

Envelope Design Guidelines for Federal Office Buildings: Thermal Integrity and Airtightness

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Office building envelopes are generally successful in meeting a range of structural, aesthetic and thermal requirements. However, poor thermal envelope performance does occur due to the existence of defects in the envelope insulation, air barrier and vapor retarder systems. These defects result from designs that do not adequately account for heat, air and moisture transmission, with many being associated with inappropriate or inadequate detailing of the connections of envelope components. Other defects result from designs that appear adequate but can not be constructed in the field or will not maintain adequate performance over time. Despite the existence of these thermal envelope performance problems, information is available to design and construct envelopes that do perform well. In order to bridge the gap between available knowledge and current practice, NIST has developed thermal envelope design guidelines for federal office buildings for the General Services Administration. The goal of this project is to transfer the knowledge on thermal envelope design and performance from the building research, design and construction communities into a form that will be used by building design professionals. These guidelines are organized by envelope construction system and contain practical information on the avoidance of thermal performance problems such as thermal bridging, insulation system defects, moisture migration, and envelope air leakage.

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PREFACE

The exterior envelopes of office buildings perform a variety of roles including keeping the weather outdoors, facilitating the maintenance of comfortable interior conditions by limiting the transfer of heat, moisture and air, providing a visual and daylight connection to the outdoors, limiting noise transmission, supporting structural loads, and providing an aesthetically pleasing appearance. Although building envelopes are generally successful in meeting these requirements, there are cases in which they do not perform adequately. Shortcomings in thermal performance are manifested by excessive transfer of heat, air or moisture that can lead to increased energy consumption, poor thermal comfort within the occupied space, and deterioration of envelope materials. While some cases of poor performance occur due to the specification of insufficient levels of thermal insulation or inappropriate glazing systems, other cases occur because of discontinuities in the envelope insulation and air barrier systems, such as thermal bridges, compressed insulation and air leakage sites. These discontinuities result from designs that do not adequately account for heat, air and moisture transmission, are difficult to construct, do not have sufficient durability to perform over time, or can not withstand wind pressures or differential movements of adjoining elements. Other thermal envelope defects occur due to poor technique during the construction phase.

Despite the existence of these thermal envelope performance problems, information is available to design and construct envelopes with good thermal envelope performance. In order to bridge the gap between available knowledge and current practice, the Public Buildings Service of the General Services Administration has entered into an interagency agreement with the Building and Fire Research Laboratory of the National Institute of Standards and Technology to develop thermal envelope design guidelines for federal buildings.

The goal of this project is to take the knowledge from the building research, design and construction communities on how to avoid thermal envelope defects and organize it into a form for use by building design professionals. These guidelines are not intended to direct designers to choose a particular thermal envelope design or a specific subsystem, but rather to provide information on achieving good thermal performance for the design that they have already chosen. Given that the designer has made decisions on the envelope system, materials, insulation levels and glazing areas, the guidelines will provide specific information to make the building envelope perform as intended through an emphasis on design details that avoid thermal defects. Much of the material in these guidelines is in the form of design details for specific building envelope systems, both details that result in thermal defects as well as improved alternatives.

1.0 INTRODUCTION

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1.1 DESCRIPTION OF THE GUIDELINES

Scope

The purpose of these guidelines is to provide practical design and construction information directed towards achieving good thermal envelope performance through the avoidance of thermal defects. It is assumed that the designer has already chosen the envelope system and will use the guidelines as a source of information on design and construction issues key to thermal performance.

The guidelines are concerned primarily with conductive heat transfer, air leakage and airborne moisture transport through the building envelope. The guidelines do not cover the many other issues important to the thermal envelope performance such as appropriate levels of thermal insulation, daylighting and other glazing system issues, thermal mass effects, design methodology, thermal load calculations, and interactions between the envelope and HVAC equipment. The control of heat, air and moisture transfer constitutes only a portion of the performance requirements of building envelopes, and obviously the envelope design must address all of the varied requirements. Some of these other envelope design issues include structural performance, aesthetics, fire safety, lighting and rain penetration.

The guidelines present many design details that lead to thermal defects, along with improved alternatives. The alternative details have been selected based on their being practically constructable and having a demonstrated record of performance. Suggested fixes that do not have a well-established record of performance are intentionally omitted, though they may turn out to provide acceptable performance.

Organization

The guidelines are organized into three sections: principles, design and systems. Each section consists of a series of stand-alone “fact sheets” addressing a specific issue or system. The first section, principles, provides background information on thermal envelope performance including a discussion of thermal defects and their potential consequences. The material in this section is not necessary for the user, but does provide useful background information and describes the motivation and bases for the guidelines. The second section, design, contains fact sheets on basic design principles for achieving good thermal performance and avoiding thermal envelope defects. The material in this section describes air barriers, vapor retarders and thermal insulation, specifically addressing the design features of each that are essential to envelope thermal integrity. This section also contains a discussion on the control of rain penetration. The third section, systems, constitutes the substance of the guidelines. This section contains fact sheets on particular envelope systems, each one describing those design features that are crucial to achieving good thermal performance.

