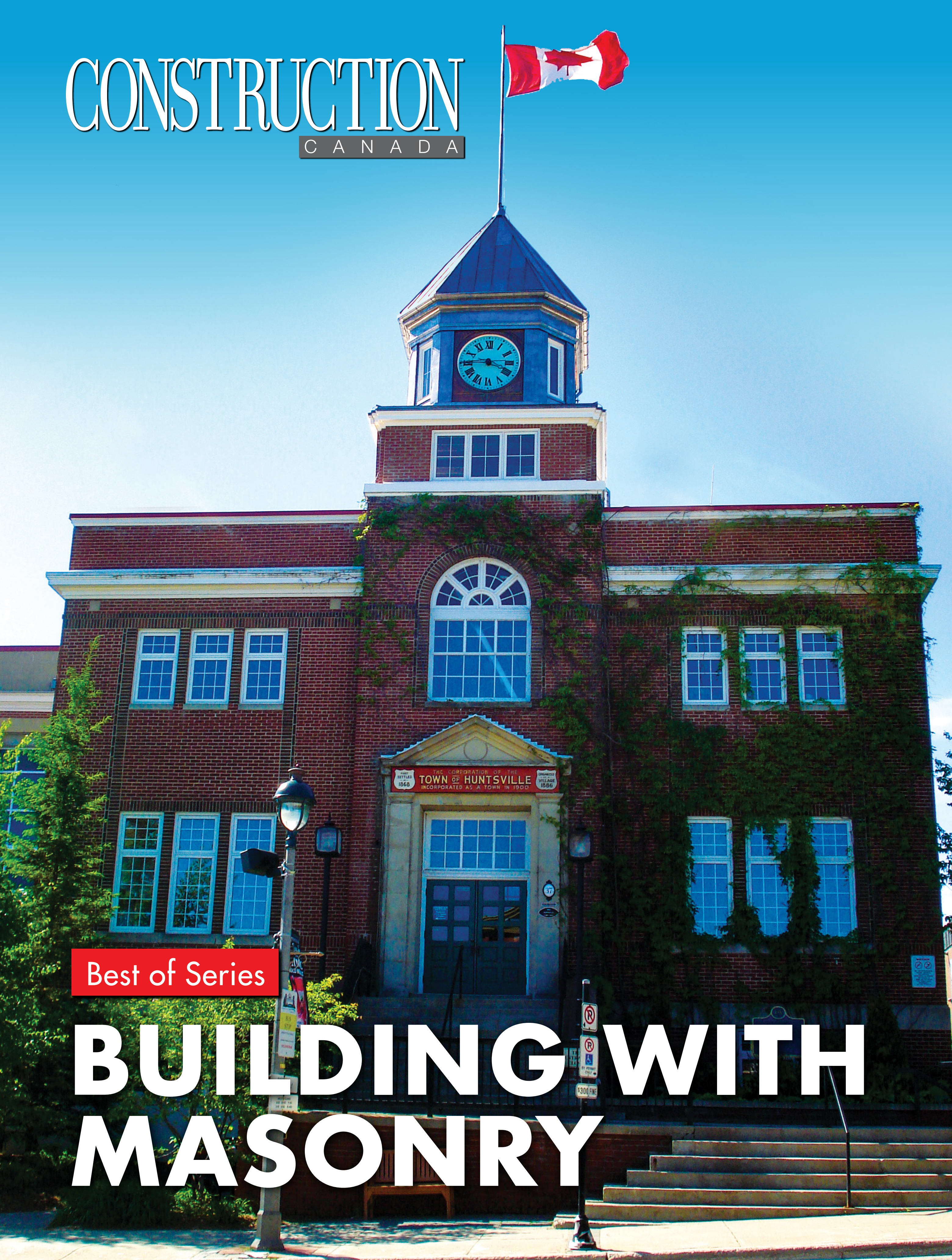

Best of Series

BUILDING WITH MASONRY

Contents

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Building with Masonry

Part One

Restoration of a Heritage Brick Clock Tower

BY KEVIN HUGHES, M.A.Sc., P.ENG., CAHP

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All images © Kevin Hughes

Restoration of a **Heritage Brick Clock Tower**

The Town of Huntsville is home to roughly 20,000 people and is located two hours north of Toronto in the Muskoka Region of Ontario.[1] The Town Hall, a two-storey, multi-wythe brick masonry structure, is the only administration building in the region of the Classical Revival style. It is constructed of loadbearing brick masonry exterior walls with a combination of wood stud framing, hollow clay tile, and brick masonry interior walls. The focus of this article is restoration of the eight-sided clock tower, home to a four-sided clock that was moved from Union Station in Toronto to the Town Hall in 1927.

The two-level clock tower consisted of two wood floors and roof framing supported on multi-wythe brick masonry walls. The square-shaped lower level of the clock tower was at the same framing elevation as the main roof. The eight-sided upper level of the tower was supported on wood floor joists spanning between the brick walls of the lower level. The lower and upper levels of the tower had the approximate plan dimensions of 4900 x 4900 mm (193 x 193 in.) and 3950 x 3950 mm (155.5 x 155.5 in.) respectively. The tower extended above the main roof structure approximately 8250 mm (325 in.). The roof of the clock tower consisted of an eight-sided, stainless steel standing-seam roof. The exterior of the wood stud walls of the upper tower were sheathed with painted wood panels.

Phase I

The Town of Huntsville retained a structural engineering consultant in September 2011 to prepare a repair scope of work to address the water-damaged, wood-floor framing supporting the clock tower motor and gear mechanism (Figure 1, page 6). The author was not involved with the project then. The repair work was

Figure 1

In 2011, the Town of Huntsville, Ont., decided to address the water-damaged, wood-floor framing supporting the clock tower motor and gear mechanism at the Town Hall.

intended to address the main source of water infiltration, originally thought to be the flat roof supporting the tower structure. The original scope of repair work included:

- reinforcement of upper tower floor joists;
- replacement of windows and lintels in the lower level; and
- waterproofing of flat podium level of the clock tower structure.

A restoration contractor from Toronto was retained by the Town of Huntsville to complete the repair work.

Brick deterioration uncovered

Construction of the original repair scope started in spring 2013. The clock mechanism was removed and the floor framing below it was reinforced. Construction halted after the contractor removed the interior plaster wall sheathing because significant deterioration of the multi-wythe masonry wall construction was discovered. At the contractor's request, the author was brought in to review the condition of the brick walls because the deterioration of the inner wythe was severe. Mortar loss and spalling was extensive in the exposed area. The softer inner wythe of the brick wall was in very poor condition and the structural integrity of the wall was in question. The author recommended that the remaining interior finishes be removed from the lower level in order to facilitate a more complete assessment of the conditions. The restoration efforts were put on hold until a detailed assessment of the brick could be completed. It was determined shoring of the tower floor framing would remain in place until a revised repair scope could be established.

On September 17, 2013, a detailed assessment of the brick walls was completed. The deterioration noted previously was found to be prevalent throughout the exposed structure. The damage to the brick masonry was most severe at the two loadbearing walls (Figure 2). The interior wythe was no longer significantly contributing to the structural integrity of the walls. Damage was noted to be most extensive at the top of the masonry wall. The condition improved nearer to the building's main roof. It was decided the condition of the brick masonry walls posed a life-safety risk and had to be repaired immediately.

Phase II

The Town of Huntsville wanted to maintain the heritage characteristics of the structure and preserve as much of the original building as possible. It was decided to completely rebuild the two loadbearing sides of the structure where the deterioration of the brick masonry was most severe. The non-loadbearing sides would be locally repaired and the inner wythe would be reconstructed. However, there were two main concerns with the proposed remedial work: finding suitable replacement material and the sequence of brick removal and replacement.

Since the existing brick exterior wythe was still in good condition, the project team decided to reuse it after cleaning. The restoration contractor was then able to find a suitable brick to match the size, material properties, and style of the exterior wythe. This approach of blending the existing brick from the exterior wythe and the new brick was also approved by the town's municipal heritage committee.

