Seventh Canadian Masonry Symposium
McMaster University
Hamilton, Ontario June 4-7, 1995

PERFORMANCE MONITORING OF A BRICK VENEER/STEEL STUD WALL SYSTEM

Jacques Rousseau[1], Heinz Keller[2], and Steven Laviolette[3]

ABSTRACT

The widespread use of brick veneer/steel stud (BV/SS) wall systems over the last 20 years has preceded the development of adequate design and construction standards. As a result, concerns have arisen in the construction industry over the long-term safety, serviceability and durability of BV/SS wall systems. In an effort to address these concerns, Canada Mortgage and Housing Corporation has undertaken a program to evaluate the design, construction and performance of BV/SS walls. This paper summarizes the second year of performance monitoring of a typical BV/SS wall system in service (over 1992-93), including observations at an inspection opening in the test wall, made in March 1994. The findings emphasize the need for improved industry standards, since the test wall shows that buildings constructed according to current standards do not perform well enough. More attention needs to be paid to constructing a fully sealed and rigid air barrier, preventing thermal bridging and venting the air space.

INTRODUCTION

The widespread use of brick veneer/steel stud (BV/SS) wall systems over the last 20 years has preceded the development of adequate design and construction standards. As a result, concerns have arisen in the construction industry over the long-term safety, serviceability and durability of BV/SS wall systems. In an effort to address these concerns, Canada Mortgage and Housing Corporation (CMHC) has undertaken a program to evaluate the

[1] Project Manager, Housing Innovation Division, Canada Mortgage and Housing Corporation, National Office, 700 Montreal Road, Ottawa, Ontario, Canada K1A 0P7

[2] Principal, Keller Engineering Associates Inc., 1390 Prince of Wales Drive, Suite 107, Ottawa, Ontario, Canada K2C 3N6

[3] Project Engineer, Keller Engineering Associates Inc., 1390 Prince of Wales Drive, Suite 107, Ottawa, Ontario, Canada K2C 3N6

design, construction and performance of BV/SS walls. This paper summarizes the findings of Keller Engineering Associates Inc. over the second year of in service performance monitoring of a typical BV/SS wall system, which was instrumented by the Institute for Research in Construction.

Objectives

The objective of the performance monitoring work was to evaluate the in-situ performance of a newly constructed BV/SS wall system with regard to air and moisture movements and temperature gradients. The BV/SS test wall was first evaluated during 1991-92 and the findings were outlined in a report of June 1993 (Keller and Laviolette, 1993). This report discusses the Phase 2 results of the study, including the findings from performance monitoring over 1992-93 and a visual inspection upon opening the test wall to replace and recalibrate instruments in March 1994.

Selection of Test Wall

The building selected for monitoring was a seven-storey apartment building in Ottawa. A BV/SS wall on the seventh floor, with an east-northeast orientation, was selected for monitoring. This building orientation exposes the test wall to the worst combination of precipitation and air exfiltration.

In Ottawa, wind-driven rain tends to be from an easterly direction and therefore, east facing walls are more severely wetted by precipitation. Winds during winter tend to be from a westerly direction, causing air exfiltration from wind-induced suction forces to be more severe on the east elevation of buildings. Also, due to stack effect, outward air pressure differences across exterior walls are most severe at the top floor of buildings. Since air exfiltration is the principal manner in which water vapour is transferred into the exterior walls during winter, the most severe condensation at the test building will occur at the seventh floor of the east elevation. Thus, considering the combined effects of condensation and rain wetting, the selected test wall will be the location that experiences the most severe climatic loads.

Structurally, the steel stud backup wall was well designed. In fact, most features of the backup wall are considered to be in accordance with "best practices", as outlined in the CMHC publication "Exterior Wall Construction in High-Rise Buildings, Brick Veneer on Concrete Masonry or Steel Stud Wall Systems" (Drysdale and Suter, 1991). Features of the backup wall include 20 gauge steel studs (the above publication recommends 18 gauge studs for increased durability during construction), double top tracks, lateral bridging between studs, and a deflection limit of L/720. Unfortunately, some building science recommendations of the CMHC document were not implemented, including the installation of a fully sealed and rigid air barrier to minimize air leakage, the provision of exterior insulation to reduce thermal bridging, and compartmentalization of the cavity to improve pressure equalization of the wall system. The drawings did call for the 4 mil polyethylene vapour barrier to be sealed, but the drawings did not specifically identify the air barrier. A wall section with materials and thicknesses is shown in Fig. 1.

