Pressure Moderation and Rain Penetration Control

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1. Introduction

Many researchers, designers, and builders consider Pressure-Equalised Rainscreens (PER) to be the state-of-the-art with respect to enclosure wall design†. This approach is also considered to be best practise for walls with brick veneer, EIFS, and vinyl screens. Both CMHC and IRC/NRCC have supported the view that pressure equalisation is both a powerful means of rain control and achievable in practice.

This paper reviews the theory, context, and history of rain control and pressure moderation. Projects conducted by the Building Engineering Group at the University of Waterloo over the last 10 years have provided the opportunity to collect detailed and comprehensive field pressure moderation measurements, especially on brick veneers. The results of these measurements are also summarised and discussed here.

2. Rain Control Strategies

Driving rain is typically the largest source of moisture for the above-grade building enclosure. Hence, rain control is a fundamental function of the building enclosure, and a major part of moisture control. Despite thousands of years of building experience, avoiding rain-related building damage is still one of the most difficult tasks designers and builders face. There are, however, rain control strategies based on both traditional details and modern physical understanding that can be successful. Regardless of the design approach taken, building shape and site design choices can reduce the amount of rain deposited on walls. Finally, despite our best efforts, some rain often is absorbed into materials or penetrates through imperfections so drying must be provided to remove this incidental moisture.

2.1 Reducing Exposure (Deflection)

The climate and the site play a large role in defining the rain exposure that a building is exposed to. Most parts of the world experience a significant amount of wind-driven rain, and those areas exposed to typhoons can have extreme exposure conditions. While this type of climate demands good rain control strategies for enclosure walls, the rain deposited on walls can be significantly reduced by good design and siting.

The first stage of controlling rain penetration is the siting and shape of the building. For low-rise buildings exposure to the prevailing driving rains can be defended against by planting, and landscaping. For taller buildings, choosing better detailing and enclosures for the critical orientation is a sensible approach.

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† As described elsewhere, the more general term "screen" is preferred to rainscreen since much more than rain is screened by the outermost wall layer ("rainscreen"). Also, the more technically correct term pressure moderation has been used throughout this paper because this and previous work has shown that instantaneous pressure equalization rarely, if ever, occurs in service.

The shape of the roof and overhang also has a critical impact, especially for low-rise buildings. Field measurements [1] and computer modelling [2] have shown that overhangs and peaked roofs reduce rain deposition by approximately 50%. A CMHC-sponsored damage survey of wood frame buildings in British Columbia [3] found that the size of a buildings overhang correlated directly with the probability of rain-related damage (Figure 1). Peaked roofs and overhangs protect a wall from rain by shadowing and redirecting airflow (Figure 2). Hipped roofs provide an opportunity to shelter the walls from rain on all four sides of the building.

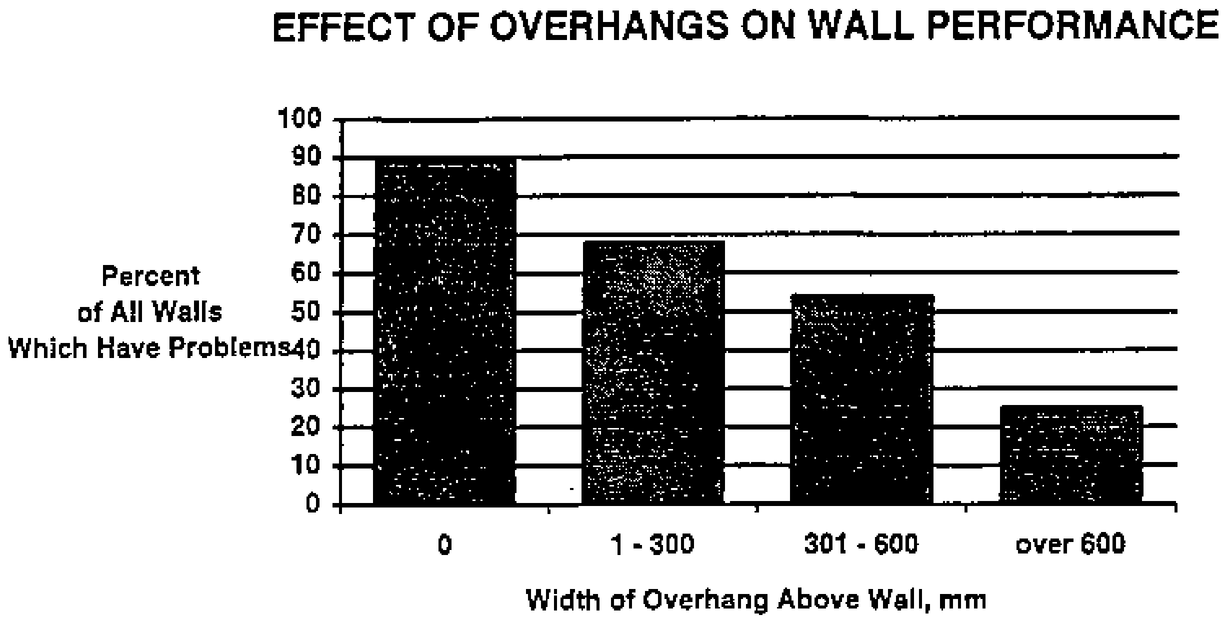


Figure 1: Overhang Size and Damage Correlation From Reference [3]

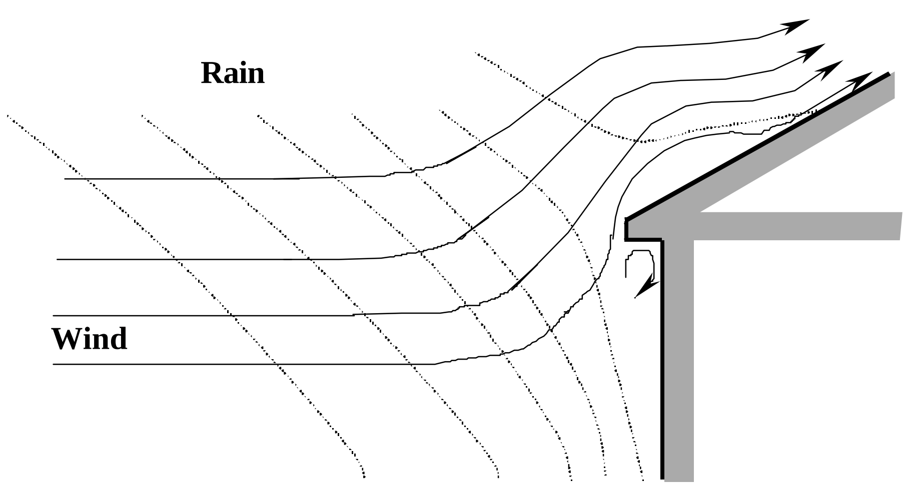


Figure 2: Influence of Overhangs and Pitched Roofs on Wind and Rain Flow

Field measurements [4,5,6,7], computer modelling [8,9], and wind tunnel testing [10] have provided an indication of the quantity of driving rain deposition that can be expected on vertical walls. For many housing situations, the amount of rain deposited is in the order of 10 to 20% of the product of wind speed and rainfall intensity. Thus the amount of rain deposited on the walls of houses erected on exposed sites could be in the order of hundreds of litres per square meter per year. Sheltered locations and single-storey houses with wide overhangs will be exposed to much less than this amount of rain.

Once water is on the wall it will form a film and begin flowing downward under the force of gravity. Wind flowing over the surface will tend to deflect the flow from this path and, in extreme cases, may even force water upward. Surface features such as trim, surface texture, and openings can greatly affect the flow paths of this surface drainage, either concentrating or dispersing surface flows.

Traditional surface details on some old and vernacular buildings (Figure 3) often served the function of directing water away from sensitive areas (e.g., windows) and distributed surface water in such a way as to prevent the concentrated streams which cause staining. The copious use of drip edges and slopes also ensured that surface water was removed from the building surface as often as possible.

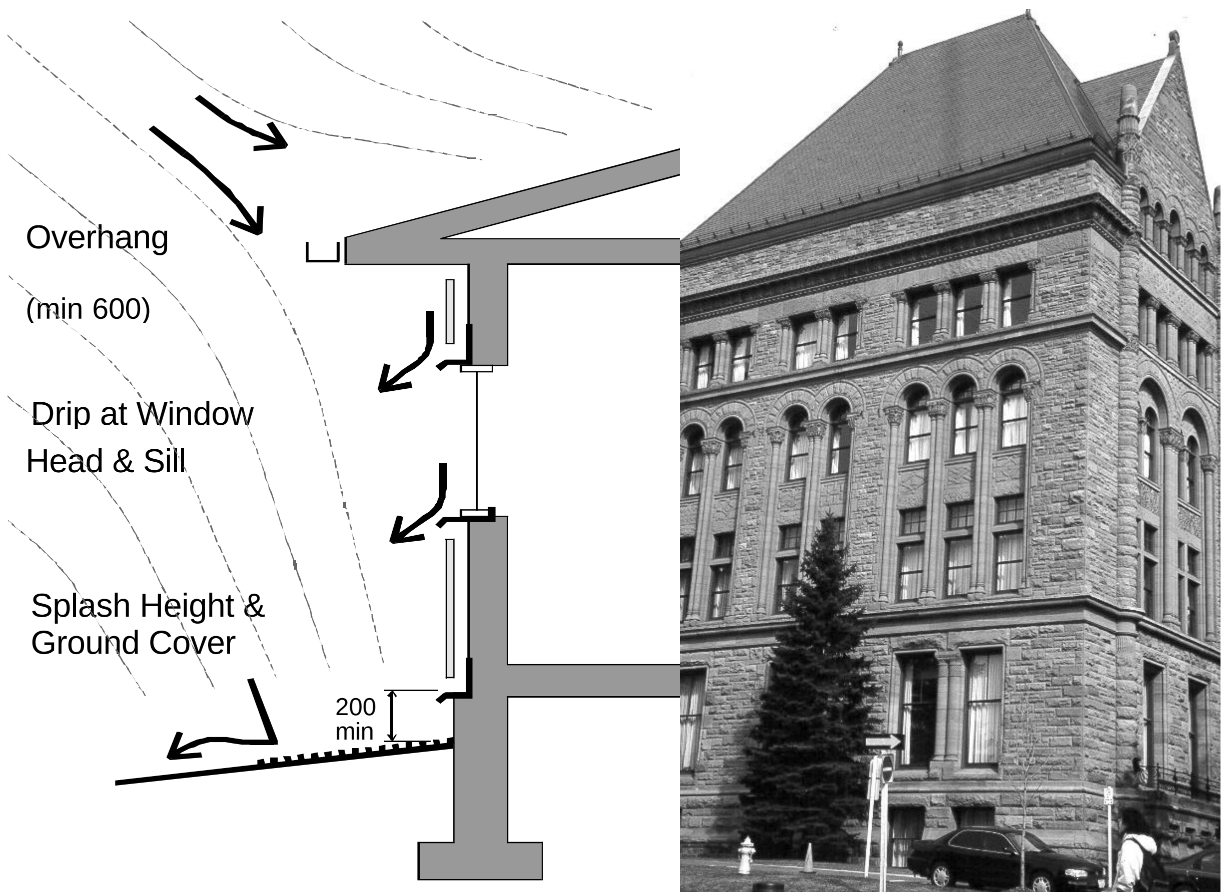


Figure 3: Principles of Rain Deflection Using Surface Features

Siting, building shape, and surface rainwater control rarely provide sufficient rain control in rainy climates. Hence, some strategy to deal with the rainwater that penetrates the surface of the wall must be employed.

2.2 Enclosure Design

There are three fundamental rain control available to the enclosure designer [11], based on how rain is controlled once it contacts the enclosure (Figure 4):

1. storage (also called mass) systems,
2. perfect barriers, and
3. drained and screened systems.

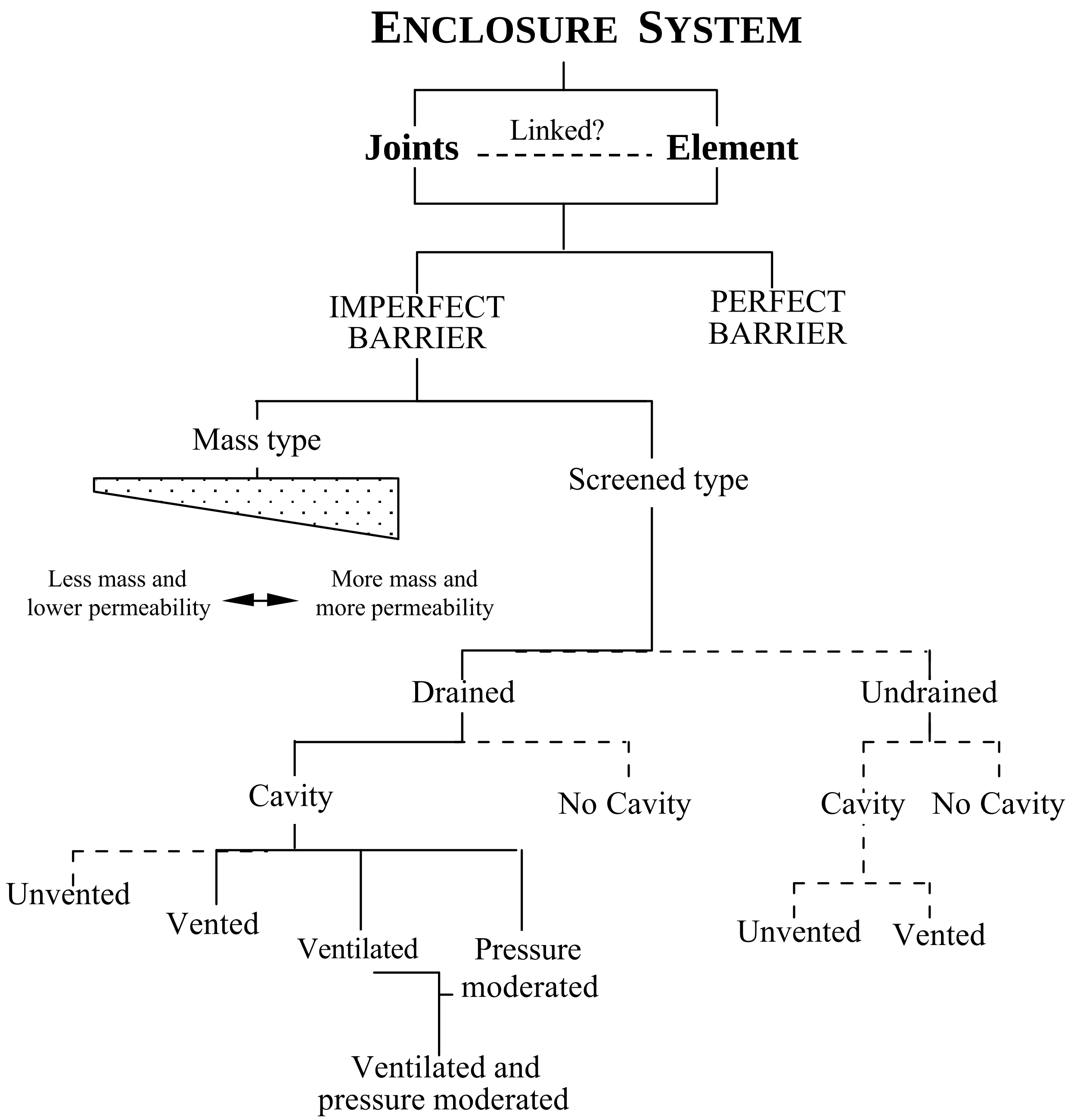


Figure 4: Enclosure Rain Control Classification System

Enclosures can be considered as comprised of elements (such as glazing units, and brickwork) and the joints between them (e.g.. window frames, caulked joints). In some cases, the joints are linked with the elements (e.g., metal panel systems). This categorisation is independent of materials or design intent and is based solely on the method by which an enclosure system controls rain penetration.

Although drained-screened systems are usually the preferred approach to rain control, both mass storage systems (e.g., single-wythe masonry in low-rise buildings) and perfect barrier (glazing and low-slope roofs) are still successfully used in certain conditions.

2.2.1 Storage Systems

Storage or mass walls are the oldest strategy. This approach requires the use of an assembly with enough storage mass to absorb all rainwater that is not drained or otherwise removed from the outer surface. In a functional mass or storage wall this moisture is eventually removed by evaporative drying before it reaches the inner surface of the wall. Although envelopes employing this strategy might be best termed "moisture storage" systems, "mass" is often used because a large quantity of material is required to provide sufficient storage. The maximum quantity of rain that can be controlled is limited by the storage capacity available relative to drying conditions. Some examples of mass walls include adobe, solid multi-wythe brick masonry, and single-wythe block masonry (Figure 5).