The sequence of construction was challenging. It was decided the best way to proceed was to work on one side and one corner of the building at a time while leaving the rest of the structure intact. A series of interior wood stud walls were constructed within the lower level of the tower that transferred the weight of the tower above to the lower tower floor. The shoring walls were sheathed with plywood to provide additional lateral rigidity to the building during construction.

Construction review

To complete the repair to brick masonry, scaffolding was constructed around the tower, allowing for a more detailed review of the exterior masonry wall facing the street (north side of the building). During a construction review on November 7, 2013, the exterior brick and mortar joints on the north wall were found to be in poor condition just like the two loadbearing walls. Another finding was two of the four walls were noted to have a full extra course of brick within the walls. The variation in mortar joint thickness around the tower can be seen in Figure 3.

Figure 2

The two loadbearing walls of the clock tower had deteriorated severely.

Figure 3

Condition of the masonry walls.

The original tower and the restored structure (right).

Revisions to brick repair work

The anomalies uncovered on November 7, 2013, and the advanced state of deterioration on the north side of the building prompted a change to the repair approach. The scope of brick repair work was modified to include the full removal and replacement of the multi-wythe brick masonry on all four sides of the tower. Drawings were revised and reissued for construction. Since cold weather had set in, the team had to follow cold-weather masonry construction practices. The scaffolding around the tower was enclosed and heated to ensure the mortar curing temperature stayed above 0 C (32 F). The complete removal and replacement of brick masonry tower walls proceeded one corner at a time to ensure stability of structure during construction. The replacement multi-wythe brick masonry walls were constructed in a similar fashion to the original.

On November 18, 2013, the author was requested to attend the site to review additional sources of active water infiltration. It was raining on that day. Significant water infiltration from the tower roof was noted. A review of the flashing and roof drainage system during the rain event highlighted the flaws of the existing systems including:

- the gutter at the eave of the tower roof was inadequately sized;
- downspout was not connected;
- flashing between the wood panels of the eight-sided tower walls and the flat podium roof was ineffective; and
- the roof hatch was poorly sealed (Figure 4, page 8).

The project team discussed the importance of addressing the cause of the observed structural damage and about how the active water infiltration

Copper recladding is underway. The image on the right shows the tower after recladding was complete.

Figure 4

Sources of water infiltration.

from the upper tower structure had largely contributed to the damage to the wood-floor framing and the brick masonry.

A comprehensive waterproofing system was recommended for the clock tower structure. Since town authorities wanted all modifications to replicate the detail of the existing tower, the following were proposed:

- remove existing rotted material and replace/consolidate as required;
- install new waterproofing membrane over the exterior surface;
- repair exterior wood sheathing of clock tower;
- reclad the structure with copper and lead-coated copper to match existing profiles;
- replace standing-seam steel roofing with lead-coated copper standing seam; and
- add a code-compliant lightning protection system.

The wood cladding required seasonal sanding and painting to mitigate the infiltration of water. The proposed metal cladding system would eliminate the need for seasonal maintenance.

The Town of Huntsville decided they wanted to proceed with the comprehensive waterproofing of the tower structure. A high-temperature resistant, self-adhesive roof underlayment was added between the new lead-coated copper cladding and plywood substrate.

The municipal heritage committee agreed the use of copper and lead-coated copper would be a more durable exterior finish than the existing wood sheathing and would be better for the overall sustainability of the building. The copper and lead-coated copper were to be handcrafted to match the exact profile of the existing clock faces and wood cladding. New eave gutters and downspouts were added as part of the waterproofing work.

The replacement of the cladding and roofing membrane addressed the cause of the observed masonry deterioration. The service life of the newly reconstructed masonry walls is greatly improved with the source of the original damage resolved.

Conclusion

The tower was unveiled in May 2014 after a year of construction and at a final cost of approximately $230,000. A successful heritage restoration project requires collaboration between all parties. The flexibility and ability to focus on long-term sustainability by the Town of Huntsville, the municipal heritage committee, Heritage Restoration, and Ultimate Construction were all critical to the project's success. The result was a beautifully restored clock tower that matched the detail and profile of the original tower structure.

Note

[1] A version of this article was published previously in the proceedings from the 13th Canadian Masonry Symposium in Halifax in June 2017.

Building with Masonry

Part Two

Meeting the National Energy Code Requirements with Masonry

BY MARK D. HAGEL, PhD

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All images courtesy Alberta Masonry Council

Meeting the National Energy Code Requirements with Masonry

Masonry is a 5000-year-old building technology proven to perform well in all types of built environments, given its inherent resistance to fire, insects, and moisture degradation. However, the expectations for buildings have grown from simply providing shelter to maximizing use of renewable, recycled, and recyclable materials, as well as space, energy, sound, and light. This historic technology must adapt to meet modern construction requirements, including high RSI/R-values, effective moisture management, and more efficient use of space.

Canada's *National Energy Code for Buildings* (*NECB*) was released in 2011, and updated in 2015. In Alberta, the 2011 *NECB* requirements became effective in 2016, and Ontario has already developed its own version of the energy code. This article explores techniques to meet the *NECB* requirements using the trade-off compliance path. It also discusses a masonry innovation that could address increased thermal performance demands using insulated structural masonry products with the potential to preserve single-wythe concrete masonry unit (CMU) construction.

Figure 1

An example of a brick-veneer-clad office building located in Calgary.

NECB tradeoff system

The 2011 *NECB* allows for tradeoff between opaque wall and less-energy-efficient fenestration and door components. By comparing the energy consumption requirements for door and walls provided by the code to the actual building's wall and fenestration components, the required RSI-value of the opaque wall can be reduced if the fenestration-and-door-to-wall ratio (FDWR) is sufficiently low.

An example would be a Calgary office building that has an elevation as presented in Figure 1. The number of heating degree days (HDD) for this location is 5000, which yields an FDWR of 0.333 (*i.e.* 33.3 per cent). For this location, opaque walls are required to have a U-value of 0.210 (*i.e.* RSI 4.75 [R-27]) while the fenestration and doors must have a U-value of 2.2 (*i.e.* RSI 0.46 [R-2.6]). Put simply, if the building under consideration located in Calgary has 33.3 per cent of the wall area comprising glazing and doors, with an average RSI of 0.4587 (R-2.6), then the opaque wall RSI required is 4.76 (R-27).

The dimensions for the total wall of the elevation in Figure 1 translate to a wall area of 43.9 m (144 ft) by 13.4 m (44 ft), yielding a total wall area of 588.63 m^2 (6336 sf). The window bands are 7.09 m (23 ¼ ft) wide by 1.6 m (5 ¼ ft) tall. On the main floor, there are 2.6-m (8 ¾-ft) tall doors and windows. The total fenestration area for this elevation translates to an FDWR of 0.243—that is, 24.3 per cent of the wall area is glazing.

Utilizing typical RSI values for thermally broken, double-glazed aluminum windows and doors of 0.387 (R-2.2) translates to a required RSI of 3.17 (R-17.7) for the opaque walls. Figure 2 shows the energy balance calculation. This goal is quite achievable with traditional 90-mm (3 5/8-in.) brick veneer, a 100-mm (4-in.) steel stud backup wall, and 76 mm (3 in.) of extruded polystyrene (XPS), which yields an effective RSI value of 3.28 (R-18.6).[1]

In addition to trading efficiencies between wall components, the *NECB* section of the National Research Council (NRC) website states that the code:

> allows you to trade enhanced energy efficiency of one component against decreased energy efficiency of another component within the same part of the Code. For example, in Building Envelope (*NECB* Part 3), higher roof insulation efficiency levels can be traded off against lower wall insulation levels, but not against lighting levels, which are included under Lighting (*NECB* Part 4).[2]

Therefore, increasing roof insulation can also facilitate the use of lower R-values in the opaque wall. In this example, increasing the roof insulation sufficiently could reduce the wall insulation from 100 to 50 mm (4 to 2 in.).