Climate

Thermal envelope design is impacted by climatic factors, including temperature, relative humidity, wind conditions, solar radiation and ambient pollution levels. For example, the need for a vapor retarder, its location within the thermal envelope and the position of the thermal insulation within the envelope are influenced by climatic factors. The literature review conducted prior to the development of the guidelines noted a definite lack of design guidance and research results relevant to warmer climates and climates with both significant heating and cooling seasons. Much of the previous work on thermal envelope performance has been done in Canada, which accounts for some of this climatic imbalance. Recent efforts have attempted to address the lack of information on warm climate thermal performance issues, but this gap is still prevalent. When design details are presented that are appropriate to only a particular climate, this is noted.

Presentation of Details

As the design details contain the bulk of the information in these guidelines, some comment on how these details are presented is appropriate. The details are schematic representations developed to highlight specific design and construction issues. While they were developed to be accurate, they are generic and not necessarily to scale. For the sake of clarity and emphasis, they do not include every envelope element, and many of the elements that are included are drawn in the most generic sense so as not to detract from the issues of interest. These details are not intended to be incorporated into an envelope design, but to serve as illustrative examples of design approaches to be used in developing the details for a given project.

1.2 BACKGROUND

The development of these guidelines was originally motivated by GSA's experience with office buildings exhibiting poor thermal envelope performance (Grot). Diagnostic evaluations of these buildings revealed the existence of high levels of air leakage and numerous thermal insulation system defects. GSA realized that improvements in building envelope design and construction were necessary to avoid these situations in future projects and entered into an agreement with the Building and Fire Research Laboratory at NIST to develop these design guidelines. Several sources of information were employed in the development of the design guidelines, including a review of published literature, voluntary contributions acquired by a BTECC/NIBS project committee, comments from the project committee itself, and a group of technical consultants to NIST.

Literature Review

The development of the NIST/GSA envelope design guidelines began with a review of research results and technical information on thermal envelope performance and design (Persily). This review included the examination of research on thermal envelope performance, case studies of thermal envelope performance defects, thermal envelope designs specifically intended to avoid such defects, and presentations of design principles for ensuring good thermal envelope performance.

The information considered in the review was drawn from primarily two sources, the building design and construction community and the building research community. Given that there is more publication on the part of the research community, this review is more extensive in the area of research findings. A variety of sources were employed in this review, and they are listed in the bibliography contained in Appendix A. These sources include the Transactions of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), along with the proceedings of the conferences on Thermal Performance of the Exterior Envelopes of Buildings sponsored by ASHRAE, the U.S. Department of Energy and the Building Thermal Envelope Coordinating Council (BTECC) in 1979, 1982, 1985 and 1989. The proceedings of the 1986 Symposium on Air Infiltration, Ventilation and Moisture Transfer sponsored by BTECC was also a useful source of information. Several STPs (Special Technical Publications) published by the American Society of Testing and Materials (ASTM) were also reviewed. In addition, the Institute of Research in Construction (IRC, formerly the Division of Building Research or DBR) at the National Research Council of Canada (NRCC) has published many informative documents containing research results and building design information. A variety of other publications were examined including architectural handbooks, construction guides, and research reports from governmental and private organizations.

The literature review identified much information relevant to the development of the guidelines, including many examples of thermal envelope defects. Research was identified in the area of calculation and modeling that has enabled the quantification of the effects of thermal defects on envelope heat transfer rates. The review identified several principles for the design and construction of building envelopes that avoid the occurrence of thermal defects. Many design details were identified that provide effective alternatives to the details that result in these defects. The main conclusions of the literature review include the determination that thermal defects have significant detrimental effects on energy consumption, thermal comfort and material performance. Publications that identify these defects and present alternative designs have been limited to specific buildings and specific envelope components. There are no thorough presentations of thermal envelope defects, poor design details or alternative designs for the great variety of building envelope constructions. This is the information that the thermal envelope guidelines are intended to present, and this information exists primarily in the practical experience of design and construction professionals.

The literature review also examined existing standards and construction guidance documents for information on thermal envelope integrity. Most of these documents contain general information on design principles and construction techniques or guidance on the selection of U-values and glazing systems. While some of these documents recognize the importance of thermal envelope defects, they do not emphasize the importance of these problems or contain the information or design details necessary to construct building envelopes that avoid these defects. Construction handbooks cover many important areas of envelope design, but do not generally address issues of thermal defects and air leakage and do not provide the design details necessary to avoid these defects. Construction guides that were developed specifically to promote energy conserving designs address insulation levels, thermal mass, fenestration and materials, but generally not thermal defects. In some cases they mention the importance of controlling infiltration and avoiding thermal bridges, but do not indicate how to design and construct an envelope that actually achieves these goals. The sections on the thermal envelope within the energy standards developed by GSA, ASHRAE and DOE concentrate on insulation levels and fenestration systems. While they refer to the importance of thermal bridges and air leakage, they do not contain sufficient criteria for their control.