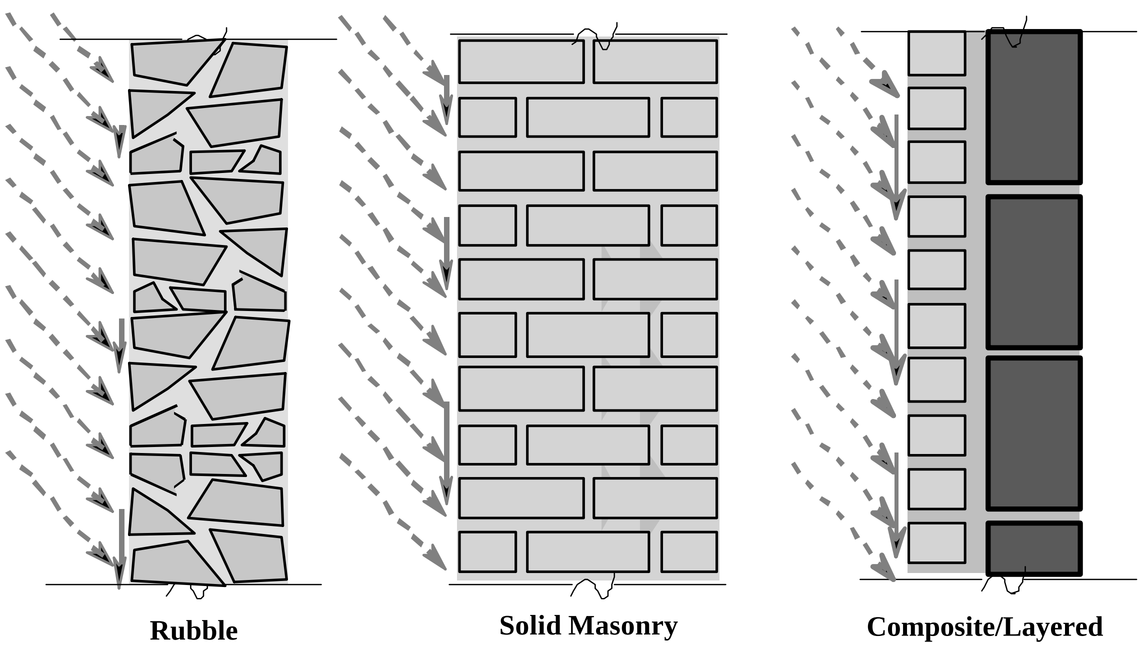


Figure 5: Examples of Mass or Storage Wall Systems

2.2.2 Perfect Barrier Systems

Perfect barriers stop all water penetration at a single plane. If that plane is located at or very near the exterior surface, the systems are called *face sealed.* Such perfect control required the advent of modern materials. Some examples of perfect barrier face-sealed walls are some window frames, and some metal and glass curtain wall systems (Figure 6). Because it is very difficult to build and maintain a perfect barrier wall, most walls are designed as, or perform as, imperfect barrier wall systems of either the mass type or the screened type. Face sealed walls are the most problematic, since the seal is exposed to the extremes of environment, and are exposed to the most rain water.

The joints between enclosure elements may be also designed as perfect barriers (e.g. a single line of caulking). Such perfect barrier face-sealed joints have a poor record of performance, are a common source of leakage problems, and should not be used to control rain entry.

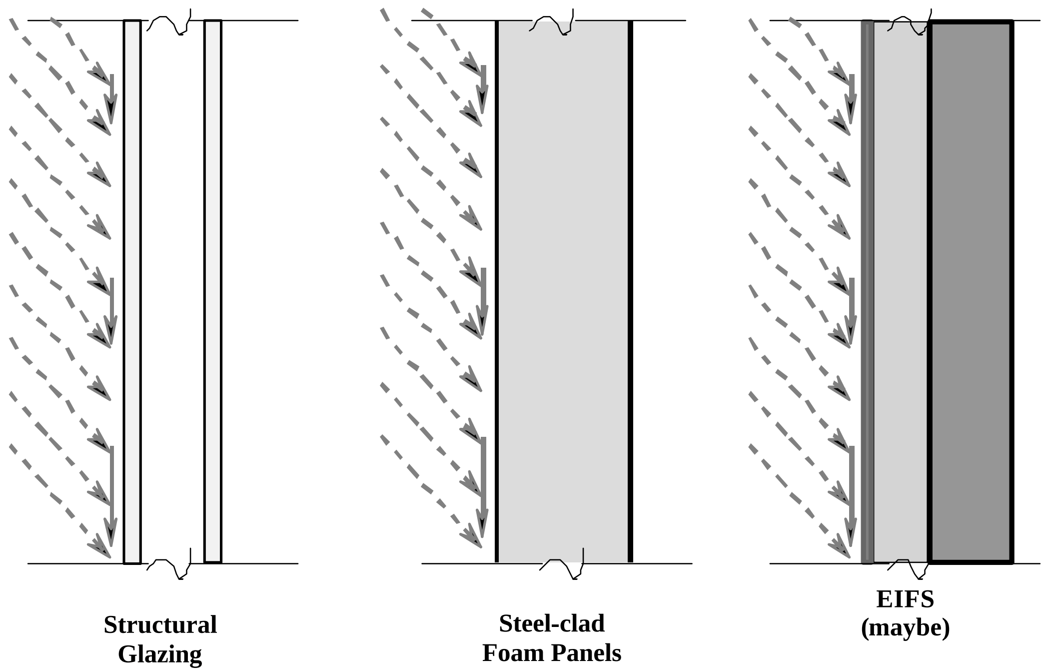


Figure 6: Examples of Perfect Barrier Wall Systems

2.2.3 Screened-Drained Systems

Screened-drained walls assume some rain water will penetrate the outer surface (hence the cladding "screens" rain) *and* remove this water by designing an assembly that provides drainage within the wall. Since it has often been demonstrated that most common claddings, e.g., masonry veneers, siding, leak significant amounts of water, this design approach is the most realistic and practical for such walls.

Supplementary mechanisms, such as a capillary break and a water barrier, are usually employed to resist further inward movement of water that penetrates the inevitably imperfect cladding. Some examples of screened wall systems include cavity walls, brick and stone veneer, vinyl siding, two-stage joints, and drained EIFS (Figure 7). It should be noted that the screen is much more than a rainscreen; it must also resist wind, snow, solar radiation, impact, flame spread etc.

An air space is usually provided to facilitate drainage and act as a capillary break between the cladding and the remainder of the wall. This air space becomes more important as the rain loading increases since under these conditions more water will drain within this space more often. The air space should theoretically be at least 4 or 6 mm wide, since this is approximately the size of a gap that can be spanned by a droplet of water. However, since dimensional tolerances must be accounted for, a dimension of 10 mm is usually quoted. Much smaller gaps formed by the space between sheets of building paper and behind lap siding have been shown to offer good drainage, and some semi-rigid water-resistant porous insulations can also be used as a drainage medium. The size of the airspace must be reasonably large (over 12 mm) if one wishes to allow for ventilation air flow (and the drying effect that this provides).

Experience with wood-frame housing from coast-to-coast in Canada [12] and in the hurricane-prone regions of the south-eastern US [13] has shown that drained and screened cladding systems are the preferred approach to reliably provide rain control. Drainage within the wall complements the drainage approach on the exterior surface while pressure moderation reduces the amount of rain that penetrates.

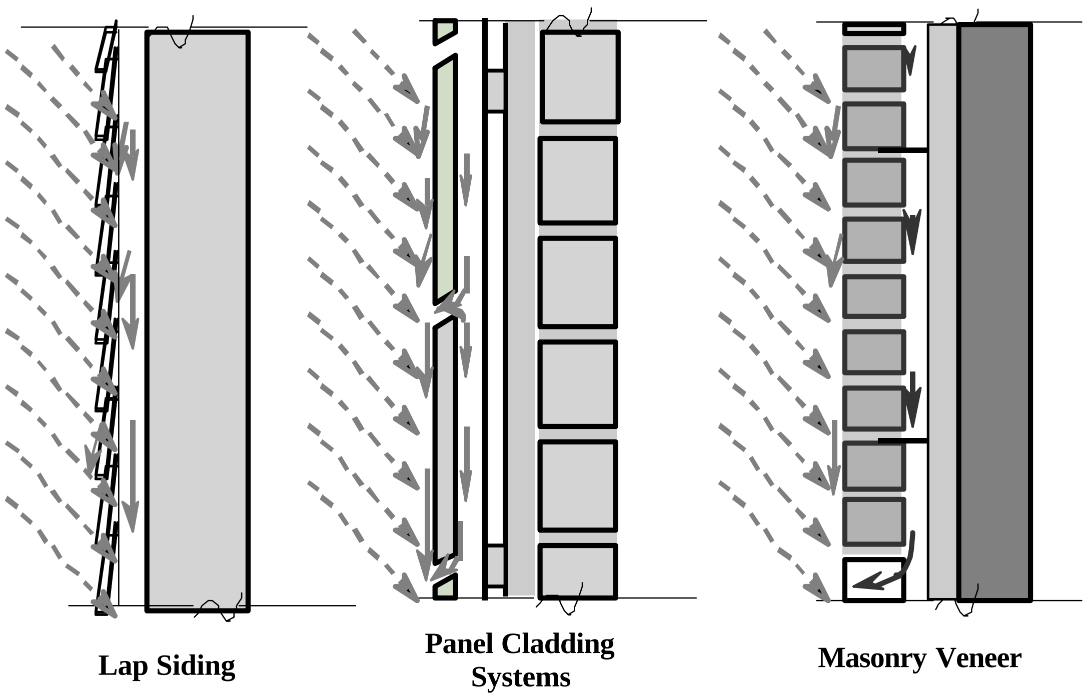


Figure 7: Examples of Drained-Screened Wall Systems

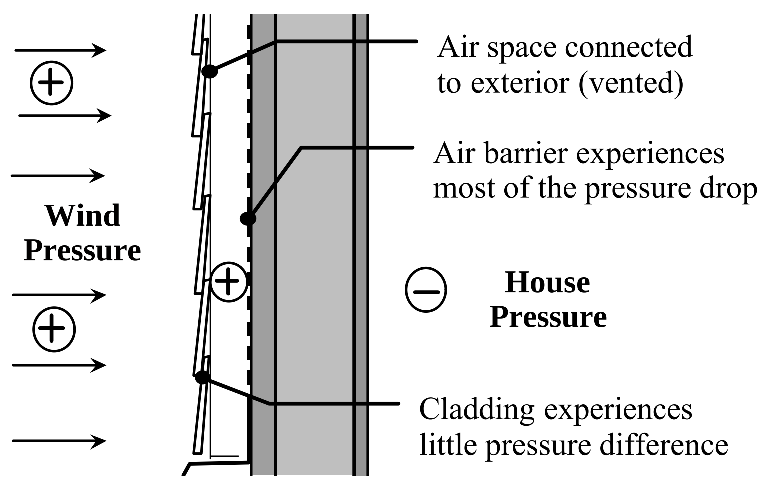


Figure 8: Pressure Moderated Air Space

A vented airspace also allows for both some degree of pressure moderation and ventilation. Pressure moderation is the term given to the mechanism whereby wind pressure differences across the cladding are reduced by connecting an air space behind the cladding with the wind-induced pressure acting on the exterior (Figure 8). By reducing air pressure differences across the cladding, rain will not be forced across openings by this force, while the standard features of capillary break, drainage, and flashing deal with the other rain penetration forces. If the air pressure is completely eliminated (not practical in the field [14,15,16]), the process is termed pressure equalisation.

Although drained-screened walls provide excellent rain penetration control, problems can still develop at interruptions in the plane of the wall. Windows, decks, and the termination of walls at grade all create conditions where rain can penetrate. Flashing must be provided at these penetrations to direct water in the drainage cavity to the exterior (Figure 9).

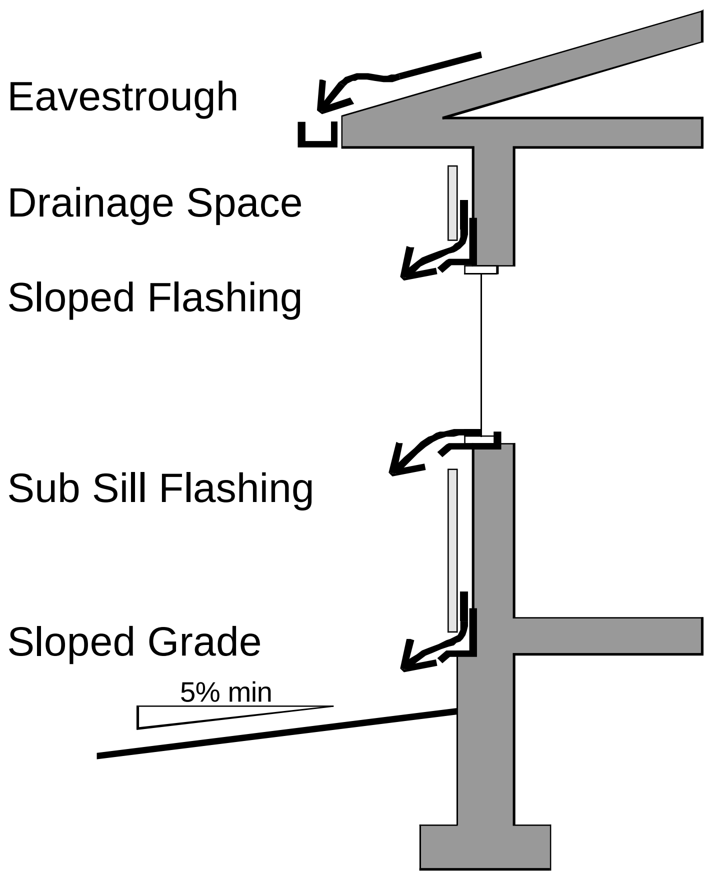


Figure 9: Drainage and Flashing Concepts

Flashing must be made of a waterproof material† since it is by necessity installed in a nearly horizontal manner [17]. Flashing must be installed in a continuous manner with an outward slope. Leaks often occur at the laps between lengths of flashing, so these should be sealed, not just lapped. Windows and especially mulled window joints and window corners often leak rain water into the wall. To deal with this eventuality (some say reality), sub-sill flashing should be installed. Since the joint between the wall and the window is sensitive to workmanship, the head of the window should also be well protected with flashing. This flashing directs water on the

† Building paper is not waterproof when exposed to standing water. Materials such as thick PVC, sheet metal, peel and stick membranes, special tapes, etc are more appropriate choices for flashing.

surface of the wall and in the drainage space behind the cladding safely back out. The flashing should extend past the window by at least 50 mm so that water flowing laterally on the flashing does not concentrate at the jamb but runs down the drainage space. Essentially the rough window should be prepared in such a way as to make it a water-resistant drained space.

Hence, pressure moderated screened walls are simply a subset of one type (albeit a high performance type) of rain control strategy. Just as importantly, pressure moderation cannot exist as a useful part of a rain control strategy without drainage layers, flashing, and capillary breaks.

2.3 Enclosure Drying

Despite all attempts, field experience has shown that some wetting of the enclosures may still occur or be built in during construction. Also, drainage cannot remove all of the rainwater that penetrates the screen. A significant portion is stored within materials and attached to surfaces. Drying of this moisture must be provided for.

Moisture can be removed from walls by:

1. evaporation from the inside or outside surfaces,
2. vapour transport by diffusion, air leakage, or both, either outward or inward;
3. drainage, driven by gravity; and
4. ventilation, if provided for.

Drainage is capable of removing the greatest volume of water in the shortest period of time. Hence, as described above, it is a very important mechanism for moisture control. Provided a clear drainage path exists (e.g. cavities, slopes, drainage openings), a large proportion of rain water penetration[‡] can flow out of a wall.

A small but significant amount of water will usually remain attached to surfaces by surface tension and held in materials by capillary forces even in walls with excellent drainage. Sidings of wood, brick, and cement will also absorb and store moisture. This moisture can only be removed from a wall system by diffusion, air flow, or evaporation.

Diffusive drying can dry in either direction, depending on the wall system and the climate. In colder climates the vapour flow is often outwards, and inward drying only occurs during warm weather or when the sun shines on a wall. In hot humid climates water vapour will be driven inward for most of the time and this drying mechanism should be encouraged.

Air movement (or leakage) through the envelope can, under the proper conditions, move a large quantity of moisture. While both cold weather air leakage outward and warm weather air leakage inward can cause condensation and hence wetting, the opposite conditions (e.g. inward flow in cold weather) will provide some drying. In some cases, this drying can be significant. Because air leakage through the enclosure is difficult to control, expensive in terms of energy, and potentially dangerous for indoor air quality, the modern approach is to limit airflow through the

‡ Drainage is also useful for removing cold weather air leakage condensation that can form on the back side of the siding, but only if a sufficiently large quantity of liquid water accumulates to allow drainage.

wall to nearly zero. This also eliminates the potential for airflow drying, so drying must be secured by other means.

Ventilation, or exterior air flow behind the cladding driven by wind pressure differences on the face of the building or solar heated air rising, is useful since it accelerates drying. Ventilation bypasses the high vapour resistance of claddings such as vinyl siding, metal panels, and cement board, thereby allowing outward drying. A recent Canadian study [18] and previous European research [19] has shown that ventilation drying occurs and explore the influence of various design variables. This research shows that a clear space of at least 19 mm should be provided behind lap siding to encourage ventilation, and that clear vents must be placed at the top and bottom for the most effective ventilation.

3. Historical Development Of PER

In traditional mass walls, e.g. a wall of solid masonry, the resistance to rain penetration was only one aspect of envelope performance. Heat flow was also controlled by the thermal storage capacity of the massive walls, not just by virtue of the materials' thermal conductivity like the specialized insulation layers commonly used in modern building assemblies. The sun's heat was absorbed, stored, and slowly released to the interior and exterior, effectively damping typical daily fluctuations and thus increasing comfort. Vapour and air flow were also controlled by the mass of the wall. It is little wonder that such walls were used for thousands of years. Built of only brick and mortar, the wall carried all structural loads as well as performing as an acceptable envelope. The small unit size of the brick allowed for planning flexibility so that such walls could be used for most purposes. Because mass brick walls allow a considerable amount of heat to pass through, the exterior surface temperature remained elevated throughout the winter and thus freeze-thaw durability and interstitial condensation problems were avoided. Compared to the poor control of air flow through windows and doors, the walls seemed airtight to the occupants. If sheltered by topography, other buildings, and roof overhangs, the amount of rainwater reaching the surface was so little that the wall could control this water before it reached the inner surface. The biggest drawbacks of such wall systems were the large amounts of material and labour needed to construct them.

With the change from low-rise buildings with solid load-bearing walls to taller framed buildings, the dead weight and cost of traditional mass wall systems became prohibitive. Chicago's 16-storey Monadnock Building, constructed with 6 foot thick base walls between 1889 and 1891, pushed to the limit the load-bearing mass masonry wall. Taller buildings with mass walls were practically impossible with the combination of high dead weight and low compressive strength. A large percentage of valuable ground floor area was lost to load-bearing walls and the resistance to seismic loads was poor. Today, poor control of rain penetration, heat, air, and vapour flow can be added to the list of drawbacks.