For multi-family residential buildings, fenestration ratios are often higher than 25 per cent. Figure 3 shows the front elevations of a wood-frame, brick-clad low-rise residential building in Edmonton. For this elevation, the FWDR is 0.328 (*i.e.* 32.8 per cent). Assuming vinyl with a spacer is being used, most windows and doors have an RSI value of 0.511 (R-2.8), and the opaque wall will require an RSI value of 3.33 (R-18.9), as shown in Figure 4 (page 14). This can be achieved using traditional 2x6 wood-frame

Figure 2

Building Type **Office building** Location **Calgary** HDD **5000**

Above Grade Walls		R-value/%
Max FDWR - Above Grade Walls	0.667	66.7%
Max FDWR - Above Grade Fenestration & Doors	0.333	33.3%
Prescriptive Above Grade Wall U-value	0.210	27.0
Prescriptive Above Grade Fen & Door U-value	2.2	2.6

ABOVE GRADE WALL					
Actual Wall area	6336	ft^2	=	588.8	m^2
Actual Fenestration & Door Area	1538.685	ft^2	=	143.00	m^2
Actual FDWR - Walls	0.7572		75.7%		
Actual FDWR - Fenestration & Doors	0.243		24.3%		
Actual Wall U-value	0.32		R-17.7		
Actual Fen & Door U-value	2.6		R-2.2		

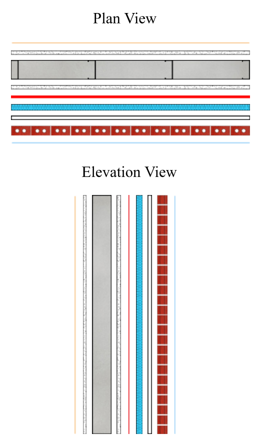
Prescriptive Path Requirements

Building Envelope Assembly	Prescriptive (U-Value)	Prescriptive (R-Value)	Wall Area (ft^2)	Wall Area (m^2)	Area Ratio due to Max FDWR		U_i x A_i
Walls	0.210	27.0	4226	392.8	0.333		82.5
Fenestration & Doors	2.200	2.6	2110	196.1	0.667		431.4
		Totals:	6336	588.8	1.00	$\Sigma(U_i$ x $A_i)$ =	514 W/K

Simple Trade-Off Path Requirements

Building Envelope Assembly	Actual (U-Value)	Actual (R-Value)	Wall Area (ft^2)	Wall Area (m^2)	Area Ratio due to Actual FDWR		U_i x A_i	
Walls	0.320	17.7	4798	445.9	0.757		142.7	
Fenestration & Doors	2.6	2.2	1539	143.0	0.243		371.8	
		Totals:	6336	588.9	1.00	$\Sigma(U_i$ x $A_i)$ =	514 W/K	OK

	R-Value	RSI
Steel Stud 100mm None 406mm	0.795	0.140
Gypsum Board 1/2" Interior	0.4	0.070
Gypsum Board 3/8" Interior	0.03	0.005
Air Film Exterior	0.2	0.035
Air Film Interior	0.7	0.123
Air Cavity 25mm	1.0	0.176
Vapour Barrier Self Adhered	0	0.000
Extruded Polystyrene (XPS) 3"	15.1	2.659
Clay Brick 90mm	0.4	0.070
Total	18.625	3.280



Energy balance for National Energy Code for Buildings (NECB) 2011 tradeoff compliance between walls and glazing on a commercial steel stud building. The RSI and R-values for the wall were calculated with an Alberta Masonry Council online tool.

construction with R-19 batt insulation in the stud and 25 mm (1 in.) of expanded polystyrene (EPS) in the cavity. This yields an effective RSI value of 3.77 (R-21.4), as shown in Figure 5 (page 14).

For buildings like warehouses and light industrial projects, the fenestration ratio is often significantly lower than 30 per cent. Figure 6 (page 15) displays two elevations of a typical warehouse.

On Elevation I, the fenestration wall ratio is 0.180 (*i.e.* 18 per cent); on Elevation II, even with the large bay doors and man doors, the FDWR is only 0.101 (*i.e.* 10.1 per cent). Assuming the typical RSI value of 2.64 (R-15) for insulated metal man doors, and 0.405 (R-2.3) for the large bay doors and glass windows and doors, yields RSI requirements of 1.90 and 1.29 (R-10.8 and R-7.3) for Elevation I and Elevation II, respectively.

Figure 3

Low-rise, multifamily residential building in Edmonton.

Figure 4

Building Type **Multi-family residential** Location **Edmonton** HDD **5120**

Above Grade Walls		
		R-value/%
Max FDWR - Above Grade Walls	0.675	67.5%
Max FDWR - Above Grade Fenestration & Doors	0.325	32.5%
Prescriptive Above Grade Wall U-value	0.210	27.0
Prescriptive Above Grade Fen & Door U-value	2.2	2.6

ABOVE GRADE WALL				
Actual Wall area	4646 ft²	=	431.8	m²
Actual Fenestration & Door Area	1523.167 ft²	=	141.56	m²
Actual FDWR - Walls	0.6722	67.2%		
Actual FDWR - Fenestration & Doors	0.328	32.8%		
Actual Wall U-value	0.30	R-18.9		
Actual Fen & Door U-value	2.0	R-2.8		

Prescriptive Path Requirements

Building Envelope Assembly	Prescriptive (U-Value)	Prescriptive (R-Value)	Wall Area (ft²)	Wall Area (m²)	Area Ratio due to Max FDWR		U_i x A_i
Walls	0.210	27.0	3136	291.5	0.325		61.2
Fenestration & Doors	2.200	2.6	1510	140.3	0.675		308.7
		Totals:	4646	431.8	1.00	$\Sigma(U_i \times A_i)$ =	370 W/K

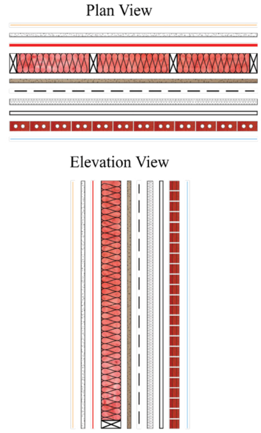
Simple Trade-Off Path Requirements

Building Envelope Assembly	Actual (U-Value)	Actual (R-Value)	Wall Area (ft²)	Wall Area (m²)	Area Ratio due to Actual FDWR		U_i x A_i	
Walls	0.300	18.9	3123	290.2	0.672		87.1	
Fenestration & Doors	2	2.8	1523	141.6	0.328		283.1	
		Totals:	4646	431.8	1.00	$\Sigma(U_i \times A_i)$ =	370 W/K	OK

Energy balance for NECB 2011tradeoff compliance between walls and glazing on a wood-frame multi-family residential building.

Figure 5

				R-Value	RSI
Wood Stud	2x6	Batt R22	406mm	14.479	2.550
Gypsum Board	1/2"	Interior		0.4	0.070
Oriented Strandboard (OSB)	3/8"			0.5	0.088
Air Film	Interior			0.7	0.123
Air Cavity	25mm			1.0	0.176
Clay Brick	90mm			0.4	0.070
Air Film	Exterior			0.2	0.035
Expanded Polystyrene (EPS)	Type 1			3.7	0.652
Building Paper	30min Building Paper			0	0.000
Vapour Barrier	Self Adhered			0	0.000
Total				21.379	3.765



With the materials chosen for front elevations of a wood-frame, brick-clad low-rise residential building in Edmonton, the effective RSI value would be 3.77 (R-21.4).

An alternative to using two separate insulation values for the two elevations would be balancing the R-value by taking an effective RSI value of 1.57 (R-8.9) for both. However, neither of these insulation requirements can be met with a single-wythe CMU wall using a typical 200- or 250-mm (8- or 10-in.) concrete block—even when filled with vermiculite or sprayed polyurethane foam (SPF) as shown in Figure 7.

To achieve an RSI value that is greater than 1.14 (R-6.5) with a single-wythe masonry wall, insulated concrete unit technologies are required. The next section describes some of the technologies already available in the market that can achieve RSI values between 1.41 and 4.93 (R-8 and R-28) with a single-wythe wall.