During the literature review and the subsequent development of the guidelines, several documents were identified of particular relevance. Several years ago Owens/Corning Fiberglas developed a design guide, currently out of print, containing many design details for walls, roofs and envelope intersections. The guide is very good on insulation system continuity, but does not deal with air leakage and air barrier systems. Steven Winter Associates recently developed a catalog of twenty-one thermal bridges commonly found in commercial building envelopes, including proposed alternative constructions in each case. A recent book by Brand is another good source of information, containing design details developed to explicitly avoid thermal defects.

BTECC/NIBS Project Committee

In order to obtain information for the development of the guidelines, a contract was issued by NIST to the National Institute of Building Sciences (NIBS) to obtain the expertise of the Building Thermal Envelope Coordinating Committee at NIBS. A BTECC/NIBS project committee was established to solicit and review voluntary contributions of materials for consideration in writing the guidelines. The project committee sent out requests for information to hundreds of individuals and organizations and received about fifty responses consisting of material for consideration. The project committee reviewed this material as to its relevance to the guidelines and provided the material and reviews to NIST. Many items of interest were obtained, primarily materials from various industry associations including the American Architectural Manufacturers Association, the Brick Institute of America, the Indiana Limestone Institute of America, the Masonry Advisory Council, the National Concrete Masonry Association, the Portland Cement Association and the Precast/Prestressed Concrete Institute. The BTECC/NIBS project committee also reviewed early drafts of the guidelines and contracted with selected consultants for more detailed reviews. Appendix E contains a list of the project committee members.

Technical Experts

Early in the development of the guidelines, a contract was issued to Steven Winter Associates to provide technical assistance on determining the appropriate content and format for the guidelines. In this effort, they interviewed selected architects across the country regarding the documents they use in thermal envelope design and how these guidelines might best suit their needs. They also analyzed the documents cited in these interviews. The results of this effort were used by NIST in selecting the format of these guidelines. In addition, based on input from the Steven Winter Associates contract and the results of the literature review conducted at NIST, it was determined that much of the information needed for the guidelines was not in published form but in the experience of design professionals and building envelope consultants. In order to benefit from this source of information, NIST contracted with selected experts in the field of building envelope design to prepare material for the guidelines in their specific areas of expertise.

References

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2.0 PRINCIPLES

2.1 Building Envelope Performance

Performance Requirements
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2.1 BUILDING ENVELOPE PERFORMANCE

While these guidelines are concerned with the thermal performance of building envelopes, the exterior envelope of a building must serve several functions. These functions, and the relationships between the elements intended to perform them, must all be considered when designing and constructing the envelope. Consideration of specific envelope requirements in isolation from one another can be a source of design and performance problems. This section discusses the performance requirements of the building envelope and establishes a context for the consideration of thermal performance issues.

Performance Requirements

Hutcheon described the overall function of the exterior wall as providing “a barrier between indoor and outdoor environments, so that the indoor environment can be adjusted and maintained within acceptable limits.” In achieving this general goal, the following requirements need to be considered:

- . Control heat flow
- . Control airflow
- . Control entry of outdoor pollutants
- . Control water vapor flow
- . Control rain penetration
- . Control light, solar and other radiation
- . Control noise
- . Control fire
- . Provide strength and rigidity
- . Be durable
- . Be aesthetically pleasing
- . Be economical

The first eight requirements relate to the wall as a barrier between inside and out, and they are met by selecting elements that provide the appropriate resistance to each of the flows. In addition, however, the arrangement of the elements meeting each requirement is important. This arrangement determines the distribution of conditions within the wall, such as temperature and water vapor pressure, and the environment under which the various elements must function. The last four performance requirements are general requirements that must be satisfied while meeting the others. The analysis and design techniques related to structural performance, fire safety, aesthetics, noise and economics are well-established and covered elsewhere.

The durability of the envelope and its components describes their ability to maintain their function over time. Durability is not an inherent material property, but depends on the environment to which the element is exposed and the degrading effects of service. The arrangement of the elements within the envelope can improve the durability of the elements, and the system as a whole, by lessening the severity of exposure. The aesthetic appearance of the exterior envelope need not conflict with the other performance requirements, but as is the case with other performance requirements, aesthetic considerations should not be allowed to predominate over the achievement of other requirements.

Arrangement of Envelope Elements

The arrangement of envelope elements is important to the fulfillment of envelope performance requirements. This arrangement influences the conditions within the wall, and therefore the environment under which the materials must function. For example, the location of the thermal insulation determines the temperature distribution within the envelope, which in turn determines the temperatures of the individual envelope elements. Temperature affects durability of materials, impacts the degree of dimensional movement to which the elements will be subjected and the ability of the materials to accommodate this movement. A considered arrangement of the envelope elements will lessen the severity of exposure of these elements and can simplify issues of material selection. Issues regarding the relative positioning of structural elements, thermal insulation, air barriers and vapor retarders are discussed frequently in these guidelines. The positioning of these elements and the impact of this positioning are complex issues, with every arrangement having both advantages and disadvantages to consider.

