FAILURE OF THE BUILDING ENVELOPE: TWO CASE STUDIES

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ABSTRACT

Two case studies involving the failure of the building envelope are presented in this paper. Both studies concern rural hospitals located in the cold climate of the north central area of the province of Alberta, Canada. In the first case study the problems encountered were cracks in the brick veneer, efflorescence and staining, stucco delamination, inadequate masonry connectors, and an oversupply of air by the mechanical system. In the second study the problems included water penetration, decay of wood sheathing, corrosion of steel supports, deterioration of shingles, and staining of stucco. In both case studies the problems were the result of a combination of faults that occurred in the original design-construction process and the post-occupancy building operation. One consequence of these faults was major air leakage through the building envelope, which resulted in damaging condensation. Both buildings had been designed and constructed to rely on polyethylene film located on the interior of the structure as the air barrier element. This approach to airtightness was found to be ineffective for these buildings. A description of the remedial repairs that were designed and carried out on both buildings is also presented in the paper.

INTRODUCTION

This paper presents two case studies that illustrate the complicated nature of real-life building envelope problems and also shows how these problems were resolved in practice. It is hoped that the specific facts in these cases will be helpful to practitioners who may be confronted with similar problems and also to researchers, who may gain further appreciation for the difficulties encountered in actual building envelope problem resolution. A second purpose of presenting these case studies is to convey some experience with different approaches to airtightness in the building envelope.

Each study building suffered from a number of visible and hidden problems. The types of problems were different in both cases, and some of the problems observed in each individual building were found to be unrelated. While no indisputable causes for the problems emerged in either study, one common finding was that both buildings suffered from air leakage through the building envelope.

The details of the air leakage problems that will be presented support two general findings that have emerged through many building envelope investigations and repairs undertaken by Alberta Public Works (APW). These are as follows.

- A lack of airtightness may result in serious building envelope problems. This is particularly true for nonresidential types of buildings, which can be humidified and pressurized by a mechanical system.
- It is very difficult to achieve satisfactory airtightness in nonresidential types of buildings using the traditional residential approach of polyethylene film located on the interior of the structure.

After initial problem identification, the solution process in both studies proceeded in five phases:

1. field investigation,
2. analysis of problems,
3. preparation and consideration of remedial repair options,
4. production of remedial design drawings and specifications, and
5. remedial construction.

It should be noted that in both cases monetary, operational, and organizational constraints strongly influenced the solution process. The final remedial repairs that were adopted, therefore, cannot be considered ideal or totally comprehensive.

Both case studies involve rural hospitals located in north-central Alberta. The climate in this region is characterized by a heating season of about 6,100 degree-days Celsius and a 1% January design temperature of −38°C. Hospitals are among the most difficult of Alberta's buildings due to their requirements for high humidity.

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The complicated shapes of the buildings also invite difficulties.

CASE STUDY 1

Basic Construction

This 8,400-m^2 hospital constructed in 1982-1983 has a central service area two stories high and patient wings of one story. Windows are interior glazed, thermally broken aluminum frames with dual-sealed glazing units. Typical wall construction consists of

- — 12.5-mm gypsum board interior finish,
- — 6-mil polyethylene film,
- — 150-mm steel studs 400 mm o.c.,
- — 150-mm fiberglass batt insulation infill,
- — 12.5-mm exterior-grade gypsum sheathing,
- — 38-mm unfaced rigid fiberglass insulation,
- — 25-mm air space, and
- — 100-mm face brick with strip tie connectors.

A Portland cement stucco feature strip is located above the brick veneer in some areas with the same back-up wall described above. The stucco system consists of building paper, metal lath, stucco base coat, and an acrylic finish coat.

The roof is nearly flat and is shown in the original drawings as

- — metal deck,
- — 12.5-mm gypsum board,
- — vapor barrier (unspecified),
- — 90-mm rigid insulation (unspecified),
- — 25-mm wood fiberboard overlay,
- — 4-ply built-up asphalt and felt membrane, and
- — gravel protection course.

Figure 1 shows typical wall sections and elevations as shown in the original architectural drawings.

Building Envelope Distress

By 1989, six years after completion of the building, several defects in the building envelope had become apparent to the maintenance staff.

- Large cracks had formed in the brick veneer surrounding many of the windows. The crack formation process appeared to be accelerating.
- There were stains and efflorescence on the brick veneer.
- Portions of the exterior stucco were cracking and delaminating. This had already caused the hospital to replace several stucco panels.

Preliminary investigations by the staff and the design architect were unable to establish the cause of the defects and in 1992 the hospital asked an APW for help in resolving the problems.

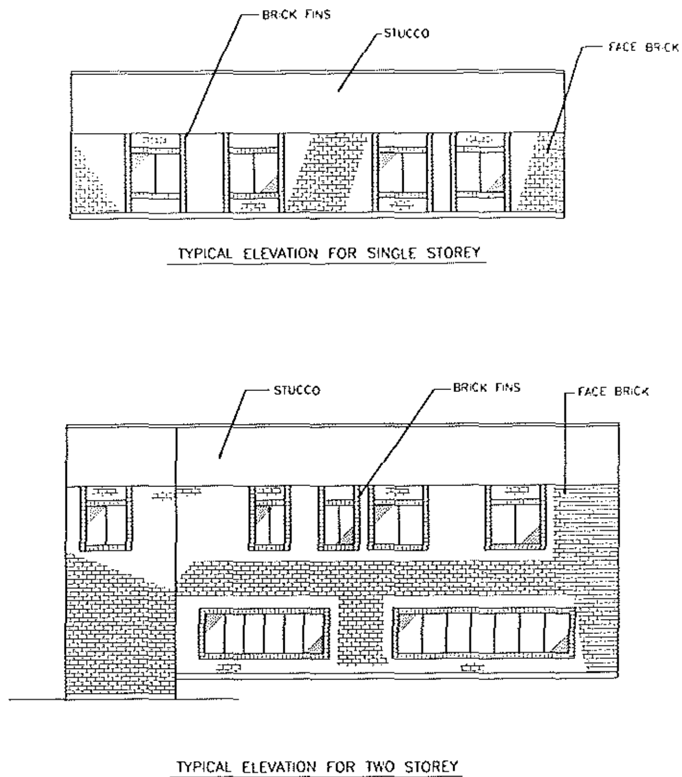

Figure 1 *Case study 1, typical elevations.*

Investigation

A survey of the condition of the exterior walls was conducted with the assistance of a private masonry consultant. In addition to overall survey drawings showing the extent of the defects, a number of test openings were made in the walls to determine specific construction details. Air leakage tests were also conducted using a smoke generator and smoke pencils. When the presence of air leakage became apparent, the performance of the air-handling system was also examined. The results of the investigation were as follows.