Insulated structural concrete block walls

One of the main advantages of a single-wythe masonry wall is achieving a highly durable finished wall inside and out, without the addition of interior or exterior claddings. However, with requirements by the 2011 *NECB* for many areas in Canada, it may be difficult to achieve an acceptable level of energy performance with traditional single-wythe CMU construction.

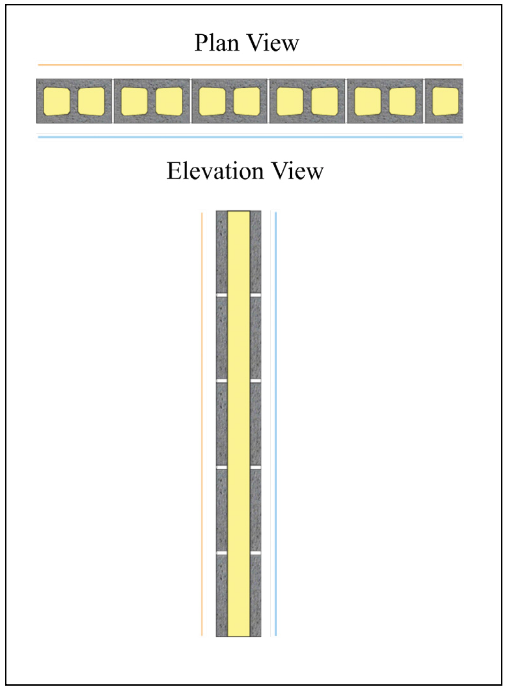
Even with the addition of SPF in vacant unit cores, traditional single-wythe concrete block walls produce a maximum RSI of approximately 1.14

Figure 6

The elevations of a typical Calgary warehouse.

Figure 7

				R-Value	RSI
Block	Light	25cm	Vermiculite	5.6	0.986
Air Film	Interior			0.7	0.123
Air Film	Exterior			0.2	0.035
Total				6.500	1.145



Single-wythe, vermiculite-filled, 250-mm (10-in.) concrete masonry unit (CMU) wall: online R-value calculator.

Figure 8

An insulated concrete masonry unit with two face shells.

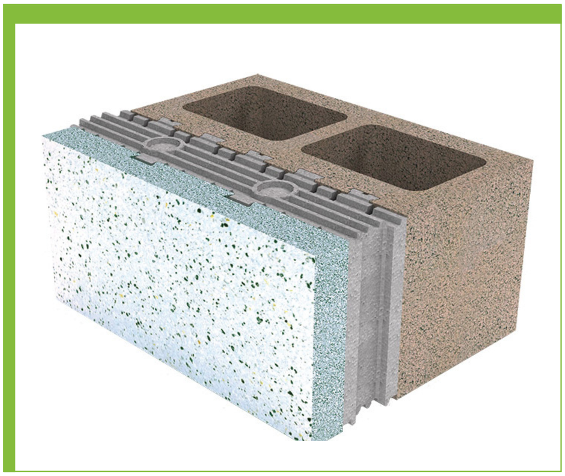
(R-6.5) using the traditional 200-mm (8-in.) block unit. Nevertheless, numerous solutions have been developed for the addition of insulation within the concrete block unit to create an insulated structural concrete block.

Insulated concrete blocks have been on the market for several years. Theses concrete masonry products (Figure 8) integrate either EPS or XPS rigid insulation into the webs. The installation of the insulation occurs at the time of the wall construction; it can achieve RSI values of up to 1.41 (R-8) with a 300-mm (12-in.) unit.

The alternative is a concrete masonry product with three face shells (Figure 9, page 16). It has the insulation inserted during the manufacturing process and achieves an RSI value of 2.64 (R-15) with a 300-mm-width, three-face-shell unit. The grooved insulation also provides for drainage.

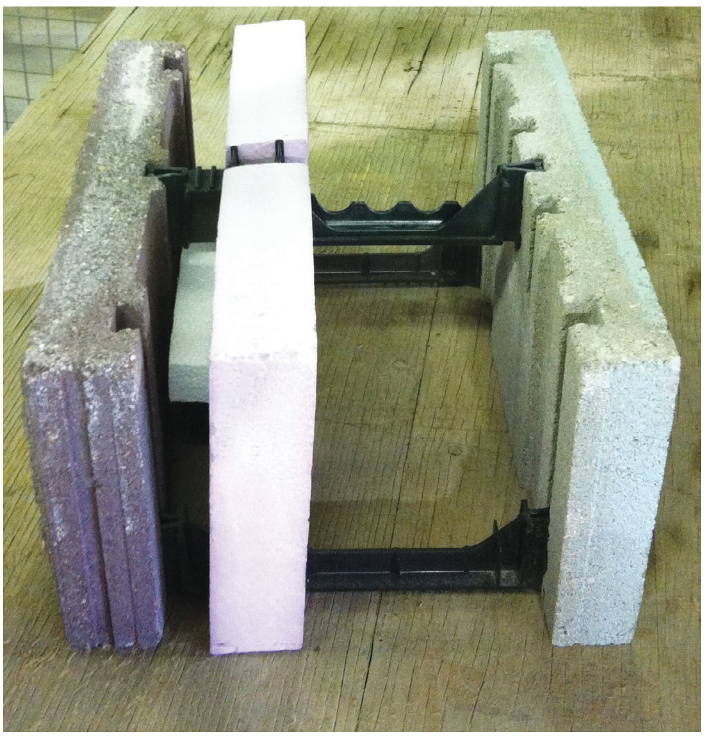
An alternative to the insulated concrete masonry unit is the insulated concrete masonry form (ICMF). This type of masonry unit is typically manufactured using XPS insulation and replaces the EPS insulation in an insulated concrete form (ICF) with concrete

Figure 9



An insulated concrete masonry unit with three face shells.

Figure 10



An insulated concrete masonry form (ICMF).

masonry unit shell faces. However, unlike ICF, these concrete masonry units are still laid like a traditional concrete block wall and then filled with concrete (Figure 10). Thus, the system is essentially a fully grouted concrete wall, but without the web interference. These concrete masonry products have units that are typically 310 mm (12 1/4-in.) thick, with 50 mm (2 in.) of XPS insulation embedded into the unit at the time of manufacture.

The advantage of this system is the exterior and interior walls are finished with durable architectural finishes in a single step. The system achieves an average insulation rating of RSI 4.93 (R-28). A 25-mm (1-in.) gap for capillary break and drainage between the exterior shell and the embedded XPS insulation mimics a cavity wall system and significantly reduces the likelihood of water ingress through the mortar joints that can occur in single-wythe concrete masonry walls. Integral water repellant on the interior wythe also helps mitigate water ingress.

The face shells of the 310-mm thick units are tied together with plastic webs that double as horizontal reinforcement cradles and ties for vertical bars like ICF units. These plastic webs/handles/rebar cradles create a much lighter block than if concrete webs were used. These CMUs, which are approximately the same width as a traditional 300-mm (12-in.) units, weigh about the same as a standard 200-mm (8-in.) concrete block.

Conclusion

Canadian masons and product manufacturers are adapting to meet modern construction requirements. In the majority of Canadian locations, wall-to-glazing ratios of approximately 25 per cent permit an achievable R-value for most traditional full-bed masonry rainscreen veneers by using the tradeoff compliance path of the 2011 *NECB*. For single-wythe masonry walls, the low glazing ratios (typically less than 10 per cent) found on warehouse, big-box commercial, and school gym walls may be achievable with the trade-off compliance path; they are definitely achievable with full-building modelling or the use of insulated concrete masonry units. Insulated concrete masonry units in the form of insulated concrete blocks or ICMFs can achieve RSI values of between 1.41 and 4.93 (R-8 and R-28), ensuring there are masonry products that can meet the high R-value demands of the country's national energy code.

Notes

[1] For more information on these calculations and analysis, visit the Alberta Masonry Council's website at www.albertamasonrycouncil.ca/wall-test.