Movement and Dimensional Change

The movement of envelope elements is an important issue related to the design of those elements intended to control heat, air and moisture transfer. Envelope elements move and undergo dimensional changes for a variety of reasons including thermally induced expansion and contraction, changes in moisture content, aging, structural loading and movement of the building frame. These movements must be anticipated and accounted for in the design of the envelope. If these movements are not accounted for in the design, the driving forces will induce discontinuities in the various barriers to flow or even result in more serious failures such as the cracking or dislodging of facades. The accommodation of differential movement arises frequently in these guidelines as a source of thermal performance failures and as a necessary consideration in achieving good performance. Examples include the design of joints between precast concrete panels and the interface between spandrel beams and concrete block infill walls. In both cases the inevitability of differential movement must be recognized, and the intersection must be designed to accommodate this movement in order to maintain the continuity of the air barrier and insulation systems.

Terminology

This discussion of building envelope performance requirements provides the opportunity for clarifying the use of several terms in this document. The *building envelope*, and at times simply the *envelope*, refers to the barrier between the indoor and outdoor environments. This barrier includes the walls, roof and foundation, though these guidelines are focussed on walls. While the building envelope is composed of many elements and systems, sometimes performing very distinct functions, there is a single building envelope that must meet all of the performance requirements discussed above. The thermal envelope describes those envelope elements and systems intended to meet the thermal performance requirements of the building envelope. The thermal envelope is not in general a distinct portion of the envelope, since the same elements which perform thermal functions may also serve other functions, e.g. windows. When using the term thermal envelope, one must be careful not to consider those elements in isolation from other envelope performance requirements or in isolation from other forces acting on the envelope.

References

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2.2 THERMAL ENVELOPE PERFORMANCE

The previous section described the various performance requirements that must be considered in the design and construction of the building envelope. This section concentrates on the thermal performance requirements of building envelopes, i.e., the control of heat, air and moisture transfer between the inside and outside of a building. Discussions of these flows exist elsewhere (ASHRAE, Brand, Hutcheon), and this section presents only a brief overview.

Heat Transfer

Heat is transferred by three mechanisms: conduction, radiation and convection. The rate of conductive heat flow through an envelope element is determined by its thermal conductivity, the temperature difference across it and the thickness and area of the element. The rate of conductive heat transfer through an element is described by its U-value, the rate of heat transfer divided by the temperature difference and the area, or the R-value, the inverse of the U-value. Given the same temperature difference across a 2.5 cm (1 inch) thick piece of steel (low R-value) and a 2.5 cm piece of insulation (high R-value), heat will be conducted through the steel at a much higher rate. Controlling conductive heat flow across a building envelope involves increasing its R-value. This can be done through the use of materials with low thermal conductivities and by increasing the thickness of envelope materials, specifically the insulation.

Insulation levels are generally chosen based on an analysis of the severity of climate and the material costs balanced against future energy costs. However, specifying a certain insulation level for a building only applies to the insulated portions of the building between structural elements and only if the insulation is properly installed. Such structural elements, and other penetrations of the insulation system by elements with significantly higher values of thermal conductivity than the insulation, are often described as thermal bridges. Installation problems include the occurrence of gaps and voids in the insulation that increase the heat transfer rate through the envelope. One of the major points of these guidelines is that the actual insulating value of a wall can be quite different from the design value due to thermal bridging of the insulation, other discontinuities in the insulation system design or poor installation. In order to effectively control heat conduction, the envelope must be insulated continuously, with minimal interruptions by structural elements and other penetrations.

Heat transfer by radiation is primarily a glazing system issue, though it does occur within the envelope. Radiative heat transfer through the glazed portions of the building envelope is a complex issue involving interior heating and cooling loads and daylighting strategies. Significant amounts of energy can be transferred through radiation, making glazing system design very important to the energy balance of a building. Although glazing is a very important thermal envelope performance issue, these guidelines only address glazing systems in relation to the maintenance of airtightness and thermal insulation integrity at the connection of the glazing system to opaque portions of the envelope.

Convection is heat flow carried by the bulk movement of air between two locations at different thermal conditions, and can be a significant factor within the envelope, either intentionally or unintentionally. Air can circulate within even very small spaces, resulting in significant heat flows. While properly designed air spaces can be part of a thermally effective building envelope, it is otherwise undesirable to have gaps between envelope components, particularly between the insulation material and adjoining elements. Convective heat transfer is also associated with air leakage through the building envelope.

Airflow

Airflow through the building envelope, also referred to as air leakage, infiltration and exfiltration, can severely degrade the thermal performance of the envelope. Envelope air leakage is discussed throughout these guidelines, and the existence of poor air leakage performance in office building envelopes is a major motivation for the development of these guidelines. Air leakage carries heat and moisture between inside and out, increasing space conditioning loads, degrading the thermal performance of the insulation system and increasing the potential for condensation problems. The amount of energy transport due to air leakage through the building depends on the airflow rate and the temperature difference between inside and out. The airflow rate depends on the physical leakiness of the building envelope and the magnitude of the pressure differences driving the airflow. The energy impacts of airflow within the wall on thermal insulation performance are more complex, depending on the airflow rate, the paths of these flows, the configuration of the envelope elements and the temperature distribution within the envelope. Air leakage can be controlled by a well-designed and carefully installed air barrier system that is continuous over the building envelope.