- A visual survey indicated that cracking in the brick veneer was severe but was confined to the vertical built-out window surrounds or "fins." In the worst cases, the cracks extended over the full 2,400-mm height of the fins and were up to 6 mm in width. The severity of the cracking raised safety concerns about falling brick fragments, particularly from the two-story section.
- Brick fragments that were removed from the fins revealed severely corroded steel reinforcing bars located in the cores of the bricks.
- Twelve mortar samples were removed from the fins and tested for water-soluble chloride ion content. In 10 of the samples, the chloride ion content exceeded the limit of 0.15% by weight of cementious material stipulated in Canadian Concrete Design Standard

CSA CAN3-A23.3-M90. Some samples had chloride ion contents as much as seven times higher than the allowable limit.

- Test openings were made to inspect various metal components in contact with the mortar. Painted lintel angles and galvanized sheet steel flashings were in good condition; however, some corrugated steel strip tie masonry connectors were beginning to corrode. The test openings also suggested that the connector installation was not in accordance with the basic building code requirement of a 400-mm by 600-mm spacing. Further inspections showed that these connectors were either improperly installed or missing altogether.
- Test cuts exposing the inner wall did not reveal any corrosion on the steel studs or deterioration of the exterior sheathing.
- Soiling and staining were found on the brick veneer. The soiling occurred on sloped brick ledges located along the top of the veneer and below windows. Light-colored stains occurred on bricks located below several stucco panels that had been replaced in 1989 due to delamination.
- Efflorescence, in the form of a loose white powder on the surface of the bricks, was observed in many isolated patches distributed around the building. Tests were conducted on typical brick units in accordance with CSA Standard CAN3-A82.2-M78. This test visually rates bricks into three categories, depending on the amount of efflorescence visible on the brick after soaking in a tray of water for seven days when compared to a similar brick not exposed to water. These categories are "not effloresced," "slightly effloresced," or "effloresced." The study bricks were rated "effloresced," meaning they had sufficient salts present to cause visible efflorescence.
- Air leakage paths through the building envelope assembly were identified in a number of locations using smoke. These included paths around windows, at the floor-to-wall joint, at the wall-to-roof intersection, and through soffits. In all cases the air appeared to be leaking out of the building at a substantial velocity, suggesting an oversupply of air by the mechanical system. A spot measurement across an exit door indicated a pressure difference of +25 to +30 Pa. Some of the leakage paths corresponded to thermal anomalies identified in an infrared thermography report commissioned earlier by the hospital. Figure 2 illustrates some typical air leakage paths.
- Measurements made on the air-handling system by APW's mechanical engineer showed that system control problems were causing substantially more air to be supplied to the building than was being exhausted. The amount of oversupply varied between 1,500 L/s and 10,000 L/s, depending on cooling requirements. It was concluded that this oversupply of air was exfiltrating through the building envelope. During typical operating conditions it was estimated that the oversupply represented 20% to 30% of the supply airflow rate. This was considerably more than the 10% usually expected for this type of building. Hospital operating records from previous years showed that the interior relative humidity had fluctuated between 25% and 45% during the heating season.
- A number of test cuts were made into the stucco in the vicinity of cracking and delamination. The stucco base coat was roughly 18 mm thick and was solid and uncracked. Defects appeared to be confined to the acrylic modified finish coat. The finish coat was approximately 3 mm thick and contained numerous microcracks. In the delaminated areas it had separated cleanly from the base coat.

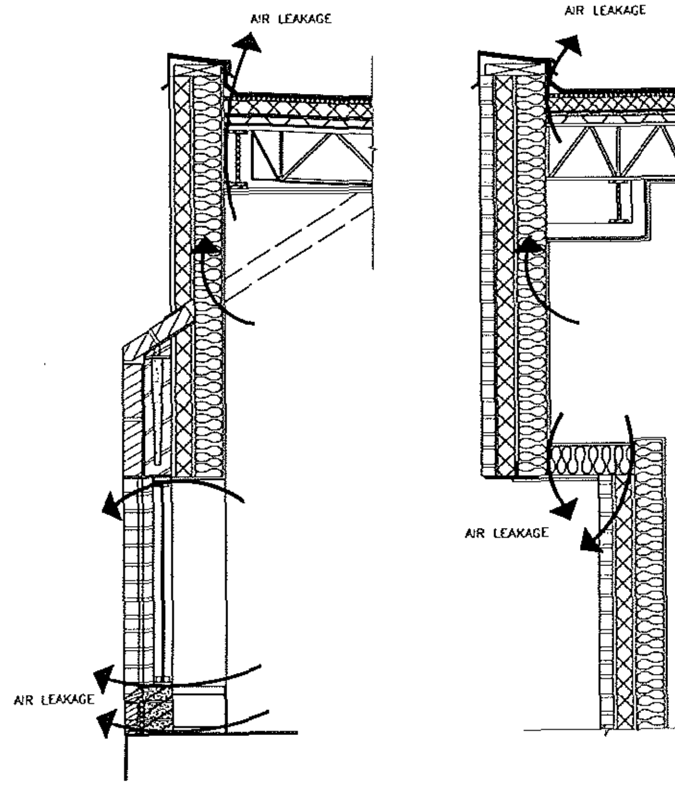

Figure 2 Case study 1, typical air leakage paths.

Analysis

It was concluded that the cracks in the brick veneer were due to corroding reinforcing steel. A similar phenomenon has been studied extensively in reinforced concrete bridge decks and parking structures contaminated by chlorides contained in deicing compounds (Erlin and Hime n.d.). The chlorides depassify the steel, allowing it to corrode in the presence of water and oxygen, thus producing rust, which expands and splits the surrounding matrix. In this particular building, the source of the soluble chlorides was probably calcium chloride deliberately added to the mortar mix in order to prevent the fresh mortar from freezing during winter construction. It is interesting to note that the contract documents contained a specific clause prohibiting this practice. Rain, melting snow from horizontal surfaces, and condensation from air leakage could all have contributed the moisture required to cause the corrosion.

The occurrence of improperly installed and missing masonry connectors was so extensive that it was apparent the brick veneer was not receiving the lateral support required by the Alberta Building Code. Construction records were never obtained for the original project, so it is not known what, if any, inspections were carried out during the construction of the brick veneer. An engineering analysis was conducted to determine the maximum spacing permitted for retrofit connectors to meet code requirements. Any contribution from existing connectors was discounted in the analysis.