[2] To read more on this visit www.nrcan.gc.ca/energy/efficiency/buildings/eenb/16598.

Building with Masonry

Part Three

Designing with Natural Stone Cladding

BY MICHAEL PICCO, P.ENG.

Michael Picco, P.Eng., is president and CEO of Picco Engineering. With 30 years of experience in natural stone cladding and structural engineering, his expertise includes stone sourcing and selection, consulting, manufacturing, installation, testing, as well as the design and detailing of stone anchors and shop drawings. Picco has spoken to various associations including Terrazzo Tile and Marble Association (TTMAC) Trade School, Saskatchewan Masonry Institute, Marble Institute of America (at Stone Expo), and appeared at various international conferences. He was elected to the board of directors of the Marble Institute of America (MIA) in 2015. Picco can be reached via e-mail at mpicco@picco-engineering.com.

Photos courtesy Picco Engineering

Designing with Natural Stone Cladding

The use of natural stone on buildings and paving can be traced back to the beginning of civilization. There are countless buildings, monuments, and structures dating back thousands of years that have stood the test of time and left generations in awe. Some examples of projects built primarily of local limestone include Egypt's Great Pyramid of Giza, the Mayan temples in Mexico, southern Italy's round Trulli homes, the Parthenon in Greece, and the Roman Coliseum (which also included local travertine). Many of these great structures were built with no mortar. The stones were simply cut and tightly fitted together and dry stacked—a method of stone installation mimicked in modern-day construction and referred to as "dry-stacked stone."

In many ways, our ancestors in the building industry applied sustainable practices by using the larger quarried blocks for building construction and smaller waste pieces for erosion control and walkways. They also used the gravel to pave small roads from town to town.

When natural stone is properly specified and installed, few cladding materials last as long and perform as well. Not only is it esthetically pleasing, but it is also a low-maintenance, sustainable material.

The greenness of stone

Natural stone's inherent characteristics make it a green building product—it can be used without any additional finishes or wall coverings, has low maintenance needs, and is highly durable.[1] Unlike the many cladding materials available on the market requiring extensive manufacturing energy, natural stone is extracted from the earth and processed, slabbed, finished, and cut.

As more emphasis is placed on the whole building design and life cycle assessment, the concept of a product's embodied energy is an important and relevant measure. Embodied energy is a measure of the carbon dioxide (CO_2) emitted from the time raw material is extracted to the point it is installed on the building. This process has been referred to as "cradle to gate."

Since building designs may be using more materials (and/or more carbon-intensive products) to achieve lower energy use, an increasing proportion of the total energy use and carbon emissions for high-performance buildings comes from its materials and products. By taking embodied energy into account, a project team can ensure it is designing for net carbon emission reductions. In the case of natural stone, this could include the CO_2 required during quarrying,

An Italian example of the timelessness of stone—the Trulli of Alberobello.

transport to the plant, energy required for slabbing and fabrication, delivery to the site, and installation. There is still some work being done by various life-cycle analysis (LCA) authorities to clearly define the definitions of what is, and what is not, included in the calculations for various products to ensure a consistent and fair measure is established. However, based on most studies and comparisons, natural stone is consistently rated as one of the building materials having the lowest embodied energy on many scales.

Different materials, different stone

With the advent of many new thin cladding manufactured products introduced to the market, there is a recent trend for designers to specify and detail very large cladding panels. When using products such as porcelain, recycled glass, glass-fibre-reinforced concrete (GFRC), fibre-reinforced polymer panels (FRP), or engineered/manufactured stone, care must be taken by architects and specifiers to make the clear distinction between natural stone and manufactured products. The design approach, attachment detailing, and structure can vary dramatically.

This author has recently seen a trend of substituting an engineered thin cladding product with large, thin natural stone panels, with the erroneous assumption they were basically interchangeable. The variability of natural stone requires a design approach quite different than manufactured products and, thus, has different limitations associated with panel size and connection design.

New natural stones are being introduced to the market on a continual basis. Many are a result of new quarry areas and stones being discovered, and many are a result of new technologies allowing extraction of stones previously impossible to quarry (described later in this article).

Some of these technologies include the use of epoxy injection at the quarry with stones that are heavily flawed and cracked. In other cases, vacuum epoxy injection is employed to stabilize heavily cracked and fissured blocks of stone. For the general consumer, these injections would be undetectable as they would just appear as another vein in the material.

The epoxy in the stone and the amount of veining can have a dramatic effect on the technical properties of the stone. In most cases, these heavily cracked and filled materials are restricted to interior use. Many of the very desirable and heavily veined onyx slabs on the market today are a result of these technologies. In the past, blocks large enough to produce slabs were impossible to extract in one piece.

Factors in selecting and detailing stone

Having been involved with stone detailing and design for more than 30 years, this author has come across numerous projects requiring complicated and costly engineering solutions due to insufficient planning and research during the initial stages of a project. The need to source a new stone material late in a project can lead to unexpected costs, schedule delays, and frustration.

In order to greatly reduce the possibility of these and other problems, it is imperative the design professional dedicates time and resources to research materials and methods of installation amongst many other details. In many cases, engaging an expert with experience in stone selection, design, and detailing to become part of the design team early can turn out to be a cost-effective solution.

In choosing a stone, several factors must be considered. Although the colour, texture, veining, and/or grain size are always critical aspects to architects and designers, there are other aspects that must override these.

Strength

Is the stone strong enough to withstand all the design loads at the thickness and size specified? Particularly when using stone on the exterior, climate conditions can make a stone suitable in one environment and not in another. Seismic loading governs many designs on the West Coast, whereas East Coast Canada is primarily designed for wind loading. It is important the design team consult both local codes and the authority having jurisdiction (AHJ).

For natural stone, there are many new proprietary anchoring systems, some of which are back-anchored into the stone to allow for an open-joint rainscreen design. Examples include (from left to right): soffit anchor on strut, and two-piece anchors without or with di-electric separation.

Block size

Is the stone specified available at the size detailed on the drawings? Depending on the stone type, quarrying equipment, and technology available, blocks are extracted in several different sizes. Standard block sizes for most granites and marbles will be approximately 1.5 x 3 m (5 x 10 ft). Many limestones, as well as more exotic stones like onyx block, can be much smaller.

Finish

Is the finish suitable for the proposed application? When using stone as paving, slip resistance is an essential property to consider. Finishes such as sand-blasting and flaming can make the stone more absorptive and potentially more susceptible to freeze-thaw deterioration.

Exposure conditions

Is the stone exposed to high levels of pollution? Will the stone undergo several freeze-thaw cycles? Is the stone exposed to high levels of sodium (coastal exposures)? In severe exposure conditions, stone selection becomes more critical, and choices may be more limited based on the material's technical properties.

Testing

Most stones quarried and sold have readily available ASTM test data including density, compressive strength, flexural strength, absorption, and abrasive resistance. Many materials are supplied with testing performed by different jurisdictions such as EN (*i.e.* European Union) and CE marking of stone also introduced in the European market.

Current test data is valuable for providing the information required for the initial evaluation and selection of a stone for a particular application in a given location. Current test data must be performed in order to determine the actual strength of the stone being quarried and used for the project. In most cladding applications, the most common test giving the most useful information is ASTM C880, *Flexural Strength Test for Dimension Stone*. Individual anchor tests should be performed with the proposed anchors being suggested for the project. These tests are also outlined in the ASTM standards.

Backup selection

The types of backup used by the building designer can, in many cases, determine the success or failure of a cladding project.

Concrete

Concrete tends to be the preferred backup for exterior and interior cladding. Anchors can be placed anywhere, allowing the stone designer the flexibility to design an efficient, installer-friendly anchoring system. Anchor capacities are typically highest when installed into concrete.