Despite common design intentions and expectations, envelope air leakage is a real problem in office buildings. While envelope air leakage rates are assumed to be on the order of about 0.1 air changes per hour, measurements in new office buildings have yielded values of 0.5 air changes per hour and higher. The results of whole building pressurization tests of envelope airtightness in modern office buildings also show that these building envelopes are generally quite leaky (ASHRAE). Some contend that infiltration is not a serious concern because of its relatively minor contribution to overall energy consumption and even try to take credit for infiltration in meeting building ventilation requirements. The energy implications of air leakage depend on the particular building and its infiltration rates, and in leakier buildings the energy impacts can be quite significant. Also, the detrimental effects of air leakage go beyond energy and include the inability to maintain thermal comfort due to increased thermal loads and drafts, interference with the proper operation of mechanical ventilation equipment, degradation of envelope materials due to temperatures, dirt and condensation, and limitations on the ability to control noise, fire and smoke. Further, it is undesirable to rely on infiltration air to meet ventilation requirements in office buildings. Infiltrating air is not filtered or conditioned, and its rate and distribution can not be controlled.

In addition to exterior envelopes, airtightness is also an issue for interior partitions such as the walls of vertical shafts and the separations between floors. A lack of airtightness in these interior partitions increases the magnitude of stack pressures across exterior walls and results in significant vertical airflows through buildings. Such airflows transport significant amounts of pollutants between the floors of a building and may affect the proper operation of mechanical ventilation and smoke control systems. Therefore, airtightness is an important design and construction issue for the walls of stairways, elevator shafts and service chases, intentional openings to these vertical shafts, and separations between floors.

Moisture Transfer

Moisture transport within and through the building envelope must be controlled to prevent moist air from contacting and condensing on cold elements within the envelope. Condensation, and subsequent freezing, within the envelope can result in efflorescence on exterior facades, shifting and failure of exterior cladding, disruption of parapets, and wetting, staining and damage of interior finishes.

Moisture moves through walls primarily through diffusion and convection, with convection generally being associated with much larger rates of moisture transfer. Gravity forces and capillary action can also be important, particularly at the facade of the building. Moisture diffuses through materials, or assemblies of materials, at a rate determined by the water vapor pressure difference across the material and the resistance of the material to water vapor diffusion. Similar to thermal conductivity, some materials (glass, metal) have a high resistance to water vapor transfer while others (some paints and insulation materials) have little resistance to diffusion. The moisture transmission properties of envelope materials must be considered in relation to the insulation properties and the expected temperature profiles within the wall as discussed in the section Design/Vapor Retarders. While moisture transfer via diffusion is generally not as significant as the convective transport of water, it still needs to be accounted for in thermal envelope design.

Convective transport of moisture refers to moisture carried by airflows through the building envelope. Warm air can carry significant quantities of moisture, and typical air leakage rates result in moisture transfer rates several orders of magnitude greater than the rate of moisture transported by diffusion. The rate of convective moisture flow depends on the airflow rate and the moisture content of the air. While an effective vapor retarder will control diffusion, a continuous air barrier system is necessary to control convective moisture transfer. In some envelope designs, a single system can perform effectively as both a vapor retarder and an air barrier.

Thermal Envelope Elements

The flows discussed above are controlled through the design and construction of the building walls, roof, glazing systems and foundation. A variety of opaque wall systems exist, employing thermal insulation, air barriers and vapor retarders to control these flows. The manner in which these elements are best incorporated into walls is the main thrust of these guidelines in the Systems section. Because of the emphasis on thermal insulation and air leakage defects, these guidelines concentrate on these opaque sections of the building envelope. In the development of these guidelines, very little information specific to the thermal performance of commercial building foundations was found. For many of the wall systems, details on the connection of the wall insulation and air barrier to the foundation are included.

The other major thermal envelope elements are windows and skylights. These guidelines do not address glazing system design other than the thermal integrity of the connection of these systems to the opaque portions of the envelope. The lack of inclusion of fenestration system design does not at all imply their lack of importance to the energy balance in commercial buildings. Fenestration systems are major elements in the energy balance of office buildings, and their design is a critical part of the building design process. The selection of glazing materials, systems and window treatments such as overhangs and shading devices can have major impacts on building energy use. Daylighting strategies are available that can improve the environment within the building and reduce energy use, and fenestration system technology is developing continually to improve performance. Information on the design of windows and skylights is available in a variety of sources including the chapter on fenestration in the ASHRAE Handbook of Fundamentals, the AAMA handbook on skylight design and in Hastings and Crenshaw.