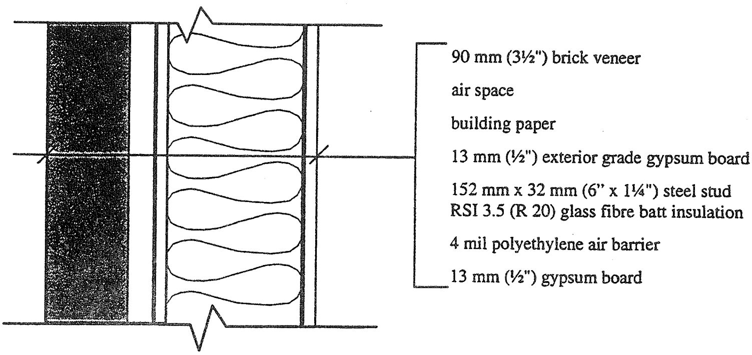

Fig. 1 Cross Section of Test Wall.

Performance Monitoring and Data Acquisition
The instrumentation consisted of various temperature, moisture and air pressure sensors which were connected to a computer-based, automatic data acquisition system that read data at each sensor every minute and calculated the average value of the data every hour. Sensors were installed within one stud region at a range of vertical locations and arranged to monitor conditions through the wall assembly at the stud and through the stud space. The test wall was monitored periodically over an 8 1/2-month period, with the following monitoring periods selected to represent the different weather conditions that occur over the year in the Ottawa-Hull area:

1. November 28 - December 25, 1992
2. January 16-19, 1993
3. February 20 - March 19, 1993
4. April 3-19, 1993
5. May 1-14, 1993
6. July 24 - August 6, 1993

EVALUATION OF WALL PERFORMANCE

Summary of 1991-92 Findings
In general, the analysis of the 1992-93 data yielded very similar results to that of the 1991-92 data. The results of the first year of monitoring demonstrated that good thermal performance can generally be expected from BV/SS walls. However, significant thermal bridging occurred at the steel studs in the test wall due to the absence of exterior insulation. This thermal bridging is typical of any steel stud backup wall without exterior insulation.

An analysis of the air pressure differences across the test wall over the various monitoring periods also indicates that the air/vapour barrier system of the test wall performed in only a marginally satisfactory manner. First, pressure equalization in the vented cavity was not fully effective, causing both the brick veneer and the steel stud backup to resist wind loads. It is desirable to have the backup wall alone resist these loads. Second, minor air leakage occurred through the air/vapour barrier even though workmanship appeared satisfactory. While the amount of air leakage was relatively small, it was enough to allow significant moisture migration into the wall system and to cause a noticeable reduction in the thermal efficiency of the wall system under strong wind conditions.

An important finding of the 1991-92 monitoring program with respect to moisture was that the cavity of the test wall did not vent effectively and, therefore, water vapour levels within the cavity were high. As a result, condensation regularly occurred on the back face of the brick veneer during temperature conditions of about 5°C or lower and frequent freeze-thaw cycles were also noted. As well, condensation occurred on the brick ties and the outside surface of the exterior gypsum board sheathing. The cavity of the test wall was unable to dry out because there was more condensation occurring due the faulty air barrier than could be removed by natural convection of air through weep holes. Experience has shown that condensation on the back face of the brick veneer may lead to spalling of the brick units due to freeze-thaw action. In addition, condensation within the cavity can lead to corrosion and eventual failure of the brick ties. Therefore, the faulty air barrier and the lack of adequate cavity venting at the test building, conditions present in many other buildings already built, will likely result in a reduced service life of the BV/SS wall system. To date there is insufficient data available to predict the service life expectancy more accurately given these conditions. It is also noteworthy that minor condensation regularly occurred on the interior surface of the exterior sheathing. This condition could be detrimental to the long-term performance of the wall system, by way of reduced thermal effectiveness of the insulation due to wetting or deterioration of the exterior gypsum board and building paper such that water penetration problems develop.