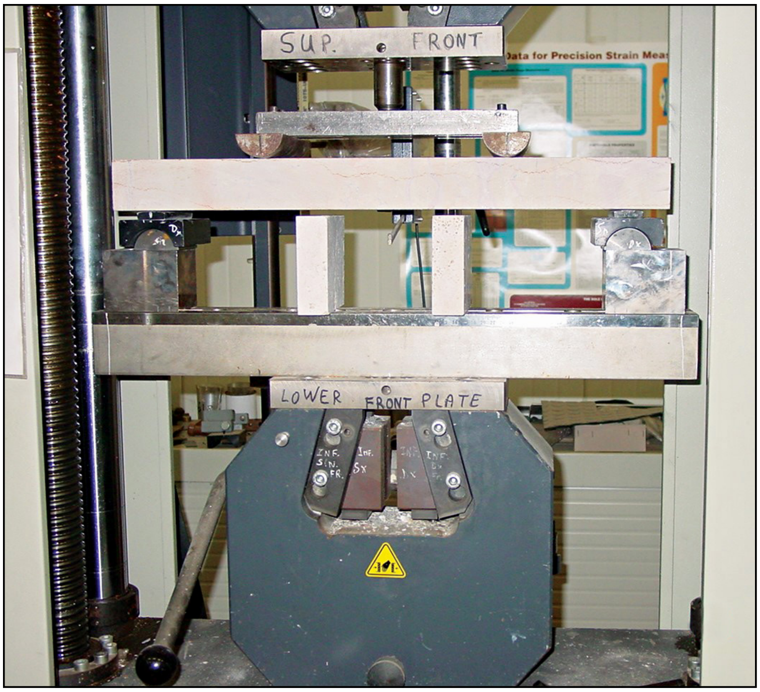
Masonry

When used for interior cladding where panels are stacked, concrete masonry units (CMUs) can comprise a very suitable backup assembly. If used for exterior cladding (*i.e.* where anchors are designed to support the weight of each panel), the CMUs must be solid-filled with masonry grout to ensure anchors can achieve the required capacity.

If masonry is not properly filled, positive anchorage is very difficult to achieve and may require the use of adhesive or epoxy anchors. These anchors are more costly and require time to set up, particularly when ambient temperatures are low.

Steel sub-frames

When designed by the stone installer's engineer, steel sub-frames can be a very effective and economical backup. However, if the frames are not designed to accommodate the stone designer's anchors, they can be ineffective and very often require either additional steel, or for the stone designer to engineer an expensive anchoring system to suit the steel provided.



In most cladding applications, the most common test giving the most useful information is ASTM C880, Flexural Strength Test for Dimension Stone*.*

Pre-panelized sub-frames
Pre-panelized sub-frames can also be an effective installation method, allowing much of the installation to take place in a shop protected from the elements. However, this method of installation requires close co-ordination with the architect and prime engineer on the project.

Metal stud
When used for interior cladding where panels are stacked, metal studs serve as an acceptable backup. When used for exterior cladding, however, this method is the least preferred. This is because the capacity of anchors into metal studs is limited. The placement of the studs is critical and usually does not align with the stone connections. Consequently, use of a continuous horizontal formed channel along each horizontal joint to facilitate the stone anchors is required.

There is also some concern with the service life of the anchorage into metal studs, given the drilled anchor must cut through the metal stud—possibly compromising its corrosion resistance at the anchor. This results in the stone having a much longer service life than the anchors.

Specifying anchors

In several cases, anchors are misinterpreted by architects and designers as "masonry ties." In the transition to thinner veneers, the traditional masonry tie and stacked stone have continued to be incorrectly used in many thin cladding projects.

Anchors must be capable of independently supporting all the loads imposed by each stone. Generally, stones should not be stacked. However, in some conditions, with proper engineering, a stacked stone system can also be used with mechanically engaged anchors. The failure or breakage of a stone should neither affect any adjacent stone nor cause the failure or collapse of the stones above.

It is highly recommended all anchoring components be manufactured from Grade 304 stainless steel; for particularly harsh environments and coastal projects, Grade 316 stainless steel is often specified. While hot-dipped galvanizing secondary anchoring components are sometimes a little more economical, use of dissimilar metals can result in corrosion problems if not properly detailed and installed. The cost to upgrade to an all-stainless anchoring system is usually negligible when compared to the total cost of the cladding project. All stainless offers peace of mind the anchors will perform as detailed for life of the building.

There are also many new proprietary anchoring systems that are available, many of which are back-anchored into the stone, allowing for an open-joint rainscreen design.

Conclusion

Provided it is correctly designed, stone can be an everlasting, maintenance-free material. Nevertheless, this author has seen scenarios where stone has the potential to be disastrous when used and detailed improperly, as evidenced by the many re-cladding and re-installations required because of either poor design and installation or the wrong stone selection.

There are readily available resources from the Terrazzo, Tile, and Marble Association of Canada (TTMAC) including the second volume of the *Dimensional Stone Guide* for stone 19 mm (¾ in.) and thicker, along with *Specification Guide 09 30 00–Tile Installation Manual* for thinner stone. Further, version 7.2 of the Marble Institute of America (MIA) *Dimension Stone Manual* is another very useful resource.

Notes

[1] This author acknowledges the assistance of Stephanie Vierra, Assoc. AIA, LEED AP (Vierra Design & Education Services LLC), in developing the article's section on stone and sustainability matters.

Building with Masonry

Part Four

Why Drainage and Ventilation are Critical for Adhered Masonry Walls

BY ART FOX

Art Fox has been the head of marketing and communications at Mortar Net Solutions since 2012. He was also the chief operating officer of the company when it was initially formed 25 years ago. Fox has been involved in the building trades since he was a contractor specializing in new home and light commercial construction in New Mexico in the 1970s. He can be reached via e-mail at afox@mortarnet.com.

images courtesy Mortar Net Solutions

Why Drainage and Ventilation are Critical for Adhered Masonry Walls

In masonry cavity walls—a design that has been in use for more than a century—the cavity provides a path for drainage and ventilation and acts as a capillary break.[1] However, adhered masonry veneers like stucco have been installed for hundreds of years without drainage or ventilation. So why do we need to add drainage and ventilation planes to adhered masonry walls now? The short answer is American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) 90.1, *Energy Standard for Buildings Except Low-rise Residential Buildings*, and the Canadian equivalent, the *National Energy Code for Buildings (NECB)* 2011.[2]

ASHRAE is an international organization that sets energy-use standards for commercial buildings. Its standards are frequently used as the basis for building codes for jurisdictions in Canada and the United States. Recent changes in building materials, as well as increasingly strict energy codes derived from ASHRAE 90.1, have made drainage and ventilation for adhered masonry walls just as important as they are for masonry cavity walls. This article looks at how modern adhered masonry veneer walls are different from those built before the 1950s, and why these differences are making drainage and ventilation essential for excellent, sustainable performance.

The physics of water

Water molecules are attracted to each other, which results in surface tension—the skin-like film on the water's surface that makes water drops possible. However, there is a limit to how many molecules can stick together before their weight or air movement overcomes the force of surface tension and pulls them apart. Molecular attraction also causes capillary action,

Factory-assembly metal lath and drainage plane systems install like regular lath.

which, combined with the tendency of water to move from wetter to drier, explains why a molecule of water entering a small hole will draw other molecules with it.

Large clumps of water molecules form liquid drops, which quickly run off smooth surfaces like stone and stucco, but will not penetrate an unbroken wall. If water gets behind the veneer, it also will not penetrate small holes in the weather-resistive barrier (WRB), such as those caused by the WRB and lath fasteners, because the attractive force of the water molecules toward each other keeps the drops larger than the holes. The weight of water alone is not enough to force it through.

That being said, when pressure differentials caused by wind-humidity differences or heat become strong enough, they can push the water through even very small holes. In building science, this is called hydrostatic pressure. It is similar to pushing a partially filled water balloon through a garden hose—it will not go through the hose by gravity alone, but put enough pressure behind it and it will. Additionally, if there is no bond break between the scratch coat and WRB, high moisture content in masonry will move to lower concentrations in the substrate.