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2.3 THERMAL ENVELOPE DEFECTS

Thermal envelope defects are discontinuities in the insulation layer or the plane of airtightness within the building envelope. Some of these discontinuities are designed into the thermal envelope. Others are the result of improper construction or occur over time when the design does not provide adequate support to materials given the wind pressures and structural movements to which they are exposed. There have been many discussions of thermal and air leakage defects in the envelopes of office buildings, either as case studies from specific building envelope designs or in terms of generic defects associated with specific envelope systems. As part of the development of these guidelines, a literature review was conducted and these defects were classified into general categories (Persily). This section summarizes the results of this review and presents a general discussion of thermal envelope defects in the following categories:

- Thermal Bridges**
- Insulation System Defects**
- Air Leakage Defects**
- Wall Assemblies**
- Roofing Systems**
- Other Assemblies**
- Component Connections**

Thermal Bridges

- **Structural elements**
- **Component connections**
- **Envelope penetrations**
- **Corner effects**

Thermal bridges are relatively high conductivity building elements that penetrate the envelope insulation, thereby leading to increased heat flow rates. The literature contains much discussion of thermal bridges, and Tye has divided them into four categories, structural elements, component connections, envelope penetrations and corner effects.

Structural elements are high strength and relatively high conductivity elements used to connect building elements to the building structure that act as thermal bridges when they penetrate the envelope insulation system. Bridges of this type include large elements such as beams, floor slabs, and foundations, as well as smaller elements such as studs, purlins, exterior panel supports, and insulation fasteners.

The penetration of the insulation system by floor slabs is a very common thermal bridge, occurring in many envelope designs as well as many construction handbooks. Figure 2.3.1 shows such a thermal bridge associated with a floor slab and an outrigger beam supporting a precast concrete panel (Childs). Both the floor slab and the beam penetrate the exterior wall insulation, increasing the heat transmission rate by a factor of two in the region of the thermal bridge.

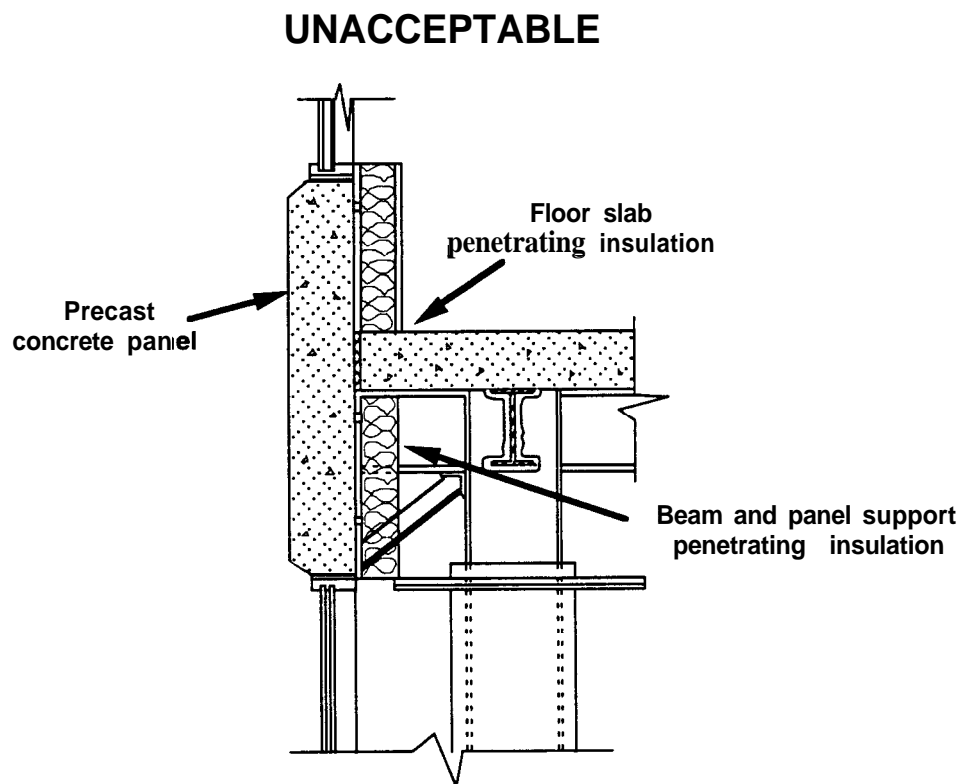


Figure 2.3.1 Beam and Floor Slab Penetrating Insulation (Childs)

Component connections are high strength, high conductivity element assemblies that serve to hold or connect building components within the envelope, such as window and door frames and window and curtain wall mullions.

Envelope penetrations include any element that passes between the inside and outside, thereby interrupting the continuity of the thermal envelope insulation. These include stacks, vents, utility conduits, pipes, and rooftop equipment supports.

Corner effects refer to constructions at corners which accentuate two-dimensional heat flow paths that exist at corners. Some of these corner constructions also lead to discontinuities in the envelope insulation layer and the air barrier.

A recent report by Steven Winter Associates identifies twenty-one thermal bridges commonly found in commercial building envelopes, calculates the effect of each on heat transmission rates and condensation potential, and proposes alternative constructions to avoid the bridging.