The industrial revolution and the scientific knowledge and technical confidence it provided resulted in attempts to produce perfect barrier wall systems. These systems very often fail to be perfect barriers because of defects in design, construction, or materials (although they may still perform as required because of inadvertent drainage, storage, or sheltering). While a unit of sealed glazing will not fail to resist rain (unless the glass cracks) the joint between the glazing and the window frame may. Similarly, EIFS lamina rarely failed to resist rainwater entry, but the joints and interfaces do. These examples reinforce the importance of considering the wall as a three-dimensional assemblage of elements and joints.

Pressure-moderated walls are not new, but in the last 30 years the advantages of pressure moderation have been rediscovered or acknowledged and their mechanics studied. A common vernacular implementation was a screen of weather boards with generous venting at the joints and/or at the top and bottom. Open-jointed wood barn cladding and board-and-batten methods have been commonly used both in Norway and in North America for over a century. Drainage and ventilation drying removed the amount of water which penetrated these claddings. While such systems are more properly simple ventilated drained-screened walls, the large venting area provided at the open top and bottom resulted in some pressure moderation since the mean cavity pressure would remain close to the mean applied pressure. A significant difference between modern screened and pressure-moderated walls and these vernacular examples is that the screen was often added over an existing mass wall [20], sometimes only to one critical orientation [21]. Thus, the inner wythe was already quite water resistant before the screen was added and the builder's intent was to add a second layer of watertightness. This lead to the term "two-stage weathertightening" in some of the early European literature.

In 1946 Johansson [22] suggested that solid masonry walls be fitted with "an outer, water-repelling screen" because plaster and masonry absorbed rainwater. As an added benefit he stated that water vapour "coming from inside is automatically removed by ventilation of the space between wall and screen". Hence, ventilated drained-screens were formally suggested well before pressure moderated screens. In Canada, Hutcheon (in 1953) developed these concepts further in terms of the general requirements of exterior walls [23],[11].

As lightweight curtainwalls were adopted in America, the joints between panels were common points of rainwater penetration. These new problems prompted the search for new solutions. In 1952 the thirty-story Alcoa Building in Pittsburgh utilized open labyrinth joints which were, in effect, pressure-moderated. These joints have from all accounts performed without leakage [24]. Before the end of the fifties, the concept of a screen with a drained and ventilated cavity for light-weight cladding was discussed in the design advice given by what is now the Building Research Establishment in Britain [25]. The understanding at this time did not explicitly include pressure-moderation, but rather the screened, drained, and ventilated wall. Building Research Note #26 authored by Ball and published by the Canadian Division of Building Research in 1956, discussed the advantages of a masonry wall with a "weather screen" and a cavity which was "freely drained and ventilated so that wind action may have a minimum effect on wall leakage" [26].

With the beginning of the scientific study of rainwater penetration, it was felt that many materials and screens could be developed to resist almost all rain penetration forces. The most problematic force for the joints between relatively impermeable materials (such as metal, precast concrete and glass) are the pressure differences imposed by the wind. By observing traditional Norwegian weather-board siding, Birkeland, in 1962 suggested that venting the cavity behind a screen would equalize the pressure on either side of the screen and essentially eliminate air pressure differences as a rainwater penetration force [27]. The screen could then deal with the other forces and a wall resistant to rain penetration could be built.

The following year, Garden introduced these ideas to North America and developed the terms 'open rainscreen' and 'rainscreen principle' in Canadian Building Digest 40 (CBD 40)[28]. For the first time, Garden discussed the concept of cavity compartmentalization to deal with the spatial variation of wind pressures on building faces. He also described lap siding and brick cavity walls as "partially pressure equalized". In 1963, Hutcheon further developed [29] and applied many modern screened wall principles to a masonry wall design example [30]. The use of an open rainscreen as described in CBD 40 was suggested:

> "The air space, being heavily vented by suitably designed open joints at both horizontal and vertical intervals, will at all times follow closely the outside air pressure so that the rain screen is substantially relieved of wind pressure differences. This not only removes the major force causing rain to penetrate the cladding, but also eliminates the wind loads on it".

At the CIB International Symposium on Weathertight Joints for Walls (held in Oslo, September 25-28th, 1967) many papers on rainscreens and pressure-equalization were presented and laboratory and field test results discussed. Several papers presented Canadian examples of walls designed as 'open rainscreens' [31,32]. At this conference, Kirby Garden, the author of the oft-quoted CBD 40, openly questioned the labeling of vented brick veneer walls as pressure-equalized rainscreens:

> "We also had it inferred that a brick cavity wall was an open rain screen wall.
>
> I wish to take some exception to this because in the basic principles of two-stage weather-tightness, or open rain screen design, one of the important requirements is that there be pressure-equalization across the outer shell.
>
> In order to get the space pressure-equalized with outside, openness to the outside must be considerably greater than the openness permitting air leakage to the inside. Thus the openness necessary is quite large. I cannot subscribe to the average masonry wall being described as a rain screen wall, unless one made a concerted effort to increase the openness to the outside."[33]

The emphasis of this symposium was balanced between the desire for pressure-equalization and the importance of the other rain penetration forces. No mention was made of the temporal variations of the wind, and although spatial variations were discussed, no quantification was attempted. Birkeland emphasised that there is a significant behavioural difference between joints and walls and between water permeable and impermeable materials [34], but it seems that these differences have subsequently been almost universally ignored.

In the general building literature on cladding during the 1960's, the concept of pressure-equalized or pressure-moderated screened walls had not yet taken hold. In one British book on cladding, wind-driven rain and wind pressure was discussed as relevant to rain penetration, but the wall and joint design emphasis was on mass walls and perfect barriers and open 'ventilated' joints were considered inferior to sealed joints [35]. A German guide to curtain wall construction neither discussed nor showed drainage or ventilation behind the screen [36]. Another German publication a few years older provided excellent and still pertinent information regarding the benefits of draining and ventilating a cavity behind a brick veneer but did not discuss pressure-moderation [37]. A Canadian magazine article described an ideal curtain wall as one which is ventilated and drained "for control of moisture or from wind blown rain" [38].

The concept of pressure-equalization was eagerly grasped by the metal curtain wall industry as a means of solving the problem of rain penetration through the joints between impermeable glass and metal panels. Indeed, the first pressure equalization design guide was prepared by the Architectural Aluminum Manufacturers Association (AAMA) in 1971 [39]. The design of pressure-equalized joints was emphasized in this guide, but the concept of pressure-equalized walls was also described. Although the difficulty in achieving full pressure-equalized walls was acknowledged, the concept was heralded as "one of the most important design principles yet advanced".

In 1973, Latta authored a National Research Council of Canada (NRCC) guide for the design of envelopes for the Canadian climate [40]. In it he examined pressure equalization and the rain penetration resistance of walls. He emphasized the necessity of a tight air barrier if pressure-equalization was to be achieved.

Latta calculated that for a 10:1 ratio of venting to leakage area, the drop in pressure across the screen (i.e. the pressure acting on the screen) is only 1% (the square of the ratio) of the total pressure drop across the wall. Latta concluded this pressure drop made such a wall essentially pressure-equalized.

The concept of the screen as a sun screen was also expounded in Latta's publication. Examples of 'pressure-equalized' masonry construction were presented and the importance of drainage was emphasized (without, however, a discussion of masonry permeability). Spatial variations in wind pressure on a building face were discussed and compartmentalization guidelines similar to those suggested earlier by Garden presented. Latta dismissed the temporal variations of wind pressure as relatively insignificant, since he felt that, based on the compressibility of air, the amount of air flow necessary to pressure-equalize a cavity to gusts was very small.

Latta's publication embodied the results of many tests and studies conducted by the NRCC Division of Building Research (DBR) and these resulted in the philosophy of a screen to environmental loadings other than rain. This philosophy had developed over the previous twenty years based on the original concept of screened walls first advanced in Hutcheon's original 1953 paper [23]. Several advantages were espoused for screened walls and the need for further building component specialization was inferred. The DBR suggested the structure be placed on the inside and separated from the control elements. The control of air, heat and water vapour flow should be accomplished by specialized air barriers, insulating layers and vapour retarders. The control of the sun's effects and ventilation of the screen to allow for removal of water vapour were discussed but cooling ventilation behind the screen was not mentioned.

The British Building Research Establishment (BRE) studied the performance of many joints and between 1967 and 1974 they presented their findings and recommendations in several publications [41,42,43,44]. These test results were extremely valuable since they were undertaken at full scale in an outdoor exposure rig and allowed for a true measurement of in-situ performance. The importance of labyrinth-type joints in conjunction with pressure-equalization was emphasized as the only true water-resistant joint designs for severe exposures. Although pressure-equalization was not directly referenced, "sealed" versus "ventilated" air barriers were compared. The sealed air barrier resulted in improved resistance but considerable penetration still occurred from the other mechanisms of rain penetration if appropriate measures were not taken.

At the same time the Norwegian Building Research Institute used laboratory tests which incorporated a complex apparatus which mimicked driving rain and variable intensity wind gusts [45]. These tests complemented the BRE tests and provided more practical design recommendations for pressure-moderated joints.

Although pressure-moderation met with great acceptance and field success in joint and window frame designs, walls employing state-of-the-art pressure-equalized rainscreens (based, for example, on the AAMA design guide and Latta's NRC publication) still encountered water penetration problems. In North America, the amount of high-rise (i.e. high exposure) construction increased and the existing inventory aged. Brick-veneer clad steel-stud walls with potentially higher susceptibility to water damage became popular. These and other factors increased the interest in walls with greater rain penetration resistance.

The laboratory study and field performance of pressure-moderated screened walls had also given rise to many unanswered questions. In the last decade, research into the mechanisms and performance of 'pressure-equalized rainscreen' (PER) walls (as they have come to be known in Canada) has increased. Recent research and the current understanding of the mechanism of pressure moderation will be discussed in the next Section.

4. Theory and Research

The goal of a pressure moderated enclosure design is to reduce wind-induced air pressure differences across the screen. There are two reasons why the reduction of pressure differences across the screen is desirable:

- the amount of rainwater that will be forced across the screen or through vent openings *by air pressures* will be reduced, and
- the screen, and its connectors to the main structure, *may* not need to be designed to carry the entire wind load.

Historically, rainwater penetration control was the primary goal of pressure equalisation, although the potential for reductions in wind loadings, on the cladding and the structural connections between the cladding and the main structure, was always considered. Confusion has sometimes resulted because different researchers have studied one or the other of these two primary goals of pressure moderation.

All pressure-moderated elements of an envelope, whether wall, window frame, or joint, have three basic components (Figure 10):

1. a screen,
2. an air chamber sealed from the building interior by an air barrier, and
3. an air vent (or vents) connecting the chamber to the exterior through the screen .

Of course, wall systems must fulfil many other envelope functions as well. This means that a pressure-moderated wall is composed of more than the three basic components shown Figure 10. Since water will penetrate the screen (the basic assumption in all screened walls), drainage is also very important for the control of rainwater penetration. At the same time, the control of heat, air, and water vapour flow cannot be compromised—that is, an enclosure design must balance the benefits of various rain-control strategies with the equally important needs of controlling air leakage, energy consumption, etc. Therefore, although this report focuses chiefly on pressure moderation and the control of rain penetration, the reader should bear in mind that the sometimes-conflicting requirements of other envelope control and support functions also need to be addressed where appropriate.

The components of a more realistic pressure-moderated enclosure wall system are shown in Figure 11. It should be evident from this figure that the absolute and relative locations of the air barrier, water barrier, and the support and control elements of the inner wythe are not fixed. For example, in some wall systems, insulation is used to protect the air barrier, and it is therefore placed inside the air chamber. The air and water barrier may be the same material, may be located next to one another, or may be completely separated. In many systems, the air barrier is located close to the interior face of the wall assembly (e.g., the air tight drywall approach). The vertical supports for the screen (e.g., a shelf angle in brick veneer construction), the base flashing, and horizontal compartment separators often occupy the same location (and may even be the same component). These complications do not change the functions of the components, but they may affect the requirements for good performance. For example, an air barrier located on the inner face of the wall will remain warm and protected (and thus the requirement for durability will be less), but the volume of the air chamber may be larger and may negatively affect the capacity for pressure-moderation.

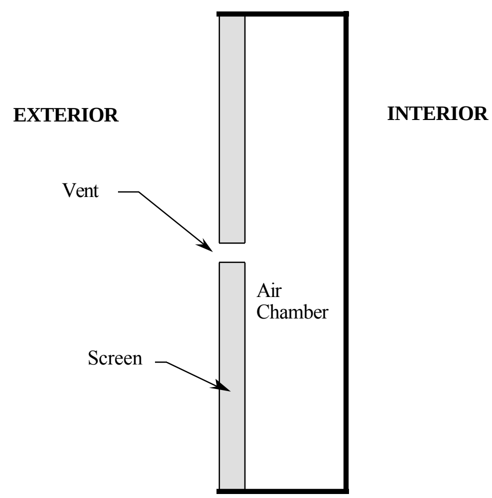


Figure 10: Basic components of a pressure-moderated enclosure system

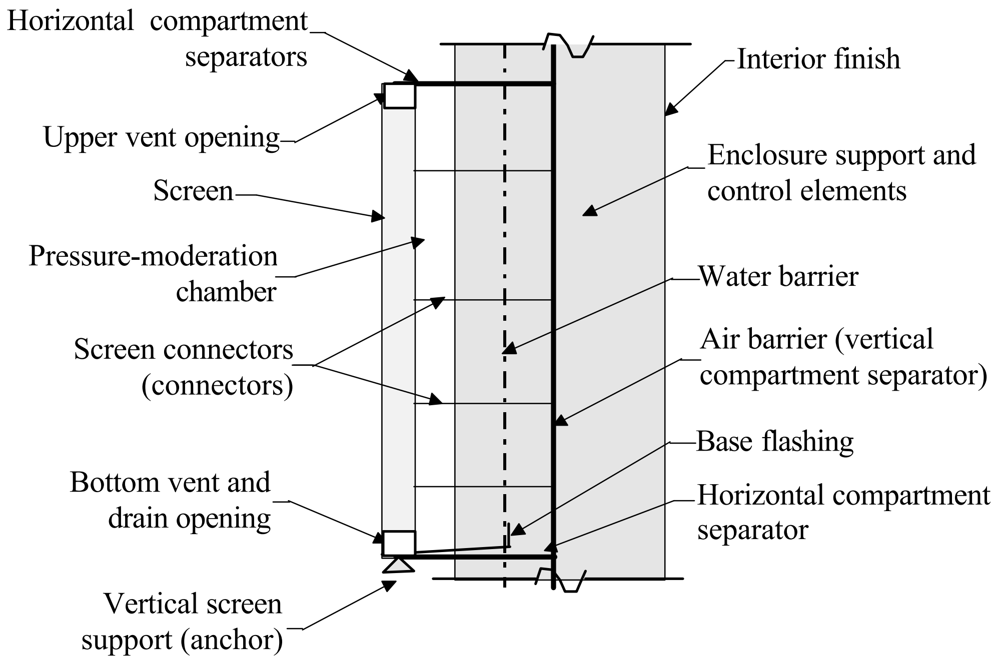


Figure 11 :Schematic of pressure-moderated wall system components

4.1 Factors affecting pressure moderation

The theory and research conducted to date has resulted in a consensus view of the factors that affect pressure moderation performance. The relative importance of each factor, and requirements for design are not yet fully established.

On a general level, pressure moderation performance depends on two general classes of factors:

A. the enclosure system characteristics, and

B. the nature of the wind loading.

The *enclosure system characteristics* can be further sub-divided into categories of characteristics that

I. minimise the volume of flow required to achieve pressure equalisation, and

II. maximise the flow of air into the chamber.

Factors included under the first sub-category are:

1. the volume of air in the chamber;
2. the spatial extent of the chamber, i.e. compartmentalisation;
3. chamber deformability (this includes the flexibility of both the screen and the air barrier); and
4. air barrier leakage, or more precisely, the nature and amount of air barrier permeance.

The second sub-category includes factors such as:

5. venting, or more precisely the nature and amount of screen air permeance;

6. the air flow characteristics within the chamber; and
7. the spatial distribution of venting across the screen.

The *wind load characteristics* that affect pressure moderation are:

1. the mean pressure across the enclosure system;
2. the mean gradients (in two dimensions) across the exterior of each compartment;
3. the time-varying pressures across the system; and
4. the instantaneous pressure field acting across the exterior of each compartment (i.e., the spatio-temporal pressure variations).

Almost all of the existing PER research has examined wall characteristics, although it has been shown in most field research that the characteristics of the wind tend to govern the performance of most common wall systems. Lab tests of pressure equalisation, the basis of most design recommendations, are of the spatially-uniform, temporally dynamic type. It is, however, widely recognised that most screened and vented walls will be almost pressure equalised if exposed to a steady, spatially-uniform pressure (as in most lab tests), but very few wall systems can significantly moderate very short-duration, localised, and high-intensity pulses of pressure.

Requirements for air-barrier tightness, venting area, air-barrier stiffness, etc., have been developed by various organisations — primarily IRC [46] and CMHC [47]. Based on lab tests which applied large sinusoidally-varying but spatially-uniform pressures [48,] and simple computer models, requirements for air barrier tightness, venting area, air barrier stiffness, etc. have been developed.

Recommended values for venting are from 1 to 2% of related wall area and at least 40 times the equivalent air barrier leakage area. Chamber depths should be from 50 to 300 mm (the minimum value is based on the need to ensure drainage), and all sides of the chamber should be stiff. These preliminary requirements are sometimes conflicting and it can be shown that they are difficult to implement in practice for some wall systems [49]. For example, achieving more than about 0.3% vent area in brick veneers is practically very difficult, and this makes the 40:1 ratio impractical. Hence, more recent recommendations use a 5:1 ratio [47], even though this ratio will even not provide good static pressure equalisation.