The cause of the cracking and delamination of the stucco acrylic finish coat could not be determined with certainty. Due to the large number of microcracks, resembling shrinkage cracking, it was speculated that the surface coat may have been improperly mixed and applied. This resulted in a poor bond to the base coat. Condensation created by air leakage within the wall system may have contributed to the delamination. The condensate may have passed through the permeable base coat and accumulated behind the less permeable finish coat, where it froze and delaminated the coating.

Soiling of the brick veneer was attributed simply to airborne dust and dirt accumulating on sloped brick surfaces. It is for this reason that sloping brick surfaces are usually discouraged in design.

Discussions with staff suggested that the light-colored staining below the stucco replacement panels was caused by leaching of the fresh acrylic stucco coloring. Apparently the contractor had not provided weather protection and a chance rain had washed some of the uncured acrylic material onto the bricks below.

The patches of efflorescence observed on various portions of the brick veneer appeared to correlate with areas where air leakage paths had been identified. It is believed that humid interior air leaking through discontinuities in the envelope assembly created condensation on the brick and that this condensate moved through the bricks, leaving visible salt deposits at the surface when it evaporated. The source of the salts was the brick itself, as demonstrated by the efflorescence tests, which showed that this type of brick was susceptible to efflorescence.

A review of the architectural drawings showed that the original design intent was to provide a continuous air barrier by the use of polyethylene film on the interior of the structure. APW's experience with this method of air sealing in nonresidential types of buildings has been that the expected level of airtightness is usually not achieved (see "Discussion"). Serious condensation within the building envelope is one possible consequence of air leakage resulting from a lack of airtightness. Fortunately, in this particular building, damage to the inner wythe of the walls was not observed. The bulk of the condensation appeared to have occurred after the interior air had passed through the inner wythe, forming on the back of the outer wythe of brick. While this resulted in efflorescence on the brick, moisture damage to the wall appeared to be minimal.

Remedial Repairs

After the investigation and analysis phases of the work were completed, an architectural consultant was retained to prepare the design documents for remedial repairs.

It was concluded that the brick fins could not be stabilized or repaired due to their advanced state of deterioration and that, in the interest of public safety, the fins would have to be demolished. Due to cost considerations, it was decided not to rebuild the fins out of brick but to replace them with galvanized structural steel columns covered by wood and a sheet-metal cladding. With the careful use of hand tools and shoring it was possible to demolish the fins with a minimum of disturbance to surrounding construction. The new steel columns were bolted to the concrete floor slabs and welded to lintel angles. Wood was used to frame around the columns, and metal cladding was then installed over the wood. Figure 3 shows the implementation of typical remedial repairs.

Since the existing connector spacing did not meet Alberta Building Code requirements, retrofit masonry connectors were installed at a spacing of 600 mm by 800 mm. An engineering analysis showed this was the maximum practical spacing that satisfied strength and deflection criteria. The new connectors were a proprietary product consisting of an adjustable V-shaped rod and L-shaped plate, both made from galvanized steel. In order to place each new connector, a single brick was broken out and the connector was then fastened to the inner wythe, as shown in Figure 4. A new brick and mortar was then installed. Approximately 4,000 connectors were used in the repair.

Because the delamination and cracking of the stucco was confined strictly to the thin surface coat, the problem was basically one of appearance. It was expected that delamination would continue to occur in the future. Rather than replace the stucco, it was decided to remove all loose-finish coat and to cover the stucco with metal siding supported on steel Z-girts fixed to the existing backup wall, as shown in Figure 4.

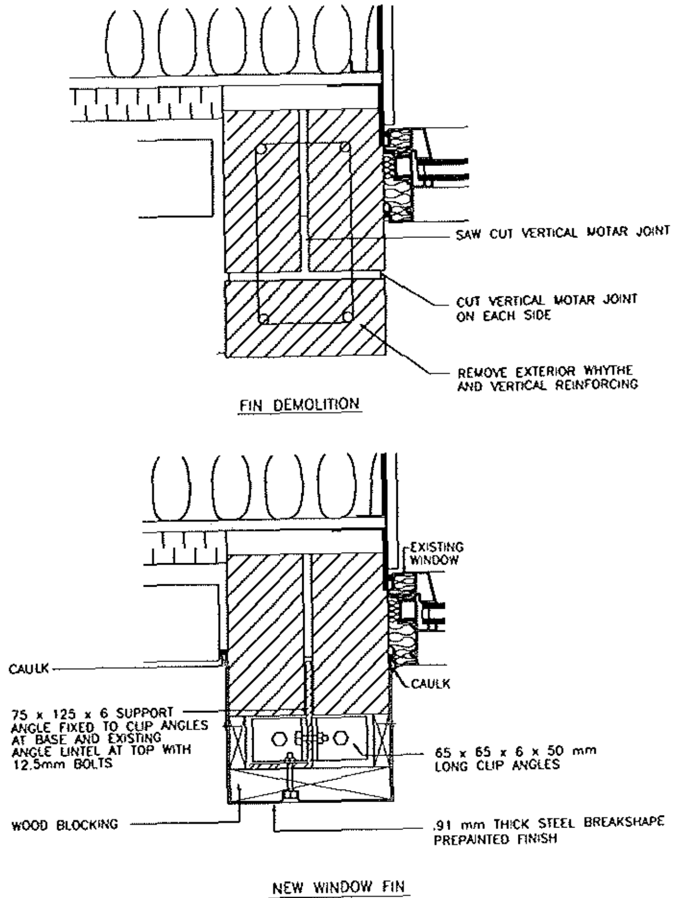

Figure 3 Case study 1, remedial repairs to brick fins.