Insulation System Defects

- **Discontinuity in insulation system design**
- **Voids and gaps**
- **Unsupported insulation**
- **Compression by fasteners and other elements**
- **Fibrous insulation exposed to air spaces**
- **Poor fitting batt insulation**

Defects in the envelope insulation system include both discontinuities in the insulation layer and arrangements of the insulation which decrease its effectiveness. Envelope performance is then degraded by the increased heat transfer rate and the potential for condensation when components in contact with moist interior air attain colder temperatures than anticipated. Such defects include insulation system design details which incorporate discontinuities in the insulation layer, voids or gaps in insulation systems due to improper installation or deterioration of the insulation material, movement of the insulation due to a lack of adequate physical support, and compression of insulation caused by fasteners or other building elements.

The thermal effectiveness of fibrous insulation is greatly reduced when the insulation is installed with air spaces or cavities on one or both sides of the insulation layer, due to convective airflows through and around the insulation. This defect can be avoided by designs in which the insulation completely fills the cavity or which employ a continuous air barrier on the cavity side of the insulation.

Batt insulation may be associated with performance problems when the batts are poorly installed or do not fit well within the available space. These include arching or air channels caused by oversized batts, gaps due to undersized batts, and gaps and air channels caused by poor installation of batts. The existence of gaps or air channels within the insulation system and the air movement through these spaces severely degrade the effectiveness of the insulation.

Air Leakage Defects

- **Discontinuity of air barriers**
- **Inappropriate use of insulation or insulation adhesives as air barriers**
- **Punctured or displaced air barriers**
- **Polyethylene: inadequate support, lack of continuity**
- **Inappropriate selection of sealant materials**
- **Sealant failure due to differential movement**
- **Lack of interior finishing**

Achieving an airtight building envelope depends on the maintenance of a continuous air barrier system over the entire envelope including the selection of appropriate materials and means of attachment (Ashton, Handegord, Perreault 1986, Quirouette 1989). Air leakage defects include designs that fail to maintain the continuity of the air barrier system, the inappropriate use of insulation or insulation adhesives as air barriers, and the puncture or displacement of air barrier materials either during construction or as a result of the movement of building components. While polyethylene is a relatively airtight material, it will not perform as an effective air barrier when it is not adequately supported or when used in situations where it is difficult to maintain continuity. Additional sources of failure in air barrier systems include the inappropriate choice of sealant materials given the conditions (e.g., temperature, humidity, solar exposure) to which they will be exposed and joint designs and sealant selections that can not accommodate differential movements within the envelope system.

Some cases of air leakage occur because air barrier and sealant joint details are not developed for all locations in the envelope. While adequate details are generally developed for the more straightforward connections, the more complex intersections of envelope elements are sometimes neglected. For example, the details for the connection at the window head, jamb and sill may be adequate, but no air barrier details are developed for the corners. Similarly sealant joints may be designed for both horizontal and vertical panel joints, but no details are developed for sealing the intersections between the horizontal and vertical joints. In these cases, achieving an airtight seal is left to the installer or mechanic, who must develop a solution rather than employ a seal that has been designed for the circumstances.

One important source of discontinuities in air barrier systems is a failure to finish the entire interior facade of a wall system when this facade is serving as an air barrier. These failures sometimes occur because only the visible portions of the interior facade are finished, allowing air leakage through the unfinished areas.

Two examples where incomplete finishing of the interior caused air leakage problems are described by Kudder. The first, shown in Figure 2.3.2, was caused by a lack of finishing of the interior drywall behind a spandrel beam. Because of the obstruction from the beam, it was impossible to install drywall screws or to tape the drywall joints all the way up the height of the wall to the floor above. An air path therefore existed from the building interior to the cavity behind the exterior facade.

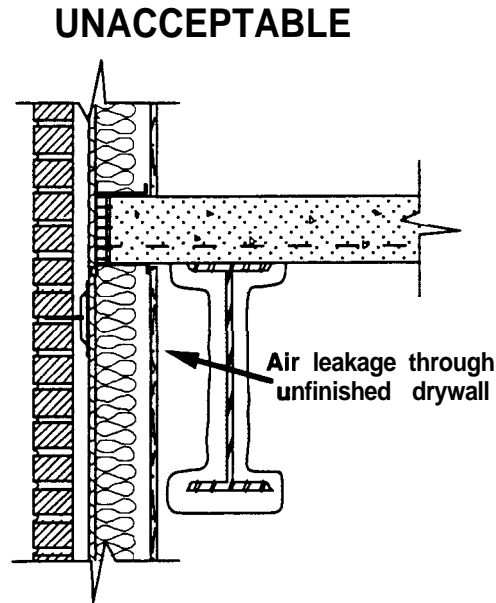


Figure 2.3.2 Unsealed Drywall due to inaccessibility (Kudder)

The second air leakage site described by Kudder is shown in Figure 2.3.3 where a diagonal brace for a spandrel hanger penetrates the interior drywall and the insulation above a suspended ceiling. An air leakage problem occurred because the brace penetration of the drywall was not sealed, providing an air path from the interior to the cavity behind the facade. The penetration of the wall insulation by the brace also constituted a thermal bridge.