4.2 Static pressure moderation

Static pressure moderation is the term used here to describe the performance of a system under time-invariant pressures, e.g., long-term averages. If one assumes that a wall system can be modelled as a chamber with a vent opening and a leaky air barrier system, the following analysis, first presented by Latta [40], is appropriate.

Air flow through both intentional vents, as well as cracks and openings in the screen or the air barrier can be reasonably accurately modelled by a power law equation of the form:

$$Q = C_d \times A \times \Delta P^n \qquad \text{(Eq. 1)}$$

where Q is the air flow,

C_d is the flow coefficient,

A is the area of the opening,

ΔP is the pressure difference acting across the opening, and

n is the flow exponent

Latta further assumed perfect sharp-edged orifices for both the screen venting and the air barrier leakage. Such idealised openings have a flow exponent of 0.5. Therefore,

$$Q_{scr} = C_{d,scr} \times A_{scr} \times \Delta P_{scr}^{0.5} \text{ and} \qquad \text{(Eq. 2a)}$$

$$Q_{ab} = C_{d,ab} \times A_{ab} \times \Delta P_{ab}^{0.5} \qquad \text{(Eq 2b)}$$

Under steady-state pressure differences, the flow of air through the screen must equal the flow through the air barrier imperfections, e.g.,

$$Q_{scr} = Q_{ab} = Q_{total}$$

so,

$$C_{d,scr} \times A_{scr} \times \Delta P_{scr}^{0.5} = C_{d,ab} \times A_{ab} \times \Delta P_{ab}^{0.5}$$

and therefore,

$$\frac{A_{scr}^{2}}{A_{ab}^{2}} = \frac{\Delta P_{ab}}{\Delta P_{scr}}. \qquad \text{(Eq.3)}$$

Using Equation 3, the ratio of the pressure drop across the air barrier and across the screen can be calculated for steady-state conditions, regardless of the size of the pressure drop or the amount of air flow. The ratio of screen venting to air barrier leakage is the only parameter that affects static pressure moderation. Supported by the results of Equation 1.3, Latta concluded that a wall with a venting-to-leakage ratio of 10:1 would be 99% pressure moderated, i.e., practically pressure equalised. Changing the flow exponents to more realistic values (e.g., 0.65 to 0.80 for air barrier leakage) does not significantly change the results of this analysis.

The field testing reported later in this paper found that the average chamber pressure measured in field tests reported could be related to the average exterior pressure by the simple expression given in Equation 3.

4.3 Dynamic pressure moderation

As shown in the history section, it has long been recognised that the dynamic and spatially varying nature of the wind has an effect on the actual pressure moderation performance of a wall. However, only in the last fifteen years has research been directed toward assessing the actual dynamic response. The wind pressures on the face of a building change quickly both in time (temporal variations) and space (spatial variations). Each of these dynamic effects is considered below.

4.3.1 Temporal Pressure Variations

Killip and Cheetham [50] were the first to perform laboratory tests of dynamic pressure variations. Using a small scale experimental set-up with turbulent (not modelled on the wind) flow, they concluded that a venting-to-leakage ratio of 2.5 to 4 times that proposed by Latta was required. This research generated the recommendation that the venting area should be from 25 to 40 times the equivalent air barrier leakage area.

The IRC conducted much more comprehensive and detailed research into the effects of dynamic wind pressures on pressure moderation performance [51, 52 48]. Large sinusoidal pressure variations were imposed on full scale wall assemblies, and the response of walls plotted as a function of the frequency of the pressure variation. (Note that this type of testing accounts for the dynamic nature of the wind, but does not assess the influence of spatial pressure variations). Similar testing of different wall systems by Trow Consulting Engineers and other labs showed that high levels of pressure moderation could be achieved at 1 Hz provided good design principles were followed. For example, Choi [53] showed the influence of vent area and air chamber stiffness on the pressure moderation of curtainwall spandrel panels. For many practical scenarios (vent area of less than 1% of screen area), pressure moderation of 50% or less was achieved at 1 Hz. All of these lab tests showed that the pressures in the airspace behind the screen followed the ideal gas law rather closely, i.e., the major determinant of response speed was the compressibility of the air.

That time-varying wind pressures would be easily transmitted to the airspace behind cladding had long been predicted. Holmes developed an analytical solution of the response of a vented chamber to an instantaneous exterior pressure change [54]. Harris extended the analysis to include leakage from the chamber [55]. This theory predicts very fast response to exterior pressure changes, in the order of 0.1 seconds, for typical enclosure wall arrangements. Because brick veneers tend to have low vent areas and most walls have imperfect air barriers, their response is relatively slow, but almost instantaneous pressure equalisation is still expected at frequencies of 1 Hz.

Computer models based on the compressibility of air have also been developed by RWDI (distributed by CMHC [47]) and others [56]. The results of computer simulations have lead to the same conclusion as the analytical solutions: pressure-moderated walls designed with vent areas of more than 0.1 %, and a vent-to-leakage area ratio of more than 10 should be able to moderate spatially-uniform exterior pressure variations quickly, (i.e., >95% pressure moderation at 1 Hz).

4.3.2 Spatial pressure variations

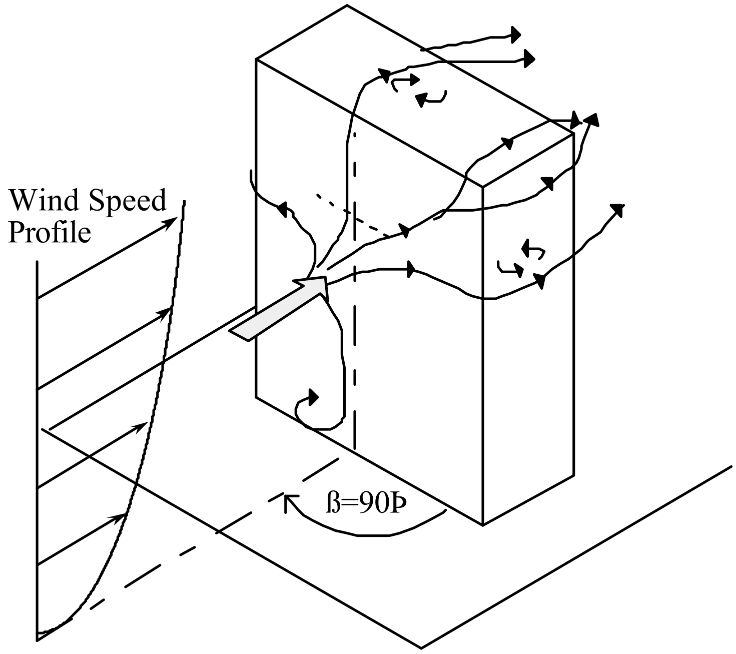
The study of wind pressures on buildings over the last three decades has shown that significant average and short-term pressure variations are present over all faces of a building. The more complex the geometry of the building and the more turbulent the wind, the greater the spatial pressure variations. In fact, almost all of the original research referenced earlier presumed that the spatial pressure variations would have a larger effect than the temporal variations, which they ignored as unimportant.

The mean and short-term spatial variations of the wind can affect pressure moderation for two reasons. One influence is that spatial pressure variations allow pressures to occur across the screen which cannot be equalised by flow since they occur at some distance from the vents. A second concern is that spatial differences that exist for long enough may induce flow in one vent, through the air space, and out another vent. These longer-duration flows could draw water into the chamber. By separating a wall into properly sized compartments the mean and temporal-spatial variations that occur will be relatively small.

The average spatial variations can be described by the hourly average pressure gradients, typical plots of which can be found in many design codes (e.g., Figure 12). The study of short-term spatial-temporal variations has only recently been studied in depth. Surry, Skerlj, and Inculet have used orthonormal decomposition to condense pressure gradients (both average and long-term) from a wide range of building shapes to statistically significant average values [57, 58, 59]. This work has shown that the mean and instantaneous pressure gradients across the face of a building near the top and side edges of a building are much larger than near the middle. Gradients due to short-duration wind gusts are especially severe. Based on its own and other wind-tunnel studies, these researchers recommend a maximum compartment area of 1 m^2 to achieve 80% dynamic pressure moderation. Even "static" pressure moderation can be negatively affected by the steep average gradients near edges. As shown elsewhere, the top and side edges of a building are precisely where most of the water is deposited by driving rain.

Experience with testing small panel, well-vented European rainscreen overcladding has shown that while a reduction in wind load can be achieved, the spatial variations remain. In fact, Cook states that "The principal loads on the outer skin and its fixings comes from the variation in pressure distribution over the skin" [60]. In one of the few detailed field studies of pressure moderation, it was concluded that spatial variations governed the wind load on slate roof panels, but that, not surprisingly, pressure moderation of average pressures (static pressure moderation) was achieved [61].

Cook [60], Gerhardt [62, 63], and Solliec [61] have all found that wind loads on the cladding can be predicted given the pressure field (e.g., the spatial pressure variations) and the flow characteristics of the system. Essentially this is more evidence that *the compressibility of air simply does not govern the response of typical wall systems under realistic wind loads*.



Wind Streamlines On A Building Face

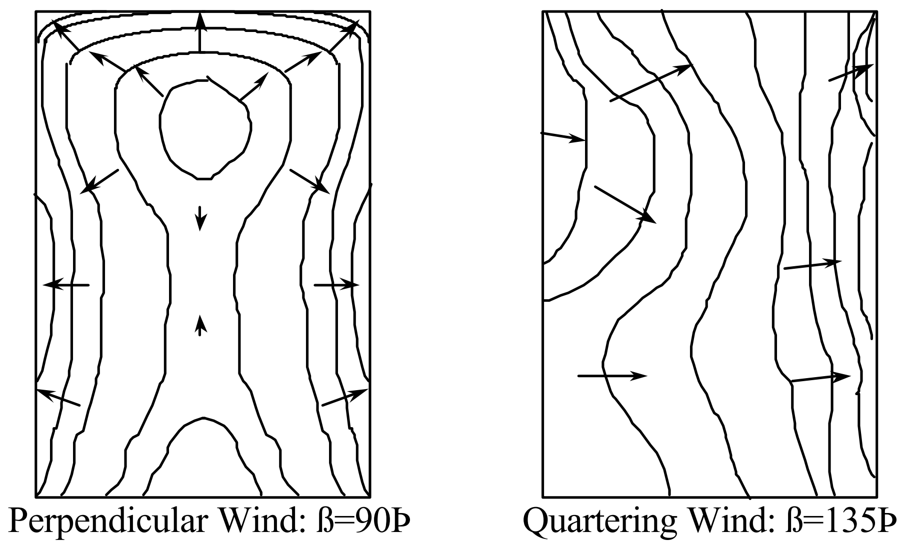


Figure 12: Average Hourly Spatial Pressure Gradients on a Building

Although some best practise guides suggest that a single large vent is the best distribution of vents [46], this is not supported by theory or field and wind tunnel measurements. Distributing vents over the compartment should increase the averaging of compartment pressures (and thus increase the pressure moderation over the entire screen area). If, however, spatial variations are large relative to the mean pressure, the increased airflow through more than one vent could result in inertial effects reducing the response time and decreasing overall performance. There has been no field evidence to suggest that the latter mechanism has any significance.

4.4 Previous field monitoring

Although theoretical and lab studies have provided important information about the performance of pressure moderated systems, the field performance needed to be confirmed.

To fill the need for field results, the NRCC's Institute for Research in Construction (IRC) comprehensively monitored two full-scale buildings in the early 1980's. One building was a high-rise precast concrete clad office tower in Montreal (Place Air Canada) [64] and the other was a low-rise brick veneer courthouse in Lethbridge, Alberta [65].

The monitoring of Place Air Canada showed that the static pressure moderation of this tightly compartmentalised, stiff, and airtight wall system was excellent, but that short term (a few seconds) pressure differences could exist because of spatial pressure variations in the wind. The Lethbridge Court House monitoring showed static pressure moderation of about 50%, and short-term pressure moderation of as little as 10%.

More recent CMHC-sponsored field monitoring has shown that typical brick veneer walls may moderate only 50% [66] and glass curtainwall spandrels may moderate only 25% [67] of *static* pressures. Dynamic performance was not measured in these studies. The lack of sufficient vent area, blocked air spaces, and leaky air barriers probably account for the lack of steady-state (long-term) pressure moderation in these and many other typical walls.

A recent field study of an open-jointed metal panel system has also been reported [68]. Although the tested wall system was not described (e.g., no information of vent area, cavity size, air barrier leakage, etc), the results appeared to be good. Like much of the available data, the data was analyzed in the time domain only and therefore cannot necessarily be extrapolated to different wind conditions or different wind events. The system appeared to provide good results (pressure moderation of 50 or 60%) as expected from the large vent areas and small panel sizes typical of this type of cladding. The majority of the benefit is due to static pressure moderation, not dynamic moderation.

Field monitoring of the pressure-moderation performance of several brick veneer panels at the Univeristy of Waterloo test house was conducted as part of a CMHC-sponsored project [69]. This monitoring showed that the airtight and tightly compartmentalised (1.2 by 2.4 m) panels provided a high degree of static pressure moderation, but short-term gusts were poorly moderated (e.g., between 20% and 50% moderation of gusts 1 to 10 seconds long).

The fact that the results of lab tests and computer simulations, both, which assume a dynamic but spatially uniform wind pressure field, match well, while field measurements show inferior performance is strong evidence that spatial pressure variations are very important.

Several significant conclusions can be drawn from the few reported field measurements of pressure-moderated walls:

- the wind's temporally and spatially varying nature affects the extent, frequency, and nature of pressure moderation performance,
- the probability of high wind speeds is low, the stagnation pressures generated by wind most of the time are low, and the amount of time that high winds and rain occur together is very low, (see other BEG work), and

- neither theoretical predictions based on the compressibility of air and assuming a spatially-uniform pressure nor laboratory test can, without further analysis, accurately predict dynamic pressure moderation of realistically large (> 1 m^2) panels.

4.5 Rain penetration control

Even a high degree of pressure moderation may not reduce rainwater penetration in many systems. Many forces drive water across the enclosure and pressure moderation only reduces air pressure differences, it does not address any other concerns. Rain water can also penetrate the screen as a result of the forces of gravity, capillarity, surface tension, etc. Any water penetration of the screen as a result of forces other than air-pressure differences will, of course, decrease the relative contribution that pressure moderation can make to the amount of rain that penetrates the screen.

Walls that are labelled “pressure-equalised rainscreens” by their designers often have screens that allow water to penetrate, either due to gravity-assisted capillarity or through unintentional openings. Masonry veneer walls are the most common example; significant quantities of rain will penetrate brickwork even when zero air pressure is applied [70, 71] (e.g., even if perfect pressure equalisation is achieved). In practise the rate water of permeance is relatively insensitive to air pressure differences. Hence, such walls must be designed and built with attention to proper drainage and to the water resistance of the secondary water barrier, since water will penetrate the screen regardless of whether or not air pressure differences exist across the screen.

Theoretically, pressure moderation can only provide a useful increase in rain control for screens that exhibit little or no leakage at zero air pressure difference and significantly increased leakage at reasonably likely static air pressure differences. Screens that meet these requirements are some natural stone veneers, metal panel systems, and glass and metal framing elements of curtainwall systems or windows. Hence, any benefit from moderating the pressure difference across the screen would be a reduction in structural wind loads. All screen materials that are impervious to water can be designed to resist rainwater penetration by proper detailing without any assistance from pressure moderation. In most cases, this detailing involves surface and interstitial drainage and capillary breaks. Some of these features also will result in some degree of pressure moderation.

As described previously, the *joints* between elements made of non-absorbent cladding materials usually experience much higher rain loadings since the screen drains water rather than absorbing it. These joints are exposed to all of the environmental loadings of the screen and may not be built in a water-tight manner, or may not remain perfectly water-tight (e.g., caulked joints). Designing such joints to be drained and pressure-moderated is theoretically compelling and has been shown to be successful both in laboratory and natural-exposure tests [41,42,43,44,45] as well as in practice. (The two-stage joint, when properly drained and pressure-moderated, is an example). Therefore, there is little need to pressure moderate water impermeable screens and the design emphasis should be on the drainage (and perhaps pressure moderation) of the joints between elements.