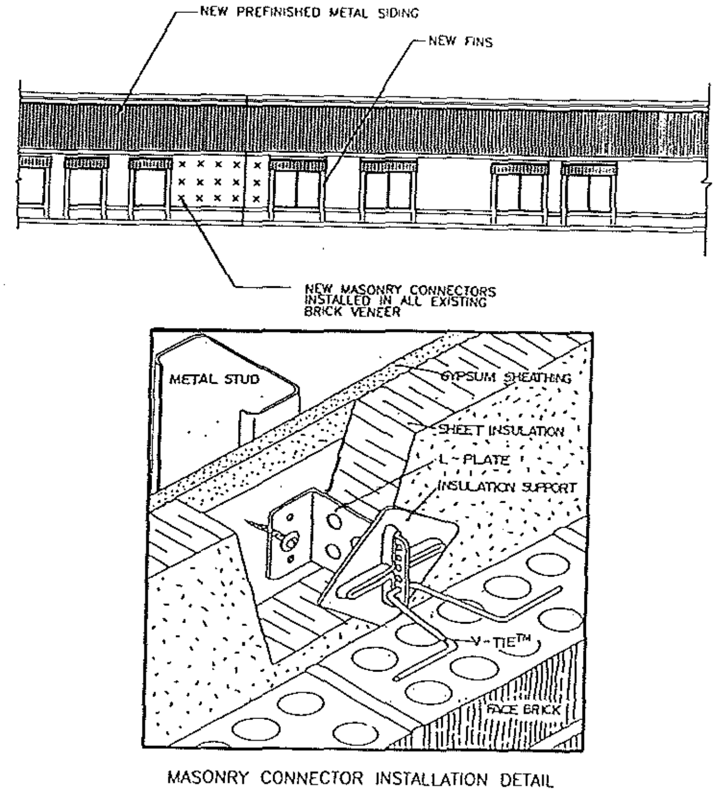

Figure 4 Case study 1, remedial repairs to veneers.

Although air leakage was likely a contributing factor to the previously discussed problems, the provision of a continuous air barrier through remedial repairs was judged to be too expensive and disruptive for this project. Therefore it was decided to reduce the severity of the air leakage problem by reducing the oversupply of air by the building mechanical system. A mechanical engineer assessed the existing air-handling control system and concluded that the flow control system required calibration and that the return fan pitch control should be repaired. As a result of these recommendations, the oversupply air problem was corrected; however, other issues have resulted in the complete replacement of the existing control system with a new building automation system. The installation of the new system is currently under way. To reduce moisture loads, the relative humidity will be limited to minimum acceptable levels during the winter. It is expected that these measures will improve the performance of the building envelope. It is intended to carry out surveys at three-year intervals to monitor the condition of the building envelope and to assess the effectiveness of the remedial repairs.

The total cost of repairs was approximately $250,000 (Canadian). Disruption to occupants was minimal.

CASE STUDY 2

Background

This hospital is approximately 2,800 m^2 in floor area and was constructed in 1982. The building consists of single-story nursing wings with sloped roofs attached to a two-story central service core with near-flat roofs. Sloped glazing, which provides skylighting, is located along one side of the core. Typical exterior wall construction consists of

- 16-mm interior gypsum board,
- 6-mil polyethylene film,
- 100-mm steel studs at 400-mm o.c.,
- 100-mm fiberglass batt infill insulation,
- 12.5-mm exterior gypsum sheathing,
- 50-mm rigid insulation with 50-mm Z-bars, and
- 19-mm rock dash stucco on wire lath.

The majority (85%) of the roof consists of 4 in 12 sloped roof constructed as follows:

- 38-mm metal deck,
- 12.5-mm gypsum board,
- 6-mil polyethylene film,
- 150-mm steel channels at 600-mm o.c.,
- two layers of 75-mm extruded polystyrene insulation,
- 19-mm fire-retardant treated plywood,

— polyethylene film ice dam protection at roof edge, and
— asphalt shingles.

The remaining 15% of the roof consists of a near-flat modified protected roof constructed as follows:

— 38-mm metal deck,
— 12.5-mm exterior-grade gypsum sheathing,
— two-ply asphalt felt vapor barrier,
— 100-mm extruded polystyrene insulation,
— four-ply BUR asphalt felt membrane,
— 50-mm extruded polystyrene insulation,
— filter fabric, and
— rock ballast.

The sloped glazing consisted of exterior-glazed, dual-sealed glazing units with aluminum framing. The framing appeared to be an early model of an overlapping double-drained system.

Figures 5 and 6 show typical elevations and wall sections from the original architectural drawings.

Building Envelope Distress

In 1993, 11 years after construction of the hospital, APW was asked to investigate several ongoing problems with the building envelope:

- Ice damming on the sloped roofs and subsequent water leakage into patient rooms.
- Deterioration of asphalt shingles and apparent "sponginess" of the plywood deck.
- Dark brown stains on stucco fascias and soffits.
- Water leakage and excessive solar heat gain associated with the sloped glazing.

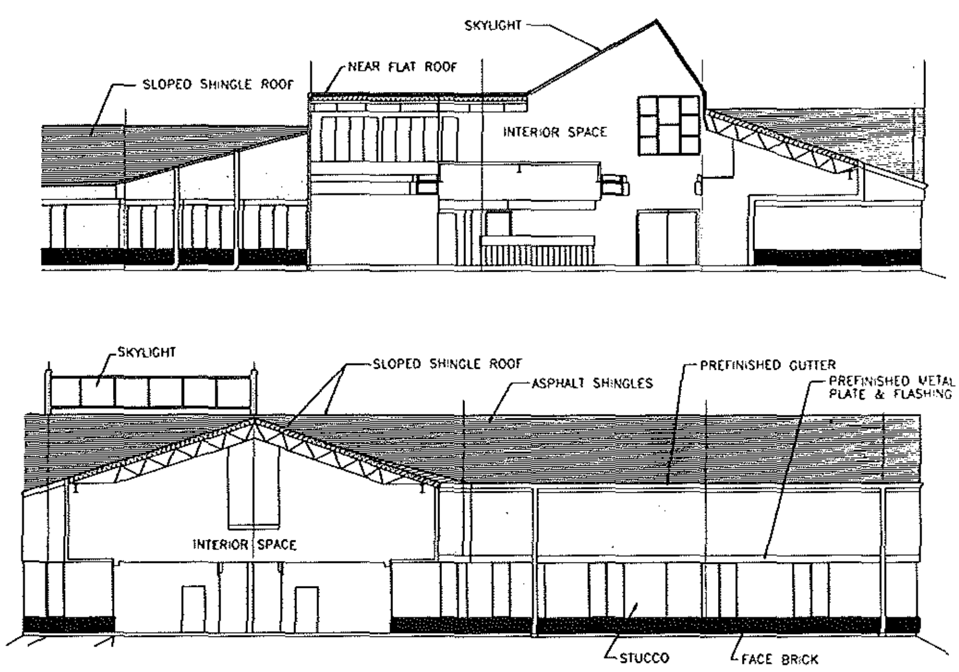

Figure 5 Case study 2, typical original elevations.

Investigation

After a preliminary investigation by the utility, a private consultant was commissioned to carry out a detailed investigation of the hospital's building envelope. The results of the investigation were as follows.