Thermal Performance

The thermal performance of the test wall was evaluated primarily using data recorded during the period of January 16-29, 1993. Exterior air temperatures only dropped to about -20°C during this period, 10°C higher than the coldest winter temperatures typically experienced in the Ottawa-Hull area. However, the low of -20°C was still sufficiently cold to evaluate the thermal performance of the test wall.

Temperature profiles across the wall at the stud and across the insulation differed, showing the thermal bridging effects of the steel studs. The profile across the insulation, showing all surfaces on the exterior side of the fibreglass batt insulation at much lower temperatures than the interior gypsum board, demonstrated that good thermal performance can be expected from a "typical" brick veneer/steel stud wall. Surface temperatures between the exterior and interior drywall were, however, much more widely distributed at the steel stud, indicating that the wall does not perform as well thermally at stud locations. The temperature at the exterior surface of the sheathing was an average of

5°C warmer at the steel stud than at the insulation. Thermal bridging also caused the inside surface of the interior gypsum board to be typically about 2.5°C colder, and on occasions up to 3.5°C colder, at the steel stud than at the insulation. Thermal bridging of this magnitude can cause "dusting" on the interior surface of the drywall at the stud locations. Dusting was, in fact, observed during the visual inspections of March 1994, and was so severe as to reveal the location of every stud and drywall screw.

It was observed that the measured thermal profile of the backup wall often differed significantly from the theoretical thermal profile. Variable in-situ conditions such as wind pressure, air leakage through the wall system, wet masonry, and direct sunshine on the brick veneer caused the behaviour of the test wall to deviate from the calculated theoretical temperature profile, which uses steady-state conditions. In general, the measured temperature profile is most likely to correspond to theoretical calculations if there is no wind, the outdoor temperature has not been fluctuating, the brick veneer is dry, and the sun is not shining on the test wall.

An evaluation of the temperature data indicated that warm air exfiltration under high pressure differences across the test wall is the key reason that the actual and theoretical temperature profiles differ. Since the wall faces east, it is on the leeward side with respect to prevailing winds. As suction pressures increase due to high winds, more warm air exfiltrates into the cavity, causing higher temperature readings across the backup wall and on its exterior surface. At lower pressure differences, corresponding to periods of lessened wind forces, the actual temperature data of the backup wall corresponded closely to projected theoretical values. Air leakage due to negative (outward) wind pressures therefore lessens the overall resistance to heat loss of the test wall.

Air Pressure Differences
During the monitoring program, the air pressures at the exterior, in the air space, in the stud space and of the interior air were measured and were denoted P1, P2, P3, and P4, respectively, as shown in Fig. 2.

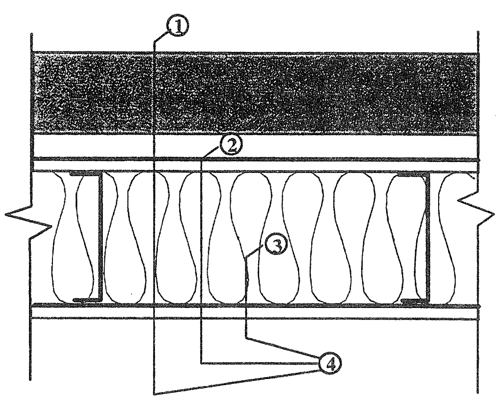

Fig. 2. Location of Pressure Taps.

Assuming that windows are closed so that outside air cannot blow directly inside, and that mechanical systems pressurize the building, the following conditions describe a well-performing wall:

1. Inside and outside air pressures should be distinctly different, indicating an effective air barrier.

2. The largest change in air pressure should occur across the air barrier, hence between P3 and P4.

3. P2 and P3 should be virtually equal. The exterior sheathing should not act as an air barrier causing a pressure difference across the sheathing, since moisture exfiltration from the interior must be able to migrate freely past the exterior sheathing.