So-called "perched" water can also wreak havoc on adhered masonry walls with trim elements such as lintels.[3] When water becomes trapped behind such walls in the narrow space between the trim and the veneer, it cannot drain due to the clumping effect of water-molecule attraction. The water then soaks into the masonry, substrate, or both. When the sun's heat causes the humidity in the space between the veneer and WRB to become higher than outside or inside the building, the solar energy drives the moisture both outward through the masonry and inward through the WRB, as well as through any holes in the WRB and sheathing.

How water gets into the wall

Every mason and masonry wall designer knows water gets into masonry walls either as liquid (such as rain or snow) or as vapour (the gaseous form of water). Water vapour does not cause any trouble until it condenses and becomes liquid water. Therefore, providing a drainage mechanism for liquid water is vital, but it is just as important to get vapour out of the wall system before it becomes liquid.

Water penetrates the wall in three different ways. It can:

- enter as liquid or vapour through tiny mortar cracks or through gaps around wall penetrations and at places where different materials meet;
- be drawn as liquid by capillary action through porous masonry; or
- move as vapour from a warm, humid side of the wall to a cooler, drier side of the wall, where it can condense into liquid if dewpoint conditions are met.

In cool weather, water vapour can move from the warmer, more-humid conditioned air inside the building to the exterior, and in warm weather, it can move from the more-humid exterior toward the cooler, drier interior. In either case, the vapour can condense at the back of the veneer.

Why old veneer installation methods do not work with modern walls

Traditional adhered veneer materials include stucco, manufactured and cast stone, and thin stone and brick. Manufactured and cast stone, and thin brick were introduced during the 20th century as alternatives to dimensional stone and full-sized brick. Traditional installation methods employ either wire mesh or expanded metal lath firmly attached to the substrate as the support for the veneer. Cementitious mortar fully encapsulating the wire or lath is then applied as an undercoat, or scratch coat, which provides a strong foundation for the veneer. Veneer materials—except stucco—are adhered to the scratch coat by applying a solid layer of mortar to the back of each veneer unit and pressing it tightly against the scratch coat for a few seconds. Stucco is applied continuously as one or two coats over the scratch coat.

When they first became popular, adhered masonry veneer walls did not have the sophisticated flashings, insulation, and WRBs used today, so they leaked a lot of air and would dry quickly if they got wet. With continuous insulation (CI) and WRBs being the best way to meet ASHRAE 90.1 and *NECB* standards, along with the use of more effective flashings and sealants around wall openings, modern adhered masonry walls leak very little air. This relative airtightness is a key difference between older adhered masonry walls and those of today, and is one reason drainage planes behind the veneer are so important in modern structures. Water that penetrates the wall stays trapped in the wall unless drainage and ventilation are added to get it out.

Weather-resistive barriers

Changes to WRBs make another difference between older and new building construction. WRBs are membranes applied continuously to a building envelope. They are rated in "perms," or permeability to water vapour. A WRB's appropriate perm rating, and whether it is placed on the inside or outside of the insulation, is determined by the average heat and humidity of the climate in which the building is constructed. Ideally, a WRB allows enough water vapour to pass through it that the substrate dries without allowing liquid water through. Using two layers of building papers such as Grade D asphalt-impregnated building paper or Number 15 felt as a WRB is common when CI is not included.

The thinking behind using two layers of building papers is the assumption the outer layer will get wet when the scratch coat is applied. When the papers dry, they wrinkle, eliminating any mortar bonding by pulling away from the scratch coat and creating a sufficiently rough surface that water drains between the papers and the scratch coat. However, since the wrinkles are shaped randomly, they do not create continuous drainage channels running the height of the wall. This means they can obstruct water flow and create pockets where water can collect. Any buildup of water can lead to its lateral migration at the laps and allow a wider area of the substrate and scratch coat to get wet.

The absence of a mortar bond allows some drainage, but very little—if any—ventilation. Since older buildings with paper or felt as a WRB leaked a lot of air, they did not need to provide ventilation. Using plastic house wraps instead of building papers is now common, and some brands can bond strongly to mortar, which minimizes potential drainage.[4] Since today's buildings do not leak much air, and modern papers and plastic house wraps allow minimal ventilation, there is very little drying behind the scratch coat with paper, felt, or house wraps.

Additionally, without a drainage and ventilation plane, building papers can absorb enough water to degrade and develop holes, which allows water to get to the substrate. They can also become saturated with water, creating an intensive vapour source inside the wall. If water stays in contact with the substrate, even if there is a WRB over it, it can migrate through fastener holes and other penetrations and be absorbed by interior materials. If even small amounts of moisture stay in contact with the substrate long enough, it can cause fastener corrosion, nail pullout, mould, and sheathing degradation.

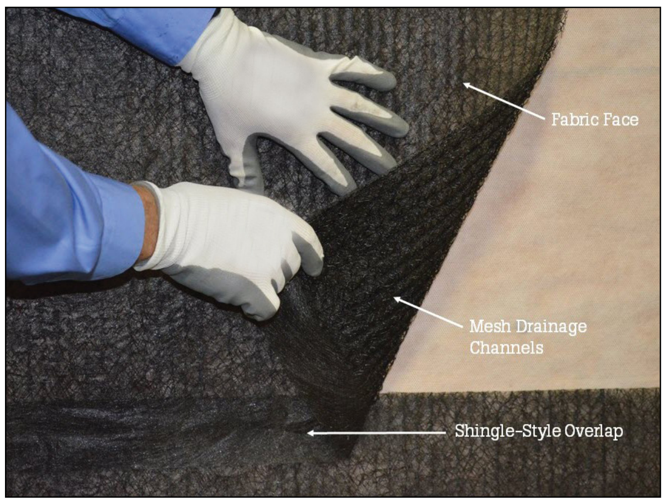
Since CI is now commonly used in order to meet energy standards, manufacturers have developed rigid insulation with sealed seams, which serves as both CI and a WRB. These systems can be more efficient to install and more resistant to damage during installation than the WRBs mentioned above, but they still need drainage and ventilation. Also, when wire or lath is attached on top of CI, the fastening system must be designed to handle the eccentric loading placed on the fasteners, because if they bend or pull out, cracks in the veneer will develop very quickly.[5]

Since modern buildings do not self-ventilate by leaking air, and since all masonry building exterior walls leak moisture, using traditional installation methods with modern materials but without a drainage plane means most of the water penetrating the veneer must migrate into the substrate or out through the face of the veneer.

Further Reading

For more information on the topics broached in this article, professionals can consult:

- Michael Anschel's "Building Things Right: Rainscreen Siding Systems," published by *Professional Remodeler* in February 2016 and available at www.proremodeler.com/building-things-right-rainscreen-siding-systems;
- John Straube and Jonathan Smegal's research report "Modeled and Measured Drainage, Storage, and Drying Behind Cladding Systems," available at buildingscience.com/documents/reports/rr-0905-modeled-measured-drainage-thermal-x/view;
- Norbert V. Krogstad's "Condensation and Rigid Insulation Placement," available at masonryconstruction.com;
- Joseph Lstiburek's "BSI-038: Mind the Gap, Eh!" and "BSD-105: Understanding Drainage Planes," available to read online by visiting buildingscience.com; and
- Steven Fechino's "Adding Drainage to Stone Veneers and Adhered Masonry," from *Masonry Magazine*—access online by visiting www.masonrymagazine.com/archive/magazine/features-2/adding-drainage-to-stone-veneers-and-adhered-masonry.



Drainage plane with factory-attached water- and vapour-permeable fabric.

Thin-brick veneer popped off the substrate.

Mould and water damage resulting from a lack of drainage behind adhered masonry. One should note how the damage radiates from the bottom corner of the window, which is a typical location for leaks.

Sheathing

This article will now cover moisture behaviour in plywood and oriented strand board (OSB), but is not recommending one sheathing type over the other. Sheathing manufacturers are constantly improving their products, so it is best to check with them about their most recent products' water absorption and drying characteristics before making a design decision.