- Asphalt shingles were in poor condition, displaying curling, cracking, and granule loss.
- The steel C-channels contained in the sloped roof structure were severely corroded in several locations where test cuts were made. In some cases, the flanges of the channels in contact with the plywood sheathing had completely deteriorated. Other metal elements, such as nails, screws, and drip edge flashings, were also corroded.
- The plywood sheathing was wet and deteriorated in some locations. However, in many other places the plywood was stiff and dry but appeared discolored. It was not obvious whether the strength of the sheathing in these locations had been affected.
- When portions of the sloped glazing were disassembled it was found that the perimeter was not adequately connected to the adjacent wall and roof construction. This resulted in large air and water leakage paths at these locations. Water stains were also noted on interior finishes below the sloped glazing system and on the system's aluminum mullions. It was also evident that various sealants had been applied to the exterior pressure plates over the years in an attempt to exclude water from the system.
- Nursing staff reported that at times heat gain in the area of the sloped glazing created almost unbearable conditions in the interior spaces below.
- Air leakage testing using smoke identified numerous air leakage paths through the building envelope. Leakage paths locations included
  — wall to flat roof junctions,
  — wall to sloped roof junctions,
  — skylight to wall and roof junctions,

— peaks of sloped roofs,
— soffits, and
— around windows and baseboards.

Figure 6 shows some of the air leakage paths that were identified.

- A spot measurement of the air pressure difference across an exit door was about +25 Pa. Hospital records obtained for the previous winter showed that the relative humidity was maintained at a level of about 35%.
- Test cuts and water tests were unable to identify external water entry locations in the sloped roofs. Although the physical appearance of the shingles was not good, they proved to be functioning as a satisfactory water-shedding element.
- Test cuts made into the near-flat roofs showed that water had been draining from the skylights underneath the four-ply BUR membrane and had saturated the upper layer of wood fiberboard insulation.
- The source of the stains on the stucco appeared to be from the roof above. The condition of the walls was otherwise good.

Analysis

- Laboratory tests were made on samples of the plywood sheathing to determine how the strength of the plywood had been affected. The tests showed a dramatic loss in strength for samples that were obviously wet and deteriorated. These are designated A—Heavily Decayed—in Table 1. Tests on samples of plywood not so obviously deteriorated but probably representing the condition of much of the sheathing also showed a significant loss of strength. These are designated B—Decayed—in Table 1.
- The severe loss of strength of the sheathing and the corrosion of metal elements in the sloped roof was probably related to a combination of moisture- and fire-retardant chemicals contained in the plywood. The plywood had been saturated, and over a long period this allowed acids to be released from the fire retardant. The lack of venting under the sheathing probably raised the temperature of the sheathing, which accelerated the process. It was the acids that deteriorated the plywood and promoted corrosion of the steel members.
- It is probable that the main source of moisture that destroyed the sloped roof was condensation due to humid interior air exfiltrating through the roof structure during cold weather. Compounding this problem was the fact that there was no venting space provided below the plywood, thereby eliminating any potential for outside air to dry out the roof system. In some areas, leakage from the sloped glazing or ice damming at the eaves may also have been a moisture source; however, the deterioration of the sheathing was far too widespread for these to be considered major sources of moisture. Further corroborating evidence for air leakage as the primary moisture source was found later during the remedial repair work. When the decayed sheathing and insulation were removed, exposing the sloped roof deck, workers reported seeing large amounts of "steam" rising from various discontinuities in the undisturbed polyethylene film.
- A review of the original contract documents showed that the design intent had been to create a continuous air seal on the interior of the building using polyethylene film. A strip of butyl rubber sheet was substituted for the polyethylene film at transitions to skylights, windows, the end of metal decks, eaves, and parapets. The exact reasons for the use of the butyl rubber are not known; however, it may be that the designer felt that this material would be less likely to be damaged at these vulnerable locations. The contract documents are not clear on how the polyethylene film and butyl rubber sheets are to be sealed together.

The project specification section for batt insulation called for the polyethylene sheets to be tape sealed at all laps, but the tape is not specified. The specification for rigid insulation called for the polyethylene sheets to be sealed at all transitions and laps with polyethylene tape.

TABLE 1A Work Plan for Testing of Plywood Samples

Test Method	Property	Sample Replications: A Heavily Decayed	B Decayed	C Control
ASTM D1037 Modified	Modulus of Rupture(MOR)	3	3	3
ASTM D1037 Modified	Modulus of Elasticity(MOE)	3	3	3
CSA 151 Modified	Wood Failure	6	6	6
CSA 151 Modified	Max. Shear Strength	6	6	6
CSA 325 Modified	Density at Test	3	3	3
CSA 325 Modified	Moisture content at test	3	3	3

TABLE 1B Mean Values of Test Results on Plywood Samples

Property	A Heavily Decayed	B Decayed	C Control
MOR (MPa)	3.2	8.9	28.8
MOE (MPa)	300	2900	2300
Wood Failure (%)	–	40	97
Shear Strength (MPa)	–	0.076	0.37
Density (pcf)	464	576	464
MC (%)	8.9	8.8	12.1

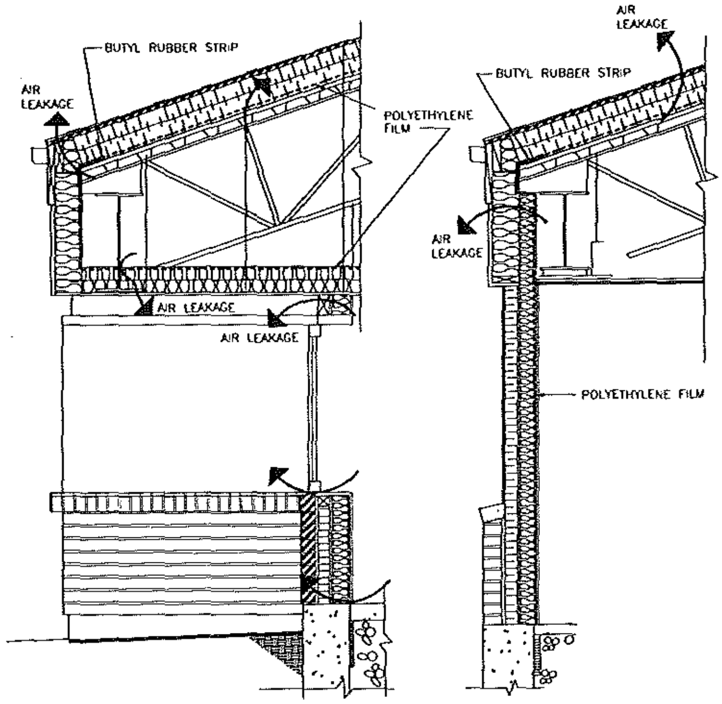

Figure 6 *Case study 2, typical existing wall sections.*

- Laboratory tests indicated that the stains on the walls and soffits below the sloped roof were due to leaching of organic compounds produced by the decaying plywood.
- A combination of poor design and poor workmanship created a discontinuity at the sloped glazing to flat roof junction. In this connection, the plane of the internal drainage channel in the skylight was below the butyl rubber flashing, making proper drainage impossible. Water leakage under the roof waterproofing membrane saturated portions of the underlying insulation.