4. There should be effective pressure equalization between the exterior air and the cavity; hence, variations in P1 relative to P2 should be consistent and small. Significant pressure differences between P1 and P2 indicate that pressure equalization is not fully effective, that the cavity is not adequately vented, and/or there is air infiltration or exfiltration through the air barrier.

5. The thermal performance of the insulated stud wall should be consistent, regardless of variations in pressure difference across the wall. If the wall does not perform as well during conditions of large differences between indoor and outdoor air pressure, air leakage through the air barrier is indicated.

High pressure differences were experienced most frequently during the first three monitoring periods, especially January 16-29, 1993. Air pressure data demonstrated that the wall system was generally effective at isolating the exterior air from the interior. The pressure differences between inside and outside were smallest when the test wall was exposed to winds from the easterly direction. While positive pressures from easterly winds still produced overall negative pressure differences from inside to outside, due to high interior air pressures from building pressurization and stack effect, strong easterly winds (of 30-50 km/h) sometimes caused positive pressure differences. Similarly, large negative pressure differences (greater than 30 Pa) were produced by strong northerly winds (40 km/h) exerting high suction forces on the test wall.

Only small pressure differences registered between the stud space and the vented cavity, indicating that the exterior drywall does not act as an unintentional air barrier on the outside of the insulation. While the data from the 1991-92 study period showed the exterior sheathing accounting for about 5% of the total pressure drop across the wall, the 1992-93 data generally show almost zero difference between the cavity and stud space air pressures, suggesting that air moves past the exterior sheathing more easily now than it did when the building was first completed. This could be explained by additional minor gaps opening up between sheets of exterior sheathing, probably as the result of normal building movements.

Only partial pressure equalization occurred between the exterior air and the wall cavity. Simultaneous increases in pressure on the exterior of the veneer and within the cavity indicate that pressure equalization does occur to some degree. However, when wind speeds and directions changed, a greater change typically occurred in the exterior air pressure than in the cavity pressure relative to the indoor air. This data indicates that a certain portion of the wind load is carried by the brick veneer rather than being effectively transferred to the backup wall.

Visual inspection in March 1994 of an opened portion of the test wall revealed sources of air leakage. A cut was found in the polyethylene; although an attempt had been made to repair it during construction, air leakage was indicated by dirt particles deposited on the insulation at this point. Although the test location was selected to avoid the effects of wall penetrations from telephone and cable outlets, air leakage through an electrical outlet was evident as significant dusting on the cover plate, despite the use of a gasket around the opening.

RAIN is a computer program which assists in the design of pressure equalized rainscreen walls. The program predicts the rate of pressure equalization of a given wall design based on the following parameters: cavity volume (height, length and depth), flexibility of the cladding, flexibility of the air barrier, vent area in the cladding and leakage area in the air barrier. Modelling the test wall with the RAIN computer simulation software, by CMHC, showed that an airtight air barrier and a more effectively vented cavity, achieved with more vents (one every brick), would allow full pressure equalization between the exterior air and the airspace. These requirements, if taken into consideration during initial design and construction, would not increase building costs.

Humidity

Moisture within the wall system consists of water vapour and liquid water. There is always water vapour within the wall system, but it is not a concern unless, during colder weather, the water vapour condenses to liquid against cold surfaces, causing wetting of building elements. Water that penetrates the cavity but cannot escape due to poor venting will lead to increased condensation on building elements within the cavity. Liquid water from exterior sources is a concern only if its presence becomes detrimental to the BV/SS wall: for example, rainwater that penetrates the brick veneer, bridges the cavity and wets the backup wall. The presence of liquid water within the cavity is best evaluated in spring and fall, when wind-driven rains are most frequent and when freezing or condensation of trapped moisture can occur as well.

The electrical resistance moisture sensors, installed during the brick laying process, were used to detect moisture levels in the brick masonry. Sensors were also installed in the air space at the shelf angle and within the stud space at the centre of the bottom track. The moisture sensors in the test wall were not calibrated to determine specific moisture content, but to indicate relative wetness. Higher resistance readings were obtained for the brick veneer when the brick was drier, while lower readings indicated the brick was wetter. However, freezing of water in the brick resulted in misleading higher readings, giving a false indication of the brick being drier; hence, freeze-thaw cycles caused extreme fluctuations in the moisture data for the veneer.