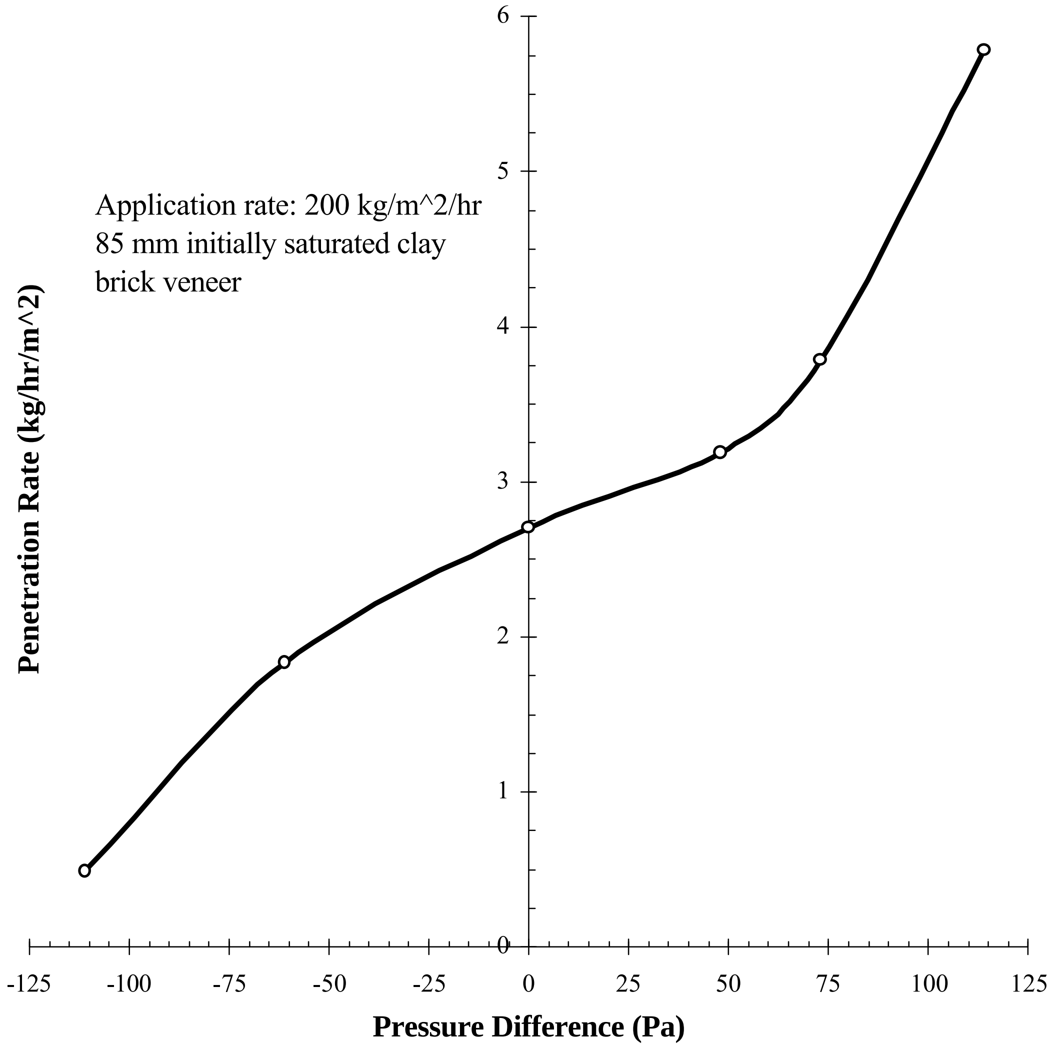


Figure 13: Steady-State Water Permeance of Brick Veneer vs. Air Pressure Difference

Drainage must always be provided in pressure moderated systems [72] because:

- pressure moderation can never be expected to be perfect, and
- air pressure is not the only water penetration mechanism.

This conclusion leads from the fact that pressure moderation *merely augments* a drained-screen's ability to control rain penetration by reducing the load on the drainage system.

Capillary suction pressures of a few hundred to a few thousand pascals may draw water into small openings such as failed sealant bond lines, cracked stucco and concrete, and small construction joints in metal curtainwalls. This water will be retained in the crack by surface tension forces until disturbed by a larger force. Wind pressures can be this force. Pressure moderation can be beneficial by reducing the peak pressures acting on these surface tension films to a level low enough that the surface tension force holding the water in the crack or opening is not exceeded. This is unlikely to be the case in practise.

Therefore, only screened enclosure systems in which:

1. air pressure differences are the *only* rain penetration force *and*
2. instantaneous pressure equalisation can be achieved under all conditions

do not need to provide drainage or storage for rain penetration control. Since there are few, if any, practical examples of such enclosure systems, it must be concluded that pressure moderation can only reduce the load on the drainage system (or the storage capacity in mass walls).

Provided sufficient drainage capacity exists, pressure moderation provides little benefit in controlling rain penetration. However, pressure moderation can *aid* rain penetration control in enclosure systems which:

- rely on storage within or behind the air space, or
- have limited or imperfect drainage, or
- have air pressures as the primary penetration force.

Therefore, even without any knowledge of actual in-service PM performance, two significant conclusions can be made:

1. S*creened wall systems with water permeable screens (e.g., brick veneers, stucco, lap siding) must be designed with drainage and/or storage. Their performance will not be much improved by dynamic pressure moderation, since drainage already is provided.*
2. *The rain penetration control of enclosure systems for which both air pressure differences are important rain penetration forces, and which have little storage capacity (e.g., EIFS, metal panels, windows, vinyl siding) can potentially benefit from pressure moderation. However, it is the joints in these systems that require attention, not the elements, so the use of drained and screened or pressure moderated joints is all that is required.*

4.6 Structural load reduction

The wind loads that must be transferred by a PM wall system to the main structural system of the building are the same as other types of wall systems. However, the manner in which these loads are transferred and the nature of the load distribution can be quite different.

Well-vented and properly compartmentalised PM systems may allow a significant redistribution of wind loads from the screen to the sides of the chamber (the air barrier and compartment separators). Potential savings can be achieved if the air barrier system transfers most of the wind loads to the structural sub-systems under all conditions, because the cladding then does not need to be designed to carry these loads. In many screened wall systems currently being built, it is well accepted that the cladding does carry a significant percentage of the wind load. Nevertheless, the air barrier system and its structural supports must still be designed for the full wind load. If the load distribution between the cladding and air barrier could be predicted, each component of the wall could be "optimally" designed for the load it actually must support. It is presently common practise to design both the cladding (e.g., metal panel or brick veneer) and the air barrier system (e.g., the drywall on steel studs) for the full wind load.

With regard to structural loads and pressure moderation, there are several potential problems that must be addressed:

- The actual distribution of wind loads is dynamic and not easily predicted. Depending on the type of loading, the cladding may in one instant carry a large load while in the next instant the air barrier system may carry the full load. Other components in a wall system also carry loads. Housewraps, rigid insulation, and any other material that has any resistance to airflow will share some of the load. Even under static pressure differentials it is far from obvious which wall components are carrying what share of the total imposed wind load.
- The structural system of screen and air barrier may not allow for a reduction in screen stresses or deflections in some situations. For example, if the structural system supporting the air barrier is more flexible than the screen, wind load shed from the screen by pressure moderation will be redistributed back to the screen by the connectors to maintain geometrical compatibility. This is the situation with most steel-stud-supported masonry veneers.
- Because structural design must be based on extreme loads, the level of pressure moderation performance and reliability required for load reduction are much more stringent than for rain penetration control. Cladding in Canada (most countries have similar requirements) must be designed to withstand the worst loading expected in 10 years. This translates to the worst second in 10 years, or one second in 315 million.

Several researchers have attempted to assess the influence of pressure moderation on cladding and connector loads. Gerhardt and his co-workers have conducted the most detailed studies of such load reductions, both in the wind tunnel and the field [62 ,63]. This work was conducted on panellised systems with large vent areas, clear air spaces, and good air barriers. They found that load reductions of 40% could be achieved if the proper amount of venting was provided. They also showed that the possible load reduction was strongly affected by the height-to-width ratio of the building and the amount of air permeance through the cladding and air space (defined by the vent area and the unobstructed area of the air flow gap behind the screen). The nature of the wind (e.g., open country or city exposure) played a smaller role. By decreasing the size of the airflow gap behind the cladding, cladding loads were reduced because the friction acted to compartmentalise the system. The minimum vent area considered was 0.5% of wall area, and only relatively small panels were assessed.

Egner [73] conducted a series of dynamic pressure lab tests on small (up to 1.35 m) cladding panels. The test panels were well compartmentalised, and small enough that the spatial wind pressure variations would have less effect. The smallest vent area investigated was 1% of wall area. He developed an equation for the fraction of the total wind load taken by the cladding panel for frequencies less than 3 Hz:

$$f = 1.13 \cdot a_{flow} \cdot a_{vent}^{-0.87} \leq 1 \qquad \text{(Eq.4)}$$

where a_{flow} is the area of the thinnest section of the airspace behind the cladding through which air can flow divided by the area of the cladding panel

a_{vent} is the area of the thinnest section of the airflow path connecting the exterior to the airspace behind the cladding divided by the area of the cladding.

A unit width of a 2.4 m high brick veneer wall with a 25 mm air space has a flow area of $0.025/(2.4 \cdot 1.0) = 1\%$. If open head joints are provided at 600 mm centres, top and bottom, the vent area is $(2 \cdot 0.01 \cdot 0.065) / (2.4 \cdot 0.6) = 0.09\%$. Egner's equation predicts a load fraction of 1.0 -

- no load reduction. Load reductions are predicted only if the vent area is increased to more than 0.6%. Equation 4 also predicts a load reduction of 38% for a vent area of 1%. Such large vent areas are difficult to achieve in practical brick veneers without, for example, the use of continuous slots along the top. These results are more conservative than other analytical procedures.

The European pressure moderation research appears to be following their previous ventilation research, i.e., the emphasis is on panellised systems and large vent areas are always recommended.

Untested calculations by Solliec et al suggest that load reductions of as much as 60% might be achieved by proper design of air permeable cladding [61]. This figure implies a very flexible cladding with a stiff backup, perfect equalisation of mean pressures and a reasonably high degree of pressure moderation at 1 Hz (about 50%).

5. Recent Field Monitoring at UW

Twenty-six test panels built as part of a province-industry funded project were instrumented with pressure taps to allow for pressure moderation performance measurement. Several different panels oriented in different directions, and built with different air space sizes etc. were monitored. The test panels, experimental set-up, monitoring protocol, and analysis methods are briefly described in this section. The following sections present and analyse the results.

5.1 Test panel description

All of the brick veneer panels were 1.2 m wide and 2.4 m high. They were vented with four open head joints, each approximately 10 x 65 mm, two at the top and two at the bottom (total vent area = 2600 mm^2). This vent area is approximately equal to 0.1% of the wall area and is at least 50 times the leakage area of the panel.

Note that all of the panels tested were built with better quality than could be expected of a real wall: the inner layer of sealed drywall acted as a perfect air barrier, the 1.2 m wide by 2.4 m high compartment size is quite small (better than most brick veneer compartmentalisation recommendations), and the 4 open head joints provide more vent area than in most practical brick veneer walls (although much less than the recommended 1 to 2%).

Although all of the brick veneer walls monitored are ideal with respect to actual practise, they are far from ideal with respect to most accepted guidelines. Wall systems such as some European cladding panel systems, that incorporate tighter compartmentalisation, much greater vent areas (usually 1 to 3%) in the form of perimeter joints (i.e., a form that acts to “smooth out” spatial pressure variations), can be expected to perform in a much different manner.

The monitored wall panels were shown to be practically airtight, i.e., air-leakage testing of the inner air barrier revealed no measurable leakage. Some of the panels were intentionally made more leaky during some monitoring periods by opening a 38 mm diameter hole in the lower middle of the drywall (total leakage area = 1,134 mm^2, equivalent to a vent area to leakage area ratio of 2.3:1).

None of the test panels were located at the corners of the Beghut test house. Because of spatial pressure variations, which are much greater near corners, wall panels located near building edges are expected to have much less dynamic pressure moderation than the panel results reported here.

The size of the pressure-moderation chamber in the brick veneer panels is difficult to define. Theoretically, the depth of the chamber extends from the back of the brick veneer to the air barrier (the drywall in the brick veneer panels). In practice, however, the housewrap or the rigid sheathing acts as the back of the chamber instead of the primary air barrier doing so. Therefore, the panels acted as if they had a chamber depth of 30 mm in the datum panels, 50 mm in the R panels, and 75 mm in the O panels.

5.2 Experimental set-up and monitoring protocol

The test panels were instrumented with numerous pressure taps. The field monitoring program involved continuous pressure measurement (at 3 Hz) at eight locations: at the four vent holes, at the centre of the exterior face, and at mid-height, the top, and the bottom of the airspace. Wind speed and direction at 3.5 m and 10 m above grade were monitored concurrently. The instrumentation used and the exact location of the pressure taps are described in detail in elsewhere [1].

As noted in previous studies, it was necessary to continuously monitor each wall for some time to obtain meaningful results (i.e., until high enough winds from the proper direction occurred). A west-facing (prevailing wind direction) brick veneer wall was monitored for more than 4 months under 4 different venting and air barrier leakage scenarios. Other walls were monitored for only one month.

The data was collected in approximately 15-minute segments: at least 5 segments were collected for each of 5 wind-speed categories and 12 wind-direction categories for each wall and each venting and air barrier leakage combination. Each record contained 2048 entries, each entry spaced at 1/3 of a second (i.e. 3 Hz). Each entry of eight pressure measurements, wind speed and direction measurements was collected at a rate of about 1 kHz, e.g., the ten readings were taken in the space of 1/100 of a second.

5.3 Analysis technique

A windspeed or pressure signal can be considered to be made up a normally distributed random component and an average component. While the average and standard deviation of such a signal provide useful information, these time-domain statistical measures do not provide much information about the distribution of gust pressures, nor the length of gusts. This information is obviously very important for an assessment of pressure moderation performance.

Like most random signals, a wind pressure signal can be approximated by an infinite series of sinusoidal waves, each with a unique frequency (f), amplitude (A), and phase shift (f):

$$P_{wind}(t) = \overline{P_{wind}} + \int_0^{\infty} A_{wind}(f) \cdot \sin[2\pi \cdot f \cdot t + \phi_{wind}(f)]\, df + n(t)$$

where $P_{wind}(t)$ is the instantaneous wind pressure,

$\overline{P_{wind}}$ is the average wind pressure over the entire period,

n(t) is a random component not described by the equation.

Based on a vast body of measurements, it is widely accepted that the wind can be accurately statistically described in the frequency domain, even though this description is an estimation. (The relative size of the term n(t) is an indicator of the accuracy of the approximation). The most useful general descriptor is the power spectrum, a plot of the amplitude A versus frequency *f*. The power spectrum varies with wind speed and terrain; this variation is described in many references including the Commentary to the National Building Code [75]

Pressures on the face of a building are different than pressures in the free wind because the airflow is modified by the presence of the building. Frequency domain methods are also useful to describe these pressure variations, especially since the random component of building pressures is not necessarily normally distributed (e.g., the standard deviation is a less reliable measure). The following equation can be used:

$$P_{ext}(t) = \overline{P_{ext}} + \int_0^{\infty} A_{ext}(f) \cdot \sin[2\pi \cdot f \cdot t + \phi_{ext}(f)]\, df$$

Although the pressure within the chamber of a pressure moderated wall system is expected to follow the exterior wind pressure, some attenuation and time lag is expected. Assuming the that the response of the chamber to exterior pressures is linear (and based on the lab-tests referenced earlier, this is at least a good approximation) the response of the chamber to a single sinusoidally varying exterior pressure can be described by:

$$P_c(t) = \overline{P_c} + k \cdot A_{ext} \cdot \sin[2\pi \cdot f \cdot t + \phi]$$

where $P_c(t)$ is the instantaneous chamber pressure at time t

$\overline{P_c}$ is the average chamber pressure

k is the amplitude attenuation coefficient, the ratio of the chamber amplitude to exterior amplitude,

f is the phase shift, the angular displacement of the chamber pressure relative to the exterior pressure (where 2π radians are one period, 1/f).

This is the equation used to describe lab test results which impose a single frequency sine wave to a wall system and measure the response.

For many superimposed frequencies, a real wind pressure for example, the following equation can be expected to apply (provided that the response is still linear):

$$P_c(t) = \overline{P_c} + \int_0^{\infty} k(f) \cdot A_{ext}(f) \cdot \sin[2\pi \cdot f \cdot t + \phi(f)]\, df$$

The amplitude attenuation and the phase shift together describe the frequency-dependent response of the chamber pressure to a random exterior pressure.

The power spectrum of many random signals can be approximated by using the Fourier transform of a record of measurements. The mathematical foundation of the Fourier technique means that N/2 estimates can be calculated from N measurements. The very efficient Fast Fourier Transform (FFT) method requires N to be a power of 2, i.e., records with 128, 1024, or

4096 measurements are acceptable, whereas records with 100 or 2000 are not. The Fourier method approximates a random signal with a series of sinusoids of the following form:

$$x(t) \cong \sum_{i=1}^{N/2} A_i \cdot \sin(2\pi \cdot f_i \cdot t + \phi_i) \qquad N, \text{even}$$

where x(t) is the estimated value of the random signal at time t

A_i, f_i, and ϕ_i are the amplitude, frequency, and phase shift of the ith component

N is the number of discrete measurements of the real signal.

By calculating the Fourier transform of a real signal, the frequency dependent amplitude and phase shift can be estimated. The transform of a signal x will be denoted $S_x(f)$ throughout this paper.

The function relating a systems output with to input is termed the transfer function in communications theory. Since this transfer function is often frequency dependent, the term frequency response function is often used. This function can be found from:

$$H_{ext \rightarrow c}(f) = \frac{S_c(f)}{S_{ext}(f)}$$

where H(f) is the frequency-dependent transfer function and the subscript indicates the relationship between the system's input (exterior) and output (chamber), and

$S_c(f)$ and the $S_{ext}(f)$ transforms of the chamber pressure and the applied pressure respectively.

The amplitude attenuation and phase shift between two signals can then be found from:

$$k(f) = \left| H_{ext \rightarrow c}(f) \right|$$

$$\phi(f) = \tan^{-1}\left(\frac{Im[H_{ext \rightarrow c}(f)]}{Re[H_{ext \rightarrow c}(f)]} \right)$$

where Im and Re are the real and imaginary parts of the complex function H.

The value that is of most interest is the pressure difference across the screen, $P_{\Delta scr}$. Using a similar development as above, a more compact description of pressure moderation performance is provided by the fraction of the exterior amplitude that generates a pressure across the screen, e.g.,

$$k_\Delta = \frac{A_\Delta}{A_{ext}}$$

which becomes, over the frequency domain:

$$H_{ext \rightarrow \Delta}(f) = \frac{S_\Delta(f)}{S_{ext}(f)}$$

$$k_\Delta(f) = \left| H_{ext \rightarrow \Delta}(f) \right|$$

$$\phi_{\Delta}(f) = \tan^{-1}\left(\frac{\mathrm{Im}[H_{ext\rightarrow\Delta}(f)]}{\mathrm{Re}[H_{ext\rightarrow\Delta}(f)]}\right)$$

The $k_{\Delta}(f)$ function is an excellent measure of the magnitude of the pressure difference across the screen. In the time-domain, the wind and wind-induced pressures on a building never behave the same way twice, whereas in the frequency domain the short-term variations do (this is why the power spectrum is so useful for assessing wind loads). Since a unique value is calculated for each frequency, the function is theoretically independent of the frequency spectrum of the applied wind. These features mean that the $k_{\Delta}(f)$ function allows repeatable and comparable results, results that can also be compared to single-frequency lab tests. The method has been developed and applied to pressure moderation by at least 2 researchers [1,74].