The specification section for the butyl rubber sheet called for butyl caulking at all laps, joints, and interruptions. In the actual as-built construction, no attempt was made to seal laps, joints, or interruptions in the polyethylene and butyl materials or at transitions between the two materials. There were no construction records available describing the inspection of the air barrier.

While the polyethylene film and butyl rubber sheet were not installed as specified, this cannot be considered the only reason why effective airtightness was not achieved. It is unlikely whether the system could actually be constructed as required by the contract documents. Furthermore, the ability of the specified system to function as an effective air barrier is questionable due to the inability of unsupported polyethylene to sustain design wind loads (see "Discussion").

Figure 6 illustrates the problem of constructing a continuous air barrier on the interior of the structure due to interference by structural members. For example, the connection between the polyethylene film and the butyl rubber sheet at the end of the deck would have been extremely difficult to execute since it is located between the spandrel steel beam and the steel studs. Note that joist hangers as well as the spandrel beam itself interfere with the continuity of the air barrier.

Figure 6 also shows the polyethylene film in a completely unsupported condition on the soffit and at the end wall. In such a condition, the film could not resist even moderate wind loads. In the as-built construction the polyethylene sheets were simply laid loosely over batts of fiberglass insulation and served no air barrier function at all.

- Ice damming at the roof edges was caused by the melting of snow high up on the roof and refreezing at the cold roof edge. Melting may have been increased by the heat provided by air leakage and thermal bridging of steel C-channels through the insulation.
- The poor condition of the shingles was likely due to a combination of moisture buildup in the roof sheathing and elevated temperatures due to a lack of venting under the sheathing.
- The precise cause of water leakage that occurred directly through the sloped glazing was not determined. Previous experience with systems of a similar age and design suggested that a permanent solution would be difficult to find.

Remedial Repairs

The deterioration of the plywood roof sheathing and steel C-channels was so severe that these components had to be removed along with the overlaying shingles. The existing steel deck and the majority of the gypsum board substrate were in satisfactory condition. A new sloped roof was constructed as shown in Figures 7 and 8. It consisted of

— existing steel deck,
— existing 12.5-mm gypsum board (reused where possible),
— 3-mm styrene-butadiene-styrene (SBS) modified asphalt membrane (thermofusible),
— existing 150-mm extruded polystyrene insulation, (reused)

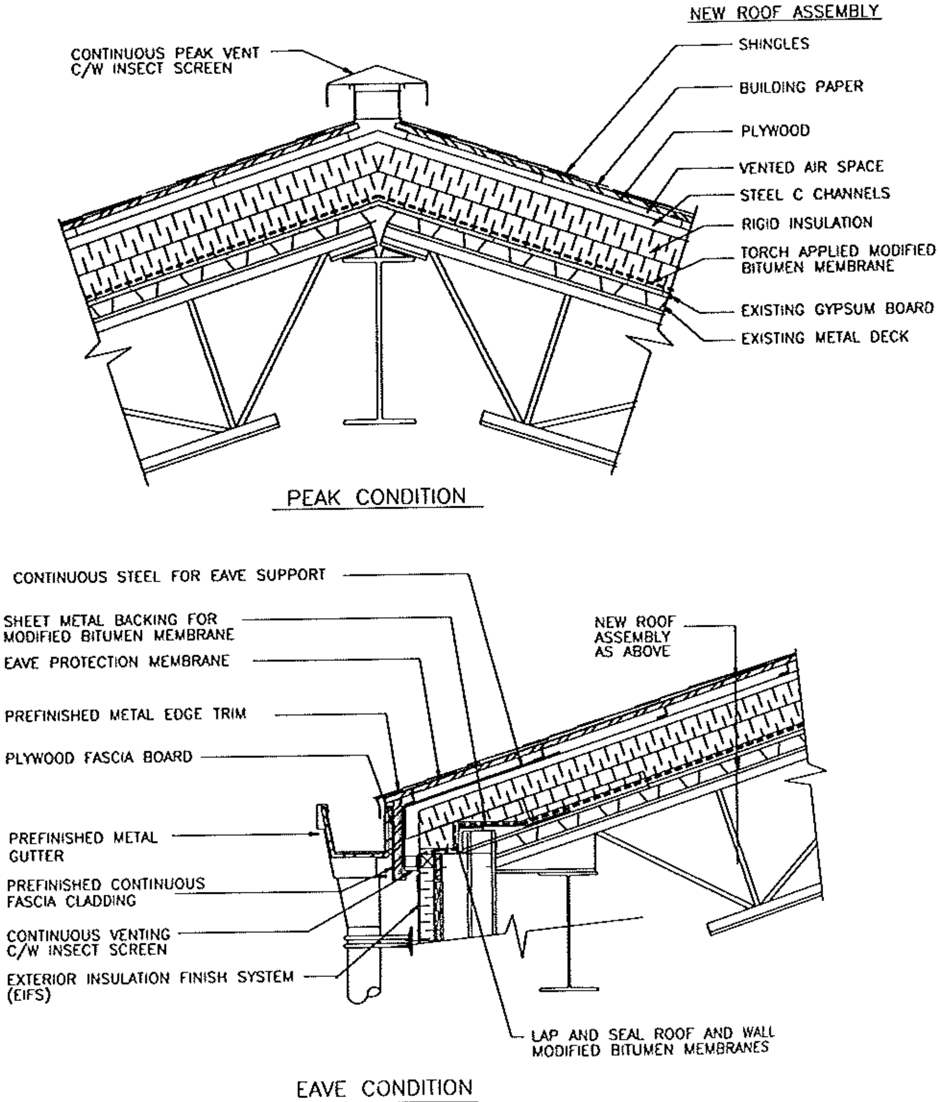

Figure 7 *Case study 2, new sloped roof design.*

— 180-mm steel Z-girts at 400-mm o.c.,
— 25-mm metal subgirts,
— 30-mm vented air space,
— 19-mm plywood sheathing (not treated with fire retardant),
— building paper, and
— asphalt shingles.