While the moisture sensors registered wetness levels, the source of the wetness was determined by evaluating weather data and the recorded data that provides information with respect to the potential for condensation. Wetness levels can be simply correlated with the occurrence of precipitation, wind speed and direction, and even sunny or overcast conditions.

To evaluate how condensation could be affecting wetness levels, the surface temperatures of building elements in contact with the air in the cavity and the stud space were compared to the dew point temperature of the cavity and stud space air. Throughout the coldest study period (January 16-29, 1993), the analysis of the surface and dewpoint temperatures revealed that cavity moisture was continuously condensing on the back face of the brick veneer. At temperatures of approximately 5°C or lower, condensation occurred on the back of the veneer, on the exterior surface of the exterior sheathing and on brick ties. Frequent freeze-thaw cycles were also noted. Condensation frequently occurred on the interior surface of the exterior drywall at temperatures of approximately 0°C or lower, though moisture did not condense at the steel stud as temperatures were warmer at this location due to thermal bridging.

The following observations were made about humidity conditions in the test wall:

1. The exterior of the brick veneer at the level of the floor slab was fairly dry during the cold season (November to May) and very dry in summer, although frequent wetting occurs. The exterior of the veneer at the roof level was very wet in winter but was generally dry in summer.

   The brick veneer was usually wetted by precipitation to a significant degree if the wind direction was toward the test wall. However, the wall dried quickly, within one or two days, after a rainfall. Precipitation was the main source of moisture on the exterior of the brick veneer. On the entire back face of the veneer, and on the exterior face of the veneer at the roof level, condensation during colder weather was a source of moisture. These last areas were so wet, nearly saturated, from November to April that moisture sensor readings often did not change significantly during heavy rain storms that obviously drove water through the brick veneer.

2. Poor venting of the cavity trapped moisture in the airspace, leading to water vapour levels within the cavity that were consistently very high in comparison with exterior water vapour levels, except during the summer. The high water vapour content of the cavity air not only caused condensation to occur regularly,

but drying of the moisture accumulated on the back face of the brick veneer could not occur until late spring.

3. Somewhat damp conditions were generally found at the bottom of the cavity from November to April, with wet conditions experienced occasionally. This area was dry in the summer.

4. The moisture sensor within the backup wall generally indicated somewhat damp to dry conditions from November to March, but dry conditions during the spring and summer. Visual inspection in March 1994 found that the building paper and exterior gypsum board were very wet. Mildew covered much of the interior surface of the exposed gypsum board near the floor, but was generally minor higher up, except for a significant amount of mildew at a joint between adjacent sheets of gypsum board. The exterior surface of the glass fibre insulation was generally damp, with a portion near the floor being very wet, and was stuck to the exterior gypsum board. Minor corrosion was observed on the tip of one exterior, corrosion-resistant drywall screw. Very minor corrosion was observed on the screws for the stud wall and brick ties, as well as on the edge of the C-channel portion of a brick tie. The steel studs, lateral bracing and bottom track were in good condition although the bottom track was suffering minor oxidation, indicating that moisture had been present.

5. There was no evidence of water penetration into the backup wall, and, therefore, the only source of water within the backup wall was the condensation in cold weather of exfiltrating interior air within the wall. Since there was no leakage into the backup wall and the back face of the brick veneer was significantly wetter than the bottom of the vented cavity, it is concluded that the brick veneer acts as an effective rain screen, even though pressure equalization is not fully effective.

Based on the data and inspection observations, it appears that condensation frequently occurs within the wall assembly, including at the exterior gypsum board, and that minor air leakage is occurring through the air/vapour barrier despite the fact that the workmanship was generally very good. While the use of galvanized metal products has so far kept the stud wall in good condition, the glass fibre insulation and exterior gypsum board are being wetted to an unacceptable degree. Judging from the observed condition of the building paper and the exterior gypsum board, it appears that condensation within the cavity is contributing significantly to the deterioration of these elements.