There are some limitations to the chosen frequency domain approach however. The basic assumptions in the development are that the wind is a stationary signal (the mean does not change over the record) and that the process connecting the pressures outside and in the chamber are linear. The former assumption can be overcome by analysing only records that are stationary. A simple means of checking is to calculate the average of three or five contiguous blocks of a record. If the average of each is similar, the record is stationary. This is common practise by researchers measuring wind in the field. During some weather events (e.g. thunderstorms), stationary records are impossible to collect because the wind velocity is increasing or decreasing.

The linearity of the process connecting the interior and exterior pressures is a more serious limitation -- in walls where inertia, flow through vents, wall stiffness, and similar non-linear processes dominate, the analysis method described above may not provide repeatable results. In the walls being analysed in this thesis, the range of pressures and the physical nature of the walls are not likely to cause significant non-linearities. This contention is supported by lab tests and field measurements. Linear computer models are able to predict the pressures in the chamber reasonably well. Also, the repeatability of the results reported later strongly support the assumption of linear processes.

5.4 Wind record selection criteria

To simplify analysis and to allow for meaningful comparisons, the analysis that follows concentrates on the response of the panels to wind conditions that favour instantaneous pressure equalisation and rain deposition, i.e., positive windward pressures. Records during which the wind speed was high (over 4 m/s) and stationary, and the mean wind direction was almost perpendicular to the wall being monitored (mean wind direction less than ±30º off perpendicular) were analysed in depth. These records have the highest positive windward pressures and some of the smallest spatial variations in the wind pressures. The nature of the wind is such that even with these restrictions, instantaneous wind direction variations of ±75º and windspeeds of ±50% of the mean windspeed were commonly observed over the course of a 15 minute record.

The frequency-domain method of analysis was used because it ensures that measurements taken at different times will yield similar results for broadly similar wind conditions. However, it was found to be difficult to analyse the results of the pressures under glancing wind conditions (angles > ±60º off normal) because the exterior pressure would change from positive to negative very quickly. The frequency domain analysis gave what are believed to be incorrect, or at least not useful, results. Wind conditions such as these do not cause the deposition of much rain and so are not important for rain control.

It is important to note, however, that cladding structural design is often governed by peak suction pressures and these typically occur under wind angles of about 100 - 120º off normal. The pressure variations in the separation zone of a building are very difficult to describe because two different types of flow processes are involved, and the type of process can change quickly between attached and fully detached flow.

In this paper, all frequency-domain plots have been calculated from a minimum of five 15-minute-long wind-pressure records collected under similar wind speed and wind direction conditions. The pressures acting at the middle of the panel on the exterior, the pressure moderation chamber, and the inside have been used in all calculations because they are considered to be the most representative or average values.

The average, standard deviation, peak loads, and correlations between all of the signals were also calculated from the time-domain records using standard methods.

6. Results and Analysis

In general, the results of the pressure moderation performance monitoring support the comments made earlier in the review of previous research and literature. However, the influence of air-barrier leakage and the amount and location of venting was also studied in the experimental program reported here.

The monitoring showed that all of the wall systems exhibit a relatively high degree of static pressure moderation (over time periods longer than five minutes) but very little pressure moderation of short-term wind gusts.

The degree of static pressure moderation is very high (well over 90%) for situations where the pressure field acting over the wall is relatively stable, e.g., under nearly perpendicular (±30º) winds or under suction pressures on the leeward face. Steady-state pressure moderation was found to be slightly lower, in the order of 75 to 90%, for highly erratic wind-direction variations and glancing wind angles (where the pressure on the wall changes rapidly from positive to negative).

Pressure changes of a few seconds duration and shorter were not well moderated by any of the wall systems. Large pressure spikes often last for only a few seconds. Note that in the National Building Code, the design wind pressures for buildings, for example, are based on a gust of 3 to 5 seconds' duration [75], and the cladding or other small components are designed for the equivalent of an approximately 1-second gust or less [76].

For most of the brick-veneer records analysed, the spatial correlation between the readings at the centre pressure tap and the corners of the panel was relatively high, between 90 and 94%: this means that there were no large *average* gradients across the face of the panel. This range of values is similar to wind-tunnel studies of the spatial coherence of pressures across a panel on a high-rise building [77]. However, average gradients near building corners can be much higher, and short-term spatial pressure variations can be very large indeed.

The single variable that correlated most strongly (usually about 70%) with the pressure difference across the screen was the difference between the pressure at the centre of the panel and the average of the pressures at all four vent holes. This result means that on average 70% of the difference in pressure across the screen was due to spatial pressure variations. The correlation of the chamber pressure with the top vent pressures was always higher than was the case with the bottom vent pressures; this result is likely because top vents are usually exposed to higher pressures than bottom vents.

There was a small positive correlation (30-35%) between the pressure at the middle exterior of the panel and the pressure difference across the screen. This result means that on average, the greater the wind pressure, the greater the pressure difference across the screen.

6.1.1 Standard brick veneer

Most of the monitoring was conducted on one set of so-called datum panels, and so most of the analysis concerns this commonly used wall system. This is a typical brick veneer wall with a 30 mm clean air space and 4 open head joints as vents.

Figure 14 is a plot of the pressure-moderation performance of the datum panel under nearly perpendicular wind conditions. The figure is a plot of the percentage of wind pressures moderated as a function of frequency (or, 1÷ wind gust duration). Therefore, 100% indicates that no pressure was acting across the screen and that full, instantaneous pressure equalisation occurred. A value of 25% at 2 Hz (a gust lasting 0.5 seconds) means that 75% of the wind-gust pressure acted across the screen

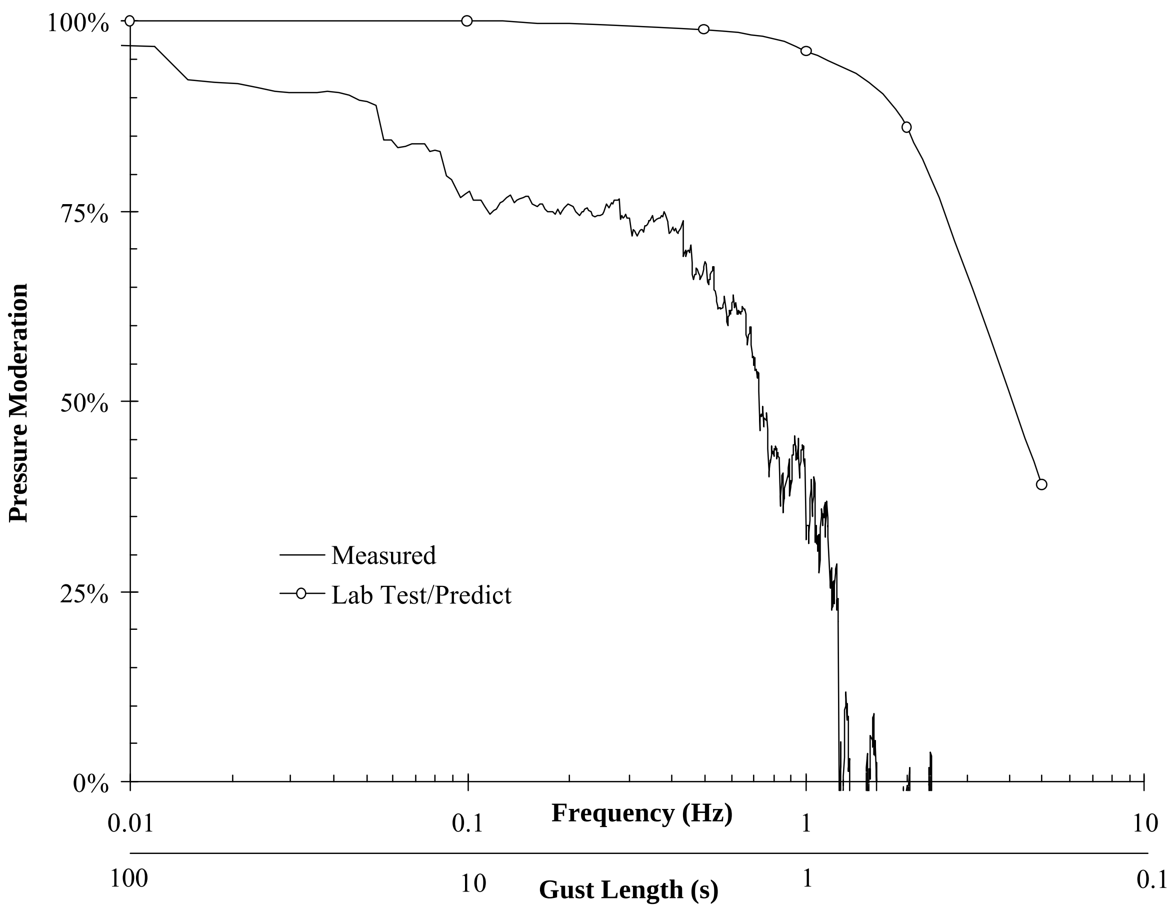


Figure 14: Pressure-moderation performance of brick-veneer panel as measured in the field, the lab, and predicted by computer model

Note: Datum panel with perfect air barrier, 30 mm air space and 4 open head joints. Wind Direction ±30º.

Figure 14 shows that the static pressure moderation of the brick-veneer wall is almost 97% under pseudo-static conditions (a 100-second gust can, for practical purposes be considered a static pressure). However, pressure changes shorter than about 5 seconds long are moderated by less than 50% for wind directions nearly perpendicular to the wall.

A wall system similar to the datum wall has also been tested in the laboratory by NRCC/IRC [78] and the pressure-moderation performance predicted using a computer program developed by the author (BEG-RAIN [1]). The results of these predictions, which match one another, is plotted in Figure 14. Both the IRC laboratory testing and the computer modelling suggest that dynamic pressure moderation should be about 95% at 1 Hz, whereas the field results show that the moderation is almost zero at this frequency. The discrepancy between lab, computer, and field results is convincing evidence of the importance of spatial variations to pressure moderation performance.

The lack of pressure *equalisation* is mostly due to the spatial variation of the wind pressure, not the slow temporal response of the wall system to gusts. Because of spatial variations, the

1 This is a program based on the compressibility of ideal gases. It uses sinusoidal loading conditions and includes the important wall characteristics. This is similar to the most recent version of RAIN, distributed by CMHC.

pressure acting over the central part of the wall can be quite different from the pressure acting at the vents, although the pressure in the cavity responds only to the pressure at the vents. The pressures acting at each vent opening are quite different, especially in turbulent winds. Turbulent winds are the result of rough upstream fetches (e.g., cities) and by building-induced turbulence near building corners, at aerodynamic discontinuities, etc. Therefore, while the panel may be able to respond quickly to temporal variations (e.g., those imposed by laboratory tests and computer models), the spatial pressure variations (and gradients) on the panel reduce the achievable degree of moderation, especially at high frequencies.

In summary, although the pressure-moderation performance of a wall panel can be "tested" in the laboratory or predicted by simple computer models, the actual pressure-moderation performance of most properly designed and built walls will be governed by spatial wind-pressure variations, not the wall design or temporal wind-pressure variations. Therefore computer modelling or lab testing, while useful, may provide misleading results and foster unrealisable expectations for performance.

6.1.2 Filled-cavity brick veneers

Two brick veneer clad walls with cavities filled with porous fibrous insulation were monitored. Both of the panels exhibited pressure moderation performance that was essentially the same but slightly lower than that of the datum panel (Figure 15). While the cavity fills do retard ventilation, the small amount of airflow required for pressure moderation is clearly not restricted by the mid- to high-density cavity fill products used in these panels. The small reduction in performance may be due to the larger chamber (50 to 75 mm deep) volume in these panels.

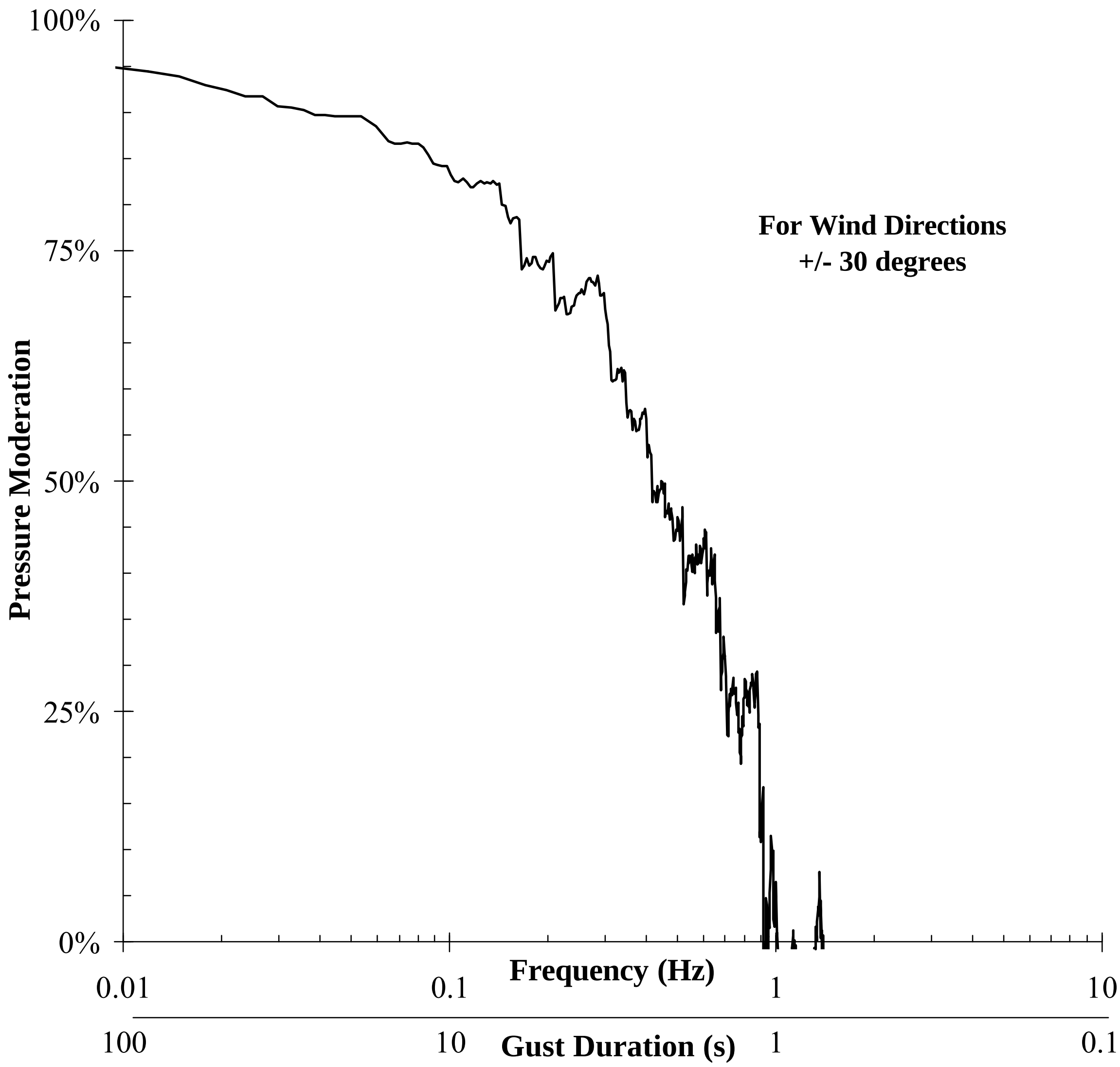


Figure 15: Pressure moderation performance of filled-cavity walls

6.2 Parametric Assessment

Although the characteristics of the wind will, in many cases, limit the maximum achievable degree of pressure moderation, wall characteristics do have an effect, especially at low frequencies. Important variables are the amount of leakage through the air barrier, the total venting area, the vent location, and the wind direction.

Air barrier leakage can have a significant effect on pressure-moderation performance. The larger the ratio of vent area to air-barrier-leakage area, the higher the degree of pressure moderation.

Another common concern is the proper location of the vent openings themselves. The IRC recommends that all vent openings be placed along the bottom [46]. However, Inculet's [79] calculations of spatial wind variations strongly indicate that distributing the vent openings over the compartment will result in the best performance.

These parameters were studied by conducting simple experiments on the datum panel. The datum panel was chosen since it is a commonly used wall system and the results should therefore be relevant to many similar wall systems. After monitoring for several months, a single characteristic was changed, and the wall monitored for another month. The results are presented and discussed below.

6.2.1 Effect of air barrier leakage

Figure 16 compares the performance of datum panel with and without a hole in the primary air barrier. Increasing the equivalent leakage area from almost zero to 1134 mm^2, has the effect of reducing the ratio of venting area to air-barrier-leakage area from nearly infinity to about 2.5:1. The results show that static pressure moderation was reduced (to about 85%) and that the degree of dynamic pressure moderation was similarly reduced, i.e., the performance was about 85% of the airtight response over the entire frequency range.

Based on Equation 3, static pressure moderation can be calculated from:

$$\text{Static pressure moderation} = 1 - (A_{leak}^2 \div A_{vent}^2)$$

Applying this equation to the datum panel with a leaky air barrier and a 2.5:1 vent:leakage ratio results in a predicted pressure moderation of about 84%. Therefore, simple theory provides a close match with the measurements. This evidence suggests that Equation 3 can be used to provide a relatively accurate assessment of long-term pressure response when both the equivalent air leakage area and vent area are known.