The SBS-modified membrane functions primarily as an air and vapor seal but also serves as a waterproofing element should any water pass through the shingles due to ice damming or flaws. At the roof edge, the SBS membrane was extended down and over the stucco fascia. The fascia was then covered by a mechanically fastened exterior insulation finish system (EIFS).

The vented air space below the new plywood sheathing was intended to help remove any condensation forming in the roofing system. Originally a system of thermally broken double Z-girts was proposed to create the venting space. However, due to cost and design considerations, a single 180-mm-deep thermally unbroken Z-girt was finally specified.

As described previously, since the existing wall system did not provide an effective air barrier, ideally the new SBS membrane would have been extended the full height of the wall to totally encapsulate the building, insulated on the exterior in accordance with the "outside air seal" approach to envelope design (see "Discussion"). However, since the existing wall system appeared to be currently in satisfactory condition and since funding for this project was limited, it was decided to stop the repairs at the fascia level. Some interior air sealing of easily accessible elements such as baseboards and windows was implemented in order to reduce air leakage. A review of the mechanical system operation to minimize building pressurization and to limit humidification to minimum acceptable levels was also commissioned. The results of the review were not available at the time of writing.

A review of the Alberta Building Code and discussions with Building Code officials revealed that the new sheathing did not have to be treated with a fire retardant. It is unfortunate that this was not recognized during the original design.

The exact cause of water penetration through the sloped glazing system was not determined. However, previous experience with similar systems suggested that an effective long-term repair would be hard to achieve. Furthermore, the large area of sloped glazing made dealing with the solar heat gain problem difficult. For these reasons it was decided to remove the sloped glazing and replace it with a limited area of clerestory windows. The window system selected was an exterior glazed aluminum box section as shown in Figure 8. These windows are pressure equalized and drained in accordance with the "rainscreen" principle and lend themselves to mechanical attachment of the SBS membrane, thereby

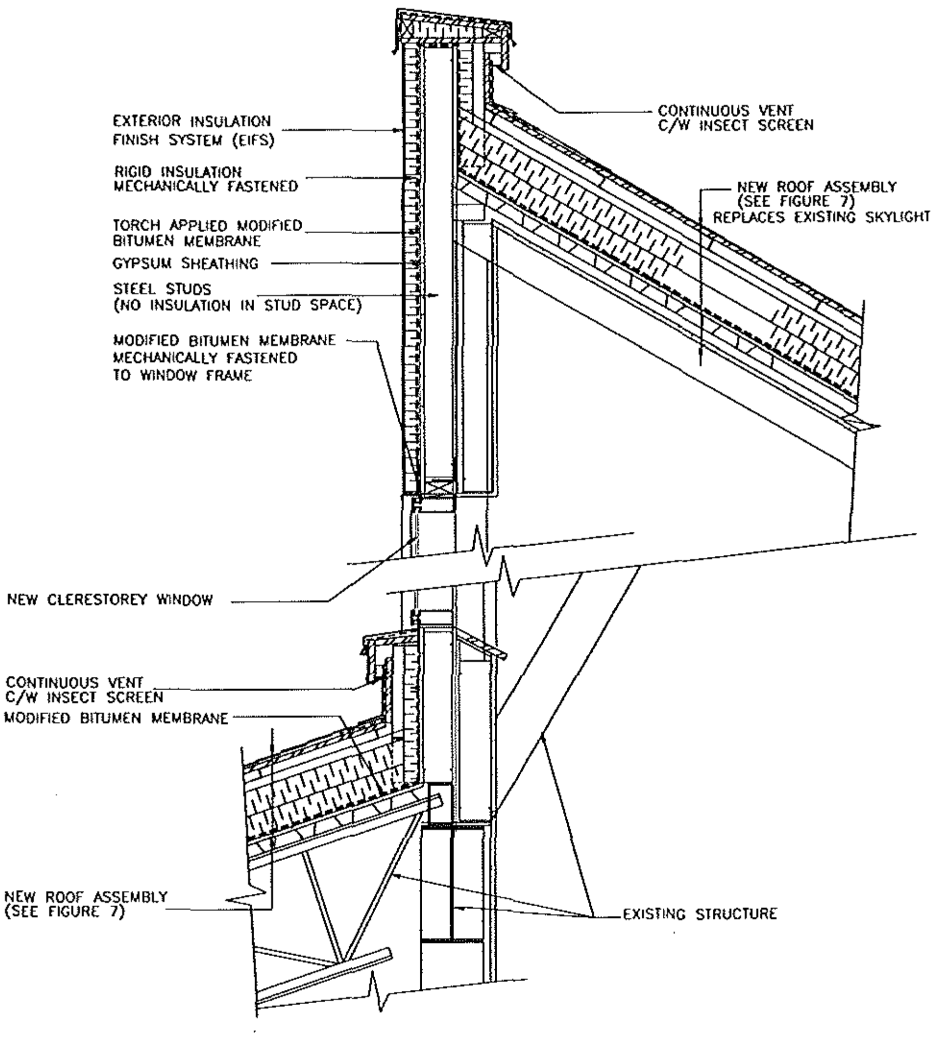

Figure 8 *Case study 2, new clerestory windows and sloped roof.*

ensuring continuity of the air seal. Such a system has been used with good success by APW many times in the past.

Two small near-flat roof areas that had been saturated with water due to the improper tie-in with the sloped glazing were replaced with a conventional two-ply SBS roofing system.

The total cost of repairs was approximately $550,000 (Canadian).

DISCUSSION

Uncontrolled air leakage has numerous detrimental effects on the performance of the building envelope (Handegord n.d.). One of the most serious effects is the deposition of moisture within the building envelope assembly (NBCC 1990). The field investigations described in this paper showed that both case study buildings were constructed with ineffective air barriers. In case study 1, the problems created by air leakage were probably secondary in nature to serious structural problems with the brick veneer; however, in case study 2, air leakage was directly implicated in the deterioration of a sloped roof.

It has been APW's experience that airtightness is difficult to achieve in a nonresidential type of building utilizing polyethylene film located on the interior of the structure. The difficulties with this approach are threefold. First, the physical properties of the polyethylene material make it both hard to seal to itself or to any other material. Second, the material is unsatisfactory to resist design wind loads in an unsupported condition (Brand 1990; Perreault n.d.; Quirouette n.d.; Shaw n.d.; CMH n.d.). Finally, the location of the plane of airtightness on the interior of the structure makes continuity of the air seal difficult to achieve in practice (NRCC n.d.; Quirouette n.d.). Leakage paths often occur at locations such as windows, soffits, roof edges, and areas where structural elements pass through the plane of the air seal. When combined with long-term positive air pressures created by the mechanical system and high relative humidities often demanded by occupants, it is not surprising that significant condensation can occur in the wall system.