Water in the substrate can potentially lead to mould growth, as well as structural, fastener, and veneer degradation. Water damage in this area can be made worse by using OSB sheathing instead of plywood. According to Joe Lstiburek of Building Science Corporation, use of OSB is important when it comes to water management behind adhered veneers because it reacts to moisture very differently than plywood.[6]

Plywood becomes more vapour-permeable as it gets wet, going from about 0.5 to 1.5 perms to more than 20 perms, which means its drying rate will increase as it gets wetter. However, OSB's vapour permeability—and therefore its drying rate—stays low and relatively unchanged no matter how wet it is. Water in plywood also moves laterally much more easily than it does in OSB, so it will migrate out faster and have a significantly lower tendency to concentrate in one area. With OSB, moisture will concentrate at the OSB/building paper interfaces, which can cause localized moisture stresses and damage such as softening, swelling, delamination, and fastener pullout. Moisture is most likely to collect around wall openings. With stucco veneers, control joints—especially horizontal joints—can also collect and hold water, meaning cracks most often appear around windows, doors, and control joints first.[7]

Water moves through the pores of masonry from wetter to drier areas. If enough water stays in contact with the masonry long enough, it saturates the masonry by distributing itself throughout via capillary action. While the rate at which a masonry wall dries depends on temperature, humidity, wind, altitude, and sun exposure, a good rule is it takes about 30 days for water to move 25 mm (1 in.) in porous masonry. Since a scratch coat and the mortar used to hold the veneer are, together, normally close to 25 mm thick, adhered masonry walls without drainage and ventilation that are exposed to wetting events more than once every 30 days are unlikely to fully dry once the masonry becomes saturated.

Continuous insulation

Continuous insulation creates a high level of thermal resistance so heat will not easily move through the wall—a good thing for occupant comfort, but not so good for drying. In poorly insulated buildings, temperature differentials between the interior and exterior walls create a heat flow across the wall that warms moisture within it, in turn making the moisture move through the wall as vapour.

Combining this high vapour movement with lots of air leaks means the wall and veneer dry efficiently, because the vapour is carried away by the air movement. More-efficient insulation means less heat flow, and therefore less vapour movement. Compounded with the much-lower airflow inside today's relatively airtight walls, this makes for much less drying.

Claddings in cold climates operate at colder temperatures in a CI-insulated building, so if the cladding temperature is at or below the dewpoint, any water vapour that touches it will condense into liquid water more readily than if the cladding is close to the same temperature as an uninsulated substrate. Colder claddings also go through more freeze/thaw cycles and will freeze harder than warmer claddings, so water in the wall has the potential to cause more damage. Finally, OSB and plywood sheathings may increase in moisture content during heating periods as insulation efficiency rises, because conditioned warm air inside the building carries moisture that gets absorbed by the sheathing but cannot move past the insulation. Modern insulation approaches mean more moisture in the sheathing, more moisture in the masonry, and more trouble if it does not get out.

Drainage and ventilation

The best way to let both the masonry and the substrate dry rapidly between wetting events is to install a mesh drainage plane at least 7 mm (¼ in.) thick between the WRB and scratch coat. Canadian codes require a minimum 10-mm (3/8-in.) thick drainage plane.[8]

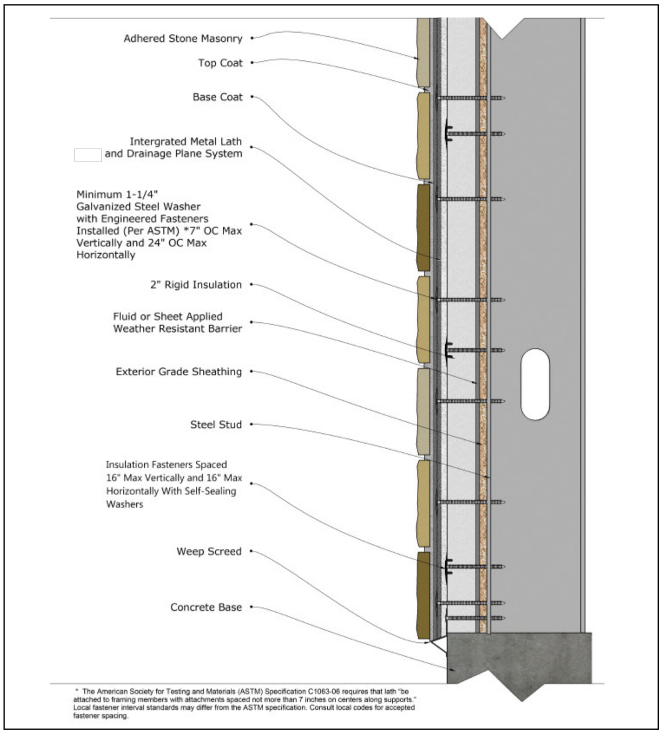
It may help to think of the drainage plane as serving the same function as the cavity in a masonry cavity wall—it allows water and air to move freely behind the veneer for both drainage and ventilation, and acts as a bond break to prevent mortar bridging so water cannot travel from the masonry to the substrate. It also helps eliminate localized water stresses on the sheathing and other components, because it allows moisture to migrate rapidly away from areas like wall openings and control joints. Further, a drainage plane allows water vapour to rapidly migrate from behind the veneer so hydrostatic pressure will not force it through small holes into the substrate, and allows masonry to dry from the back, so even if wetting events are frequent, the masonry can dry more quickly and avoid saturation.

A polyester drainage mesh with a factory-adhered water- and vapour- permeable fabric on one side is currently available in rolls of various nominal thicknesses. A system consisting of a 90 per cent open-weave mesh factory-assembled to a galvanized, G-60, 1-kg (2½-lb) expanded metal lath is also available, with variable thickness and weight.

Conclusion

A drainage plane between the veneer and substrate is not yet required by most North American building codes for adhered masonry. However, changes to building materials and construction methods are needed to meet more stringent energy codes and increase building sustainability, meaning the old ways simply do not work anymore. Further, modern building science has proven drainage planes can significantly reduce or eliminate moisture problems in adhered masonry veneer walls.

Twenty-five years ago, mortar-dropping collectors in masonry cavity walls were not part of code either, but as their value was demonstrated over and over, codes caught up, and now no mason or masonry designer would consider building a cavity wall without them. Drainage planes for masonry veneers are currently at the same stage as mortar-dropping collectors were then—quality builders are using them because they reduce problems and callbacks, and because they make the buildings that implement them a source of pride for both the builder and the designer. When codes catch up, everyone will benefit.



Adhered masonry wall detail with 50-mm (2-in.) rigid insulation and 7-mm (1/4-in.) mesh drainage plane.

Notes

[1] The author would like to give special thanks to Steven Fechino (engineering and construction manager for Mortar Net Solutions), Jim Lucas of Lucas and Associates, and Scott Wylie of Wytech Building Envelope Solutions for their invaluable advice and expertise.

[2] For more, read "The Sleeping Giant Awakes: NFPA 285," which is available at www.architectmagazine.com/technology/the-sleeping-giant-awakes-nfpa-285.

[3] More information is available in "BSI-057: Hockey Pucks and Hydrostatic Pressure," by Joseph Lstiburek. Visit buildingscience.com/documents/insights/bsi-057-hockey-pucks-and-hydrostatic-pressure.

[4] For more information, see Lstiburek's "BSI-029: Stucco Woes–The Perfect Storm," at buildingscience.com/documents/insights/bsi-029-stucco-woes-the-perfect-storm.

[5] The Foam Sheathing Coalition offers a "Guide to Attaching Exterior Wall Coverings Through Foam Sheathing to Wood or Steel Framing" with tables for determining the right fastener sizes based on stud type, insulation thickness, and veneer weight. Visit basc.pnnl.gov/resources/tech-matters-guide-attaching-exterior-wall-coverings-through-foam-sheathing-wood-or-steel.

[6] See Note 4.

[7] From "The Performance of Weather-resistant Barriers in Stucco Assemblies" by Karim Allana of Allana Buick & Bers Inc., presented at October 2016's RCI Symposium on Building Envelope Technology.

[8] See Note 4.