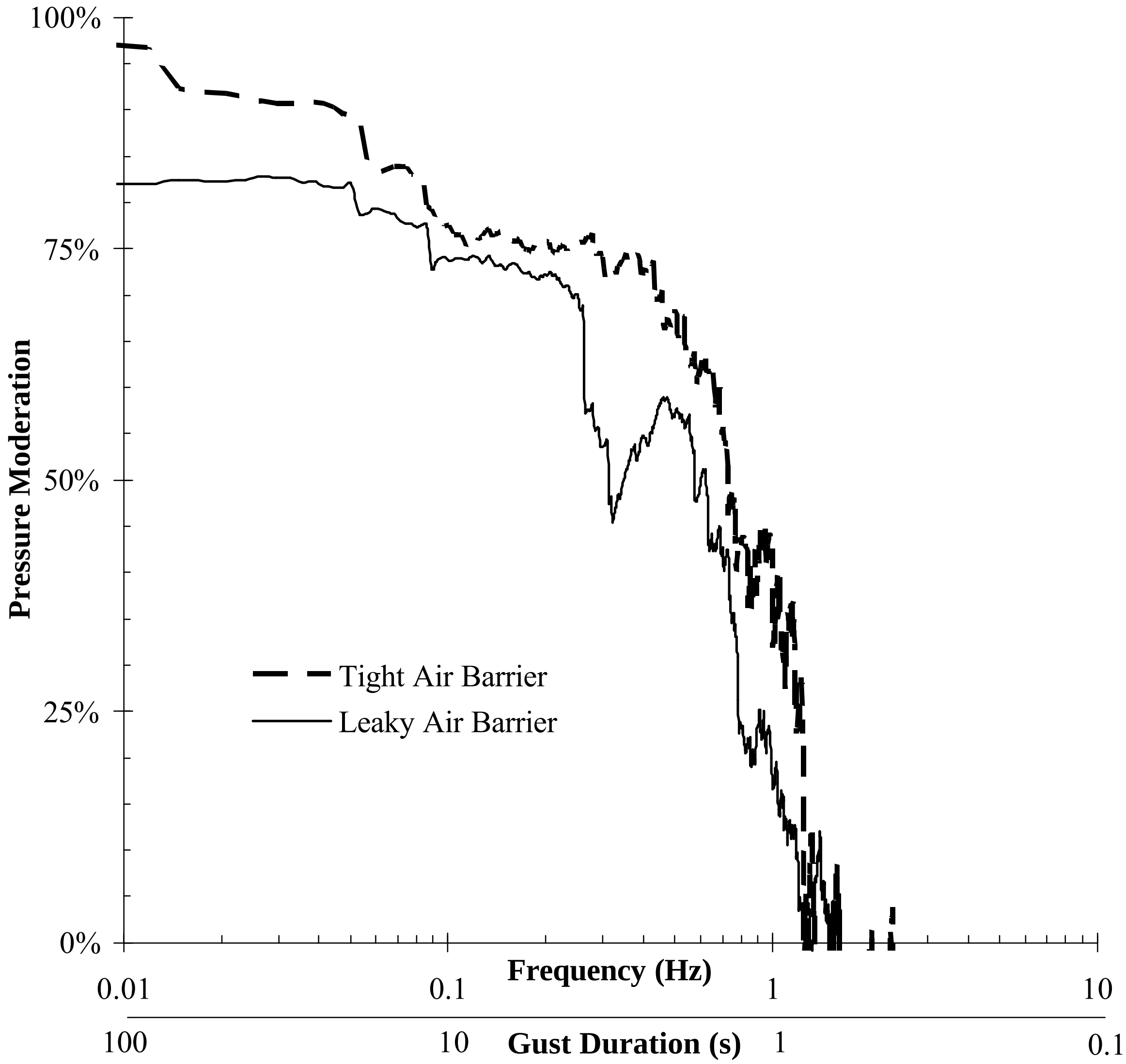


Figure 16: Pressure-moderation performance of datum panel with leaky air barrier

Vent to Leakage Ratio = 2.5:1. Wind Direction ±30º

6.2.2 Influence of total venting area

Most design guides [46] recommend a total venting area of 1 to 2% of the wall area. For a storey-high brick veneer wall system, the 1% requirement translates into about 35 open head joints per running metre of wall. Note that a metre of wall normally has only 2 or 4 head joints per metre. The walls tested in this project contained 4 open head joints per 1.2 m x 2.4 m panel: this is equivalent to approximately 0.1% of wall area. Although this amount of venting is much less than that recommended (by a factor of at least ten), it is much more than is normally provided (by a factor of about 2 to 5). Note that open head joints all along the bottom course of a veneer at 800 mm on centre provides only 0.04%. In practice, head joints are often provided with inserts to protect against the entry of insects, driving rain, etc. It should also be noted that tests have shown that most commercially available vent inserts drastically reduce air flow (by an order of magnitude), and hence significantly reduce the effective vent area.

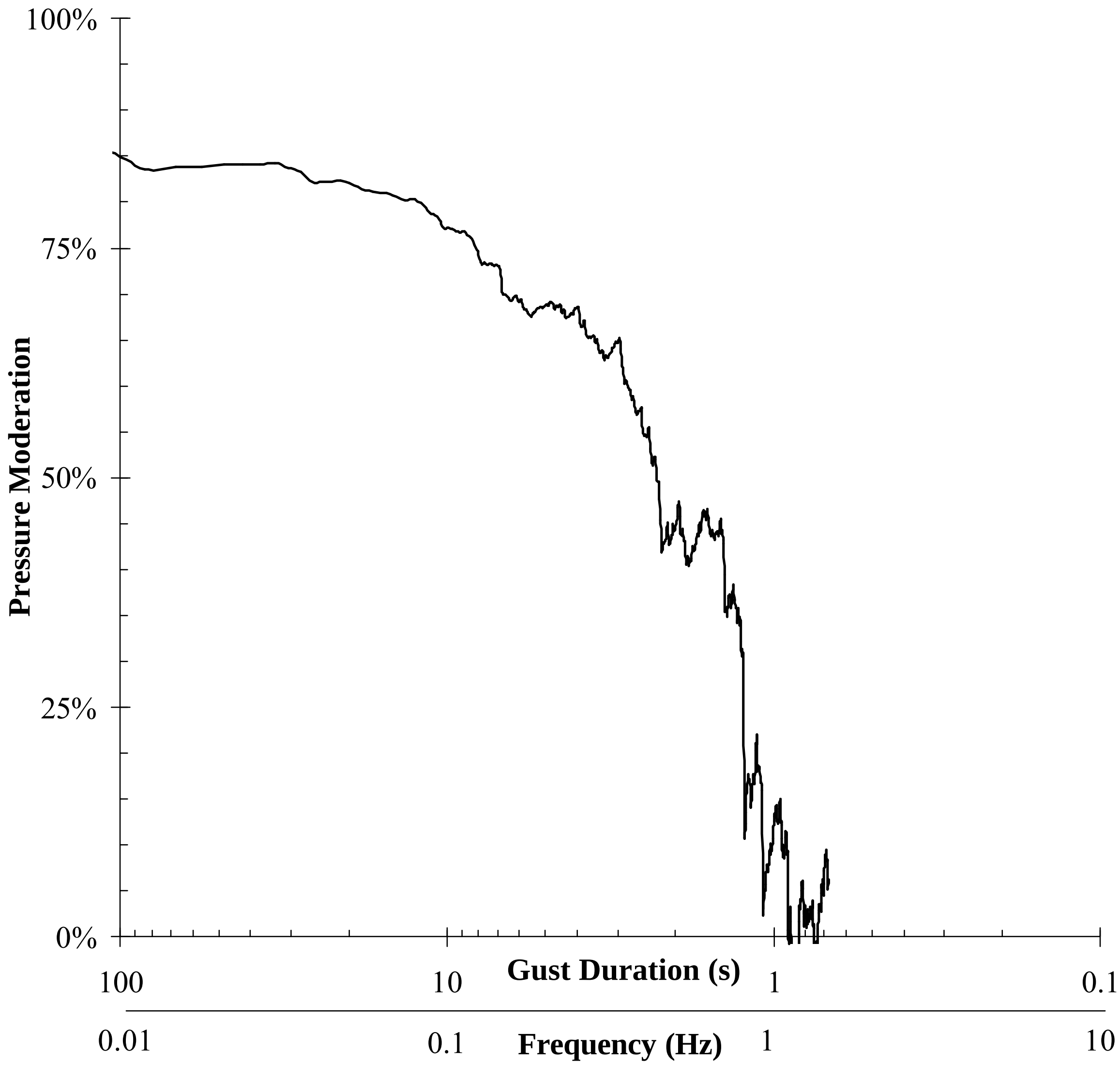


Figure 17: Pressure-moderation performance of datum panel with reduced vent area

Note: Vents were open head joints, located at the top and bottom, diagonally separated on the panel. Total vent area: 1400 mm^2 = 0.05% of Wall Area. Wind Direction ±30º

As reported above, the 0.1% vent area allows for more than 95% pressure moderation of long-duration wind-pressure changes (longer than 100 s). Measurements of the datum panel were also taken with the vent area reduced by half (by sealing two of the four vents). During one two-week period the top vents were closed, and during the next two-week period one top vent and one bottom vent were closed.

Comparison of the results in Figure 14 and Figure 17 shows that the reduced vent area significantly affected the pressure-moderation performance. The effect of reducing the vent area is almost the same as that produced by greatly increasing the leakage area. In the context of these tests, it appears that a vent area of least 0.1% of wall area should be provided for any significant degree of pressure-moderation performance to be achieved under these ideal conditions.

6.2.3 Vent location

The location of vents on the wall is another important issue. Is it better to locate vents at the top and bottom or only at the bottom? In an attempt to provide an answer to this question, pressures were monitored for one month with only the bottom vents open and for one month with one top and one bottom vent open.

Figure 18 shows the results. The pressure-moderation performance clearly was not strongly affected by whether the vents were located at the top and bottom or only at the bottom. This result was somewhat surprising because there is an average gradient of wind pressure, increasing from the bottom of the panel to the top, and it was therefore expected that the bottom-only location would be inferior. In actuality little effect was apparent, although the bottom-only venting did slightly reduce the degree of pressure moderation of the low-frequency, long-duration gusts. The bottom-only location also appears to result in slightly better performance in the high frequency range, although the results in this range are less accurate.

Locating the vents at the top *and* bottom of the cavity has three distinct advantages, however:

1. Locating vents at both the top and bottom will permit and promote ventilation drying.
2. Locating vents at the top is an easy and simple way to double the vent area so that a greater degree of pressure moderation can occur.
3. A more practical consideration is the fact that vents at the bottom of a wall are much more likely to be blocked by mortar than those at the top.

6.2.4 Influence of wind direction

It has long been suspected that the location of the wall on a building and the wind direction would have an effect on the pressure-moderation performance. The analysis presented above is for wind directions almost normal to the wall, and for walls near the middle of the building. A limited analysis of walls near the corner of the Beghut and under different wind angles has been conducted.

No panels can be installed very near the corner (e.g., within 10% of the building width). From limited measurements of panels close to the edge (about 15% of building width), the pressure-moderation signature did not change, since it is a measure of the wall response. However, the wind contains more high-frequency / short-duration gusts (the wind is more turbulent), and hence a larger percentage of the gust pressures imposed by the wind are moderated to a lesser degree. The likely consequence is poorer average or overall pressure-moderation performance. Unfortunately, the areas of a building likely to receive the most driving rain (edges and corners) are also the areas where dynamic pressure moderation is the most difficult to achieve [1]. In these areas the area of the compartments in the test panels would have to be much smaller in order to achieve the same level of performance as at the middle of the building.

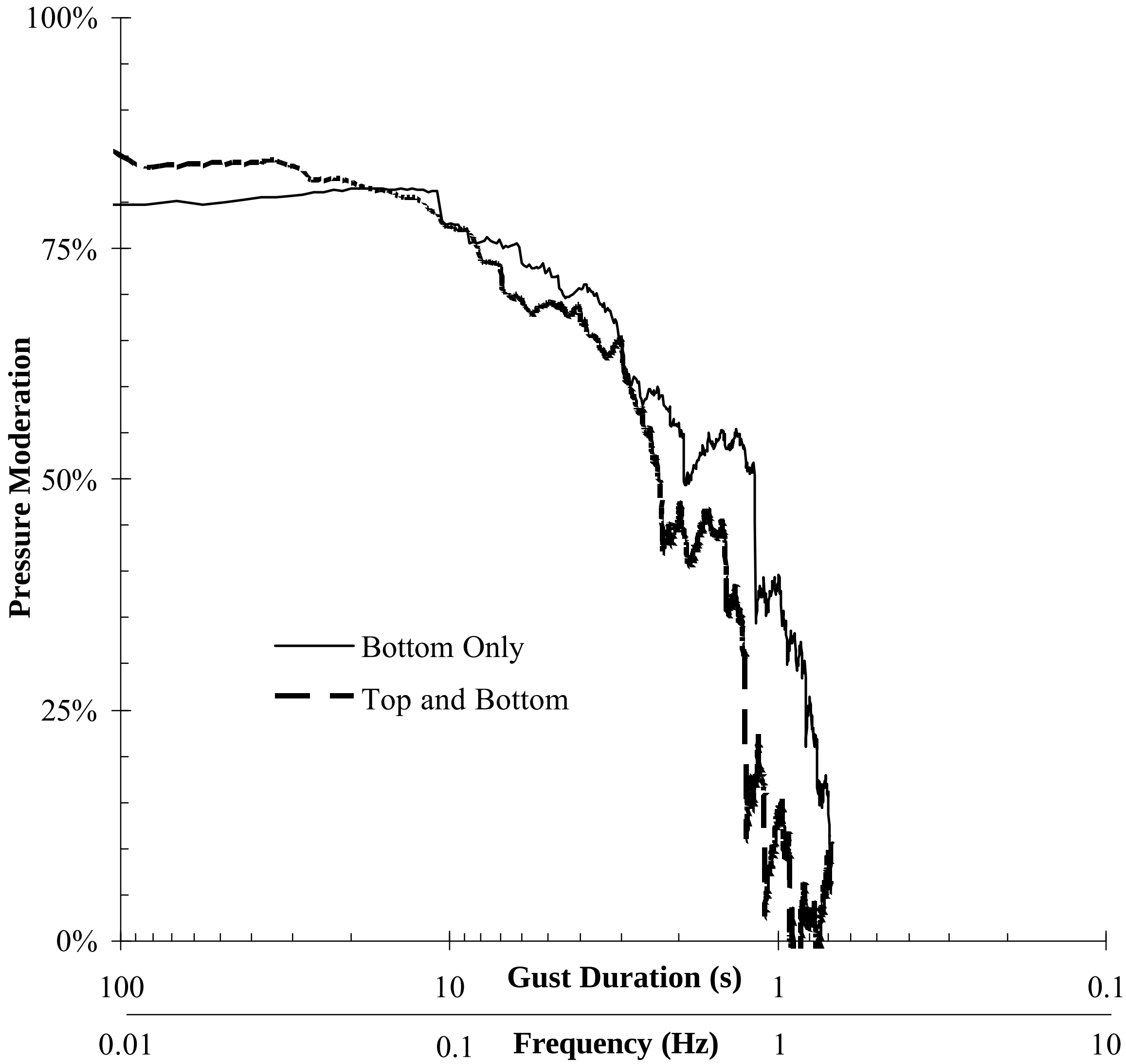


Figure 18: Pressure-moderation performance of datum panel — influence of vent locations

Wind Direction ±30º

6.3 Peak Loading of the Screen

The analysis and presentation of the previous results has concentrated on the dynamic behaviour of the wall during the majority of the time. For structural design purposes, however, it is the peak loads on the screen that are of interest. This section analyses the same pressure records in the time domain so that the peak loads can be found.

6.3.1 Analysis method

While the frequency-domain results shown earlier are very descriptive of in-service behaviour, they do not clearly show the effect of wind pressures on the structural loading of the screen. Design wind loads are typically presented in the form of pressure coefficients, which are applied to the stagnation wind pressure calculated for a particular site and building height.

The equivalent static wind-induced pressure on a building face is often expressed as a fraction of some reference pressure, usually either the stagnation pressure at the top of a tall building, the eaves height for buildings with pitched roofs, or 10 m above the ground. A pressure coefficient is defined as the ratio of the pressure of interest (e.g., the pressure across the enclosure) to the average stagnation pressure of the wind. Pressure coefficients normalise the wind loads so that the pressures measured in wind tunnels or on test buildings like the Beghut can be used on actual buildings in different locations. This pressure coefficient, C_p, is defined as:

$$C_{wall} = \frac{P}{P_{stag}}$$

The stagnation pressure is approximately equal to:

$$P_{stag} = 0.647 \times V^2$$

where V is the wind velocity in m/s, and

P_{stag} is the stagnation pressure in Pa.

The actual pressure acting on a building or component can then be calculated by using the appropriate pressure coefficient:

$$P = C_p \cdot P_{stag} = C_p \cdot 0.647 \times V^2$$

where C_p is the pressure coefficient (no units), and

P is the actual pressure in Pa.

Pressure coefficients are usually based on the hourly average wind velocity. Additional factors are applied to reflect the influence of wind gusts, terrain conditions, and the height of the building or building element.

The monitoring program measured all pressures with reference to the interior of the Beghut. Therefore, a wall pressure coefficient was defined as:

$$C_{wall} = \frac{\Delta P_{wall}}{P_{stag}}$$

where C_{wall} is the pressure coefficient (no units),

ΔP_{wall} is the pressure across the entire wall, which would normally be calculated as $\Delta P_{wall} = P_{ext} - P_{int}$, and

P_{stag} is the average stagnation pressure, calculated from the windspeed measured at 10 m using $P_{stag} = 1/2 \cdot \rho \cdot V^2$, $\rho = 1.2$ kg/m^3.