These moisture conditions have potentially very damaging effects on the BV/SS wall. The regular occurrence of condensation on brick ties could lead to the premature corrosion and eventual failure of the ties. The continuous wetness of the back face of the brick veneer during freezing weather is also a serious concern. Freeze-thaw action over the colder months could cause backspalling of the brick veneer. This could lead to unexpected failure of the brick veneer, possibly with its exterior face showing little or no distress. Even without such a serious failure, expensive masonry repairs could be required long before the building reaches the end of its intended service life.

Condensation within the backup wall may cause corrosion and deterioration of the steel stud backup wall over the long term to the point where it is no longer structurally sound. The thermal resistance of the glass fibre insulation could also be significantly reduced by wetting due to condensation within the backup wall. As well, frequent wetting of the exterior gypsum board may cause the sheathing to deteriorate to the point that it can no longer resist water penetration to the interior, especially when the deterioration of the building paper is also accelerated.

Modelling of the test wall was carried out by CMHC using the EMPTIED computer program, assuming an interior air temperature of 23°C and a relative humidity of 27% during the heating season (November to April). The modelling confirmed the findings regarding moisture in the BV/SS wall, showing that condensation occurs throughout the winter and drying of the wall does not occur until spring. EMPTIED stands for Envelope Moisture Potential Through Infiltration, Exfiltration and Diffusion. The program predicts the potential amount of moisture that is likely to accumulate, month-by-month, in a user-specified building envelope due to air leakage and diffusion.

A breakdown of condensation moisture according to source confirmed that vapour diffusion was a negligible cause of condensation compared with air leakage. The exterior sheathing and brick veneer temperatures plotted against weather data were shown to be consistently below the dew point temperature of the exterior and cavity air throughout the winter. Calculating evaporation and absorption capacity of the materials relative to the quantity of condensation, EMPTIED predicted excess moisture on the exterior sheathing from December to March, and that all condensation moisture on the brick veneer would be lost through evaporation and absorption, leaving no excess to drain.

A further simulation with EMPTIED showed that applying 25 mm (1") extruded polystyrene (EPS) insulation on the exterior of the studs would eliminate the excess condensation on the exterior sheathing. This measure would, however, lead to more moisture condensing on the back face of the brick veneer, though EMPTIED calculated that the condensation generated was still less than the amount that could be lost through evaporation and absorption. Eliminating the condensation on the back face of the brick veneer entirely could only be achieved by reducing air exfiltration from the interior.

CONCLUSIONS AND RECOMMENDATIONS

The findings outlined in the preceding sections indicate that the brick veneer/steel stud test wall is performing in an unsatisfactory manner due to air leakage through the air/vapour barrier system, a lack of exterior insulation, and poor venting of the cavity. The long-term effects of the problems observed in the BV/SS test wall are potentially severe. An examination of the test wall showed that it was built according to plans and specifications, and that the workmanship was in fact above average. Accordingly, the solution to the wall's unsatisfactory performance, lies in the design of the wall system. These findings emphasize the need for improved industry standards, since the test wall shows buildings constructed according to current standards do not perform in a satisfactory manner. More attention needs to be paid to constructing a fully sealed and rigid air barrier, preventing thermal bridging, and venting the air space.

Given the unsatisfactory performance of the test BV/SS wall, it is intended that this monitoring program be extended over several more years. Ideally, the program should be ongoing for many years so that the performance of this wall system may be evaluated over the long term. The information obtained will be invaluable to designers, investigators and building owners alike as it clearly shows the vulnerability of BV/SS to design and workmanship defects. Since most deterioration occurs primarily within the wall system such that major distress problems could remain concealed until a major failure occurs, it has been recommended that periodic inspections of BV/SS wall systems, including inspection openings, be mandatory.

Finally, it has been recommended that performance monitoring work similar to this program be carried out on other buildings, both representative of typical construction and built according to best practices, in order to gain further knowledge about the in-situ performance of brick veneer/steel stud wall systems in different climatic conditions.