One successful approach used by APW to create an effective air barrier in nonresidential construction is the so-called "outside air seal" approach. This is not to be confused with air sealing outside the insulation. "Outside" in this context means that the air barrier is located on the exterior surface of an uninsulated inner wythe of the building structure. In this location, interference in the continuity of the air barrier by major structural elements is avoided. The air barrier consists of a membrane applied to a stiff substrate capable of resisting design wind loads, such as masonry or properly supported gypsum board. The membrane material most often used by APW is thermofusible SBS-modified bitumen; however, other materials, such as self-adhering SBS-modified membranes, have also been used with success. The position of the membrane on the exterior of the structure assists in the installation and inspection processes. Rigid insulation is held tight against the membrane by me-

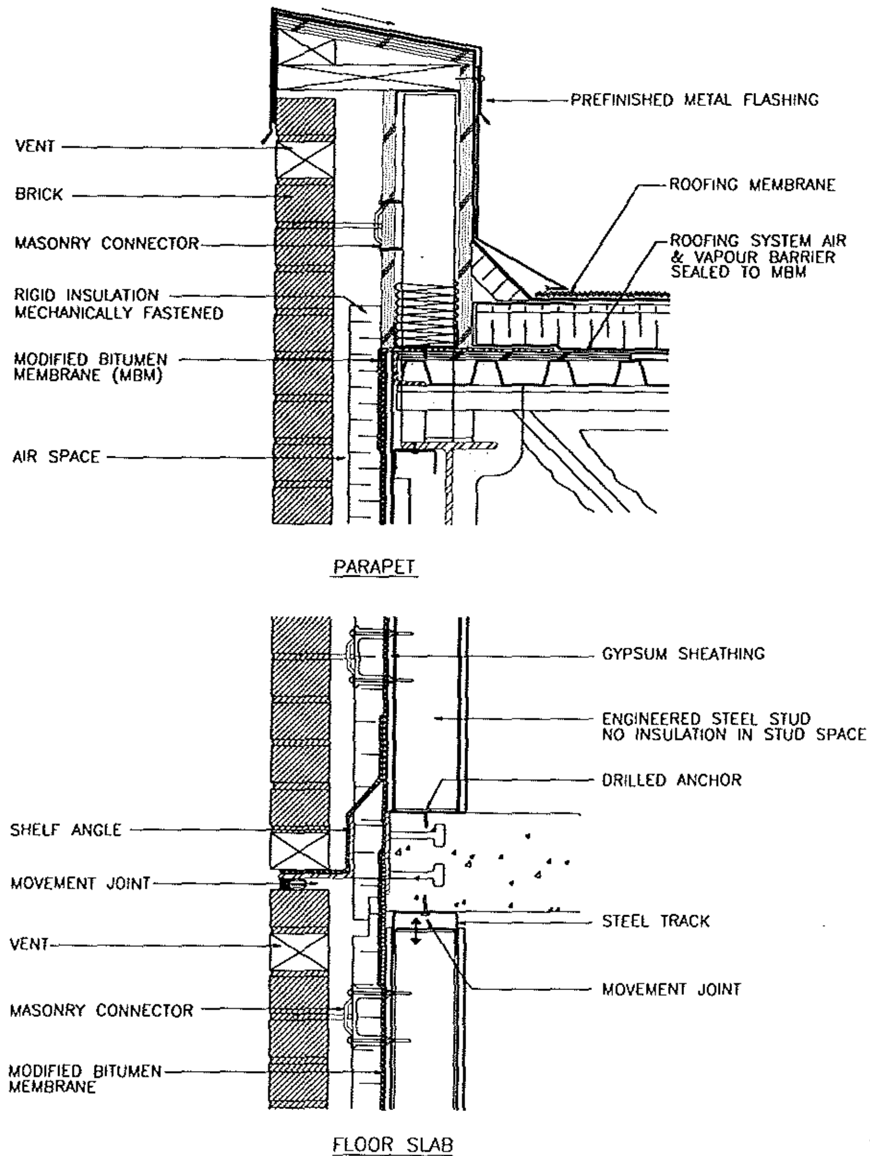

Figure 9 *Typical outside air seal details.*

chanical fasteners, and a vented air space and rain-shedding cladding element such as brick veneer or metal siding is then installed. Besides providing a high degree of airtightness, this assembly meets the requirements of the "open rainscreen" principle, which has been shown to successfully control rain penetration (Garden n.d.). Another benefit of this approach is that it provides a weatherproof enclosure at an early stage in construction, and, since the immediate installation of exterior cladding elements is not required for weather protection, critical air barrier connections such as roof-to-wall joints can remain easily accessible for execution and inspection.

Figures 9 and 10 show typical wall sections utilizing the outside air seal approach. Note that the use of the exterior glazed box-section type of window frame permits the membrane to be clamped securely to the frame. The figures also illustrate another advantage of the system: should any flaw occur in the air barrier, condensation created by escaping air will form in the exterior cavity outside the plane of the membrane. The exterior cladding elements, such as galvanized metal or brick, which might be affected by this condensation are generally resistant to moisture damage. Contrast this to the situation in which air leakage occurs through polyethylene film in a traditional construction approach. In this case, the plane of condensation will likely be the interior surface of the exterior sheathing. Condensation at this location may then adversely affect elements of the wall construction not normally expected to be in contact with water. Deterioration of the sheathing and wood studs or corrosion of steel studs may occur. A final benefit of the outside air seal approach when applied to a stud type of wall is that the stud space is free of insulation and can be used to carry electrical or mechanical services without concern for penetrating the air barrier.

Some of the objections raised to the outside air seal approach include the cost of the membrane material, the additional wall thickness caused by the location of the insulation on the exterior of the stud space, and the extra cost of rigid insulation vs. batt insulation. Also, there is often a natural reluctance by designers and contractors to adopt an unfamiliar construction system. While these concerns may have some merit, we feel that the benefits of the outside air seal approach far outweigh the concerns.

CONCLUSIONS

The case studies presented in this paper represent two complex building envelope investigations by APW. The study buildings were moderate-sized rural hospitals. In both cases, investigators were confronted with a number of different but possibly related problems with the building envelope.