6.3.2 Results

The pressure across the wall, ΔP_{wall}, was calculated using various averaging times. For example, for a 30-second averaging time, 90 samples (taken at 3 Hz) were averaged to calculate the average coefficient, the maximum, and the minimum. Since a 15-minute record contains 30 unique 30-second records, the process was repeated 30 times and 30 different coefficients for maxima, averages, and minima were calculated.

The average of these maxima, minima and averages is plotted for 5 different records in Figure 19 as a function of averaging time. The vertical bars show the range of values recorded for the different records considered. Figure 19 shows that the average pressure coefficient across a panel located near the middle of the windward face of the Beghut is about 0.8. This value is close to the results of wind tunnel and field studies of buildings similar to the Beghut. The fact that the average coefficient does not change with averaging time indicates that the record was stationary.

It can also be seen that gusts of 1-second duration may occur that are as much as four times the average stagnation pressure. Even on the windward face, the pressure can change to suction (indicated by a negative pressure coefficient). Figure 19 shows that the minimum pressures recorded are suction gusts with a magnitude of about half the average stagnation pressure. These data describe the wind-building interaction only and are the same for all panels located near the middle of the windward side of the Beghut.

As the averaging time is decreased, the wind pressures are higher. The National Building Code assumes an averaging time of about one second for cladding and three seconds for the building structure as a whole. While pressures that act for less than one second have significance for some lightweight claddings and non-adhered roof membranes, a one second averaging period is reasonable for the design of heavy brick veneer and natural stone screens.

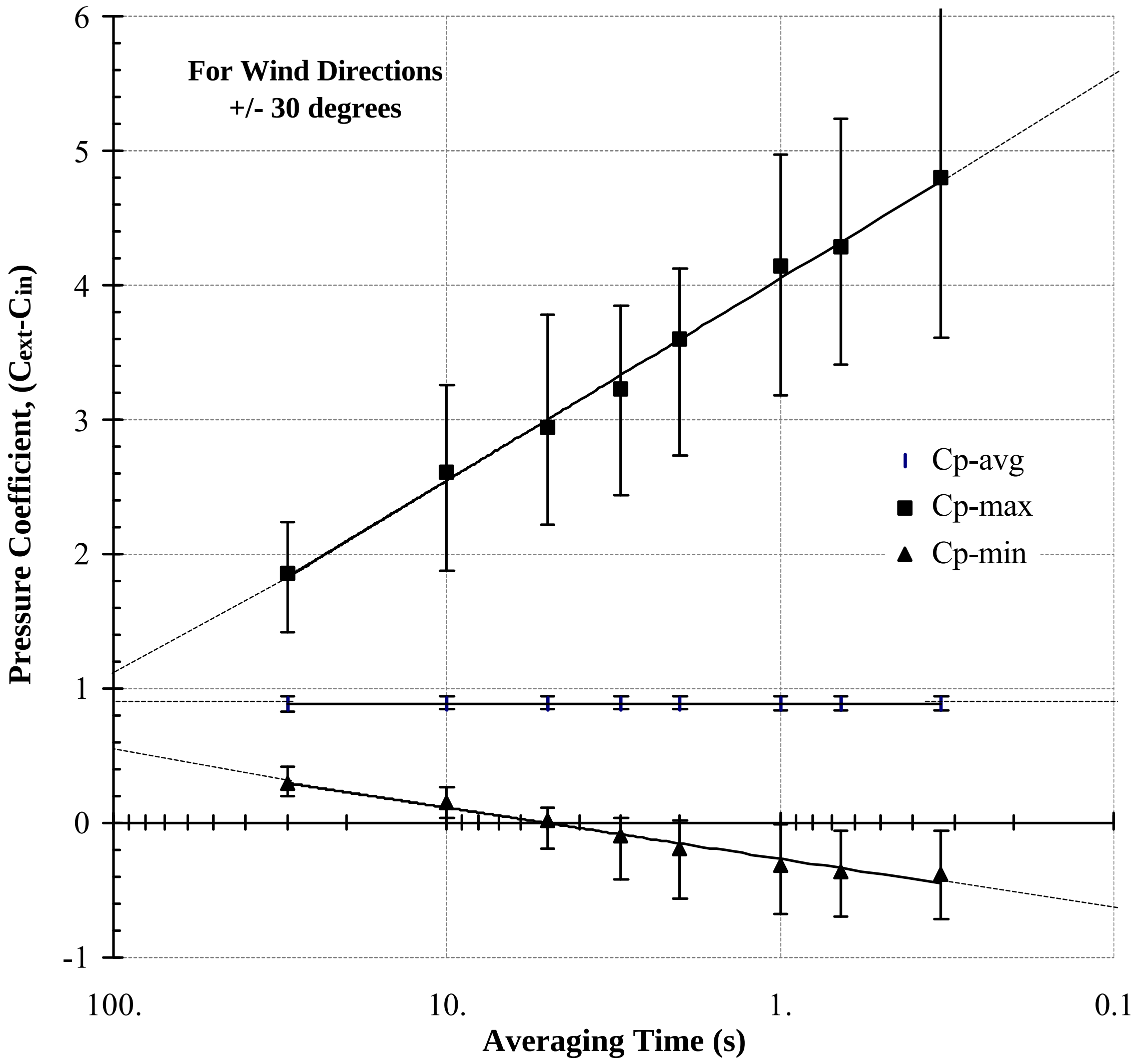


Figure 19: Pressure coefficient for a windward wall in the Beghut as a function of averaging time

Wind Direction: ±30º off perpendicular

A rainscreen coefficient was defined as the ratio of the pressure acting across the screen to the average stagnation pressure:

$$C_{screen} = \frac{\Delta P_{screen}}{P_{stag}}$$

where C_{screen} is the pressure coefficient (no units),

ΔP_{screen} is the pressure acting across the screen, and

is P_{stag} is the stagnation pressure at 10 m above grade.

Figure 20 plots the pressure coefficient for the air pressure acting across the screen of the datum panel. Just as the frequency domain plots showed, this plot confirms that, on average, the pressures are almost equalised. However, when short-term effects are accounted for, it can be seen that pressures as much as two times the stagnation pressure itself can occur.

As an aid to the interpretation of these data, consider the following example. If the wind has an hourly average speed of 10 m/s (quite a stormy day), then the stagnation pressure at 10 m above grade will be:

$$P_{stag} = 0.647 \times 10^2 = 65 \text{ Pa}$$

For a 1-second averaging period (appropriate for cladding design), Figure 19 provides a coefficient of about +4 for positive pressures and -0.4 for negative pressures, and so

$$P_{wall,\ max} = C_{p,max} \times P_{stag} = 4 \times 65 = 270 \text{ Pa}$$

$$P_{\ wall,min} = C_{p,min} \times P_{stag} = -0.4 \times 65 = -27 \text{ Pa}$$

The brick veneer screen should also be designed for the pressure acting across it. Figure 20 shows a screen coefficient value of about 1.1 for a 1-second averaging time, so:

$$P_{screen,max} = C_{screeen,max} \times P_{stag} = 1.1 \times 65 = 71.5 \text{ Pa}$$

In this case, the design load for the brick veneer is only about one quarter of that on the enclosure itself. Such an analysis suggests that some useful reduction in screen design loads might be possible in well-vented, airtight walls that have appropriately stiff backups (e.g., concrete block).

Note, however, that the screen pressure coefficient for suction pressures under glancing wind angles has not been analysed. The wind loads that tend to govern a design are suction loads on the side walls of a building. No attempt has been made to assess this situation, although the existing wind loading information in the literature and the preliminary analysis of such conditions at the Beghut indicates that the pressure moderation would be less successful in this region of the building (because of very turbulent wind conditions).

Also, since it is likely that the backup portion of the wall is significantly more flexible (e.g., wood or steel stud framing) than the masonry veneer, much of the wind load may be transferred back to the veneer through the brick ties as a consequence of composite structural action. Therefore, any reduction in wind loading would only be a benefit if the backup structure was significantly stiffer than the cladding. This is clearly the case with panellised systems over concrete or masonry backup wythes.

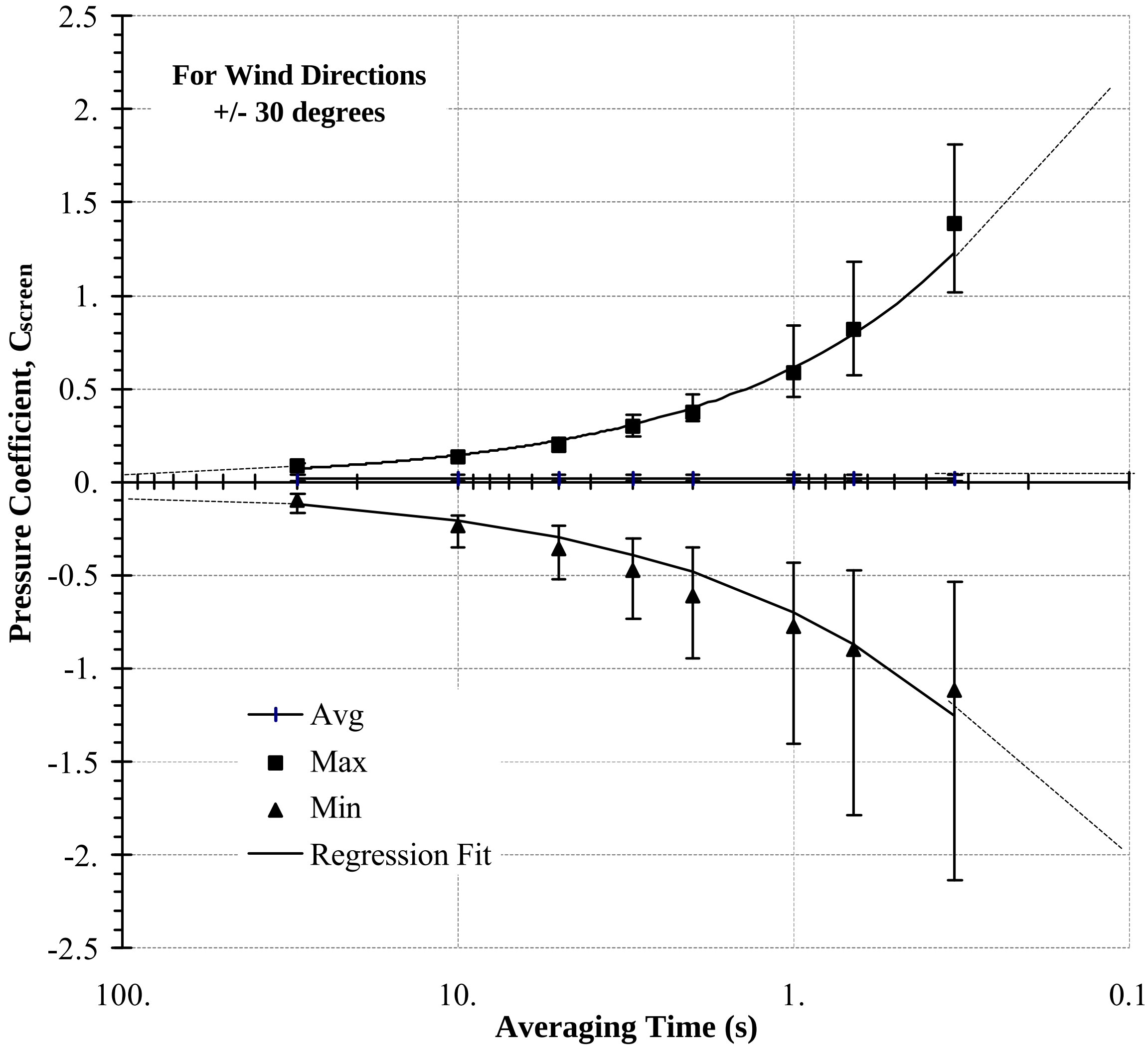


Figure 20: Pressure coefficient across brick veneer of datum panel as a function of averaging time (NBCC Assumes = 1 s)

Wind Direction ±30º

It would be conservative to continue to design both the air barrier system and the masonry veneer to each resist the full wind load. However, small savings are likely possible, especially for walls that are well vented. Before any consideration is given to screen load reductions due to pressure moderation, the designer must realise that the performance of such a structural design is dependent on the probability of the specified amount of venting and airtightness being provided. While it may be reasonable to rely on venting and airtightness being provided in some prefabricated systems (e.g., metal cladding), it is clearly not realistic for site-built masonry veneers.

7. Conclusions and Implications

The results of the pressure moderation performance monitoring, theoretical considerations, lab and field experience presented above have generated a series of important conclusions.

The wind rarely blows hard enough to generate significant pressures (i.e., greater than about 100 Pa) across the enclosure of a low-rise building, even one as exposed as the Beghut. High wind pressures (greater than 100 Pa), especially in conjunction with rain, are rare. Both wind direction and speed can change drastically and very quickly.

The degree of pressure-moderation performance is a function of both the characteristics of the wall and the characteristics of the wind. Wall characteristics, e.g., area of venting, air tightness, etc., are often of of only secondary significance for dynamic pressure moderation. Based on the available research, vent area (or, more accurately, the ratio of vent area to chamber volume) appears to be the wall system characteristic with the greatest influence on pressure-moderation performance. The spatial extent of gusts is typically the most important wind characteristic affecting the degree of pressure moderation, but the speed of the gust (i.e., frequency) and, to a lesser extent, the magnitude of the gust also play a role. Even in walls compartmentalised at 1.2 x 2.4 m spacings, it is the spatio-temporal variations of the wind that will govern the performance of most pressure-moderated wall systems. Compartment sizes of less than 1 m^2 are required to provide high levels of dynamic pressure moderation in the field.

Based on average values, pressure differences across the screen can be well moderated — almost equalised — provided that the wind is not exceptionally turbulent and that the wall is well-vented, airtight and somewhat compartmentalised. Long-term, “static” pressure moderation can be quite high (more than 90%) so long as sufficient venting is provided to accommodate the air-barrier leakage. Providing vent areas of at least 5 times the equivalent air-barrier leakage area *in service* will permit about 94% static pressure moderation. Actually achieving this ratio of venting in the field may require considerably more vent area than typically specified if realistic estimates of air-barrier leakage are considered, e.g., more than 1% of wall area will often be required. Blocked vents, vent inserts, and weep tubes all restrict the vent area to such an extent that the backup may need to be unreasonably/impractically airtight to allow high levels of static pressure moderation to be achieved.

The frequency-domain method of analysis described above results in repeatable measurements of the same wall under different wind events. Measurements show that the degree of *field* pressure moderation of short-term gusts (less than a few seconds long) is rather limited for brick veneers. This has been shown to be true for a range of different wall systems. This conclusion is also valid for any wall system with little venting (<0.5% of wall area) and with compartment sizes greater than about 1.5 m.

The dynamic pressure-moderation response *of a wall system* can be tested in the laboratory and/or predicted by special computer models. However, short-term pressure moderation of even well-vented, airtight and tightly compartmentalised walls will be poor because dynamic pressure-moderation performance is governed by the spatial variations of the wind pressures in typical walls, not by the wall characteristics. Pressure moderation is expected to be worst at upper and side edges of buildings, the same areas of cladding that receive the most driving rain. Measured pressure moderation of one-second gusts was less than 33%, and even three-second gusts were only moderated by 40% in the well-built brick veneer panels exposed to a nearly perpendicular wind direction.

Wind directions other than perpendicular will increase the spatial and temporal variations of pressure on the face of a building and therefore negatively affect the pressure-moderation performance. Because the pressures are often much lower and even negative under these conditions, and because rain wetting is less intense, rain penetration is probably not seriously affected by the reduced pressure-moderation performance.

The rain control performance of masonry veneers stucco, lap siding and similar claddings can be improved only marginally, if at all, by dynamic pressure moderation because:

- testing has repeatedly shown that mechanisms other than air pressure are the primary cause of water leakage (especially through masonry veneers). These systems leak , *even when no air-pressure difference is applied.* Even perfect, instantaneous pressure moderation cannot eliminate rain water penetration of many claddings and joints. Pressure moderation can only reduce — not eliminate — rain penetration of such claddings
- a drained-screened wall design must presume that the cladding will leak significant quantities of water and so drainage is critical and must be provided in any case, and
- pressure moderation of gusts is very difficult, not because of the wall design, but primarily because of the spatial variability of wind pressures.

Ideally, ventilation drying would be investigated as a means of removing moisture (absorbed, or adhered) that cannot be drained.

The rain control of drained-screen walls with relatively water-impermeable screens (e.g., EIFS, vinyl, precast concrete) may benefit from pressure moderation because air pressure differences are often the most important mechanism by which water can penetrate the screen. In practise, these systems experience rain control problems at joints, windows, or other penetrations, not in the field of the wall. Hence, these joints should be designed as drained screens, preferably pressure moderated and never as perfect barrier face-sealed systems.

In all cases, drainage is absolutely essential for good rain control in screened wall systems, and is certainly more important than any contribution from pressure moderation. At this time pressure moderation may be a beneficial characteristic to strive for, but many other characteristics are more important.

Factors such as exposure conditions, the control of rain water on the surface, drainage, and the quality of workmanship will all play a larger role in the control of rain penetration than pressure moderation. Even if walls could be made to pressure-equalise instantaneously, poorly installed flashing, joints, windows and brickwork can still cause failure, as field experience suggests are in fact the problems. Drainage can help deal with all of these.

It may be possible to safely design the enclosure for lower wind loads if a greater understanding of the structural distribution of static and gust pressures could be developed. Any contribution to screen or connector load reduction should be regarded as possible but not as a quantifiable nor reliable benefit without detailed product and project specific investigations. Possible load reductions should only be implemented once the relative stiffnesses of the cladding and backup, and the reliability (in the as-built and as-maintained condition) of venting, air flow and air barrier tightness, have been carefully assessed.

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