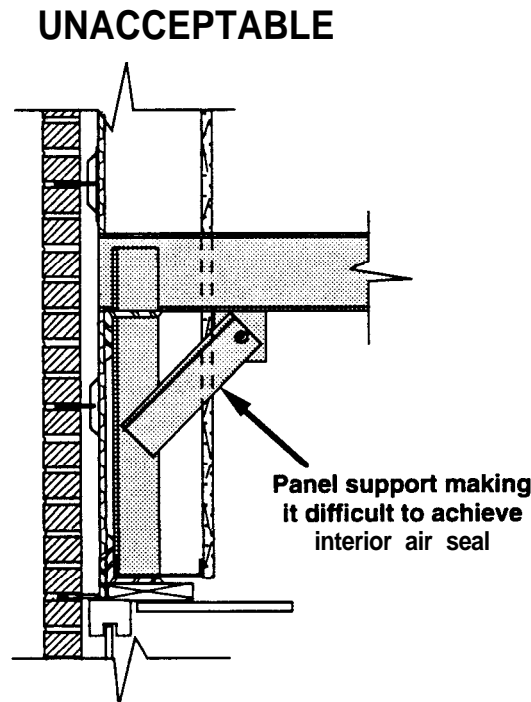


Figure 2.3.3 Diagonal Brace Supporting Spandrel (Kudder)

Wall Assemblies

- **Airflow passages within the envelope**
- **Poor material selection or attachment**

Good thermal performance of a wall assembly requires the secure attachment of the elements which make up the wall and the avoidance of unrestricted airflow passages within the system. Failure to meet these requirements causes air movement within the wall, which can severely degrade thermal performance and increase the potential for condensation within the system. While envelope air leakage from inside to out is an obvious problem, other modes of air movement also cause problems including air exchange between the building interior and the envelope system, air exchange between the envelope system and the outdoors, and air movement within the envelope system itself. Air movement within the envelope system degrades thermal performance due to airflow around and through thermal insulation and due to self-contained convective loops within the envelope system. Avoiding such air movement within the envelope requires a wall assembly that does not contain extensive vertical airflow passages and that insures that the elements remain in position over time. Vertical air spaces are sometimes designed into wall systems, for example between the interior wallboard and the inner face of the backup wall, When such air spaces extend over several stories of a building, the resultant air movement can be particularly significant. As discussed earlier, when such a cavity exists next to a layer of fibrous insulation, the thermal effectiveness of the insulation will be severely decreased. Almost any kind of wall system can develop significant airflow paths within the envelope because of designs or materials that can not resist wind pressures or structural movement or that lack adequate durability. The inadequate support or attachment of envelope components can result in the repositioning of envelope elements due to wind forces or the movement of structural components.

Roofing Systems

- **Thermal bridges: penetrations, structural elements**
- **Insulation defects: gaps**
- **Air leakage: penetrations, structural elements, flutes in corrugated steel decking, incomplete attachment of loose-laid membranes**

The thermal performance of roofing systems can be reduced by thermal defects including insulation defects, thermal bridges and air leakage. The insulation defects include those discussed previously, with gaps between insulation boards and batts being a particular problem. Childs studied three thermal bridges caused by high conductivity components penetrating the insulation of a roofing system consisting of lightweight concrete on a metal deck. These penetrations include a pipe used to support rooftop mechanical equipment, a steel I-beam also used as an equipment support, and a concrete pillar used to support a window washing system. Steven Winter Associates also discusses thermal bridges associated with equipment supports and roof railings, and calculates the effect of these bridges and alternative, nonbridging designs on the heat transmission rates.

One of the most serious thermal performance problems in roofing systems is air leakage. Air leakage through or around the insulation decreases the thermal effectiveness of the system. In cold climates the leakage of moist air from the building interior into the roofing system will cause condensation within the roofing system, leading to increased heat flow through moist insulation and possibly the degradation of roofing materials. While vapor retarders are effective in controlling the diffusion of moisture into the roofing system, it has been repeatedly pointed out that convection due to air leakage is the predominant mechanism for moisture transport into roofing systems (Tobiasson 1985, 1989). Such air leakage arises from improper sealing of roofing system penetrations, i.e., pipes, plumbing vent stacks and structural supports for rooftop equipment. Other air leakage sites are associated with structural features such as expansion joints, incomplete attachment of loose-laid membranes, and unsealed penetrations through flutes in corrugated steel decking. Many air leakage sites are associated with the connection of the roofing system and the exterior walls.

Component Connections

- . Floor /wall
- . Window /wall
- . Wall/roof
- . Column/wall
- . Wall/wall
- . Wall/ceiling

The connections between building components are associated with many thermal defects including air leakage, thermal bridging and insulation defects. Most occur because inadequate attention is given to maintaining the continuity of the insulation layer and the air barrier system at these connections. Particular concern has been directed towards the intersection of the floor slab and the exterior wall (Chang, Childs, Fang), the installation of the window in the wall (Rousseau, Patenaude), and the wall/roof junction (Riedel, Turenne). The floor-wall connection is often the site of significant thermal bridging when the floor slab penetrates the wall insulation. This location is also often the site of air leakage. Window-wall connections are associated with several thermal defects including air leakage and air barrier discontinuities, insulation voids and compression around window frames, positioning the thermal break of the window system such that air is able to infiltrate around it, and designs in which the area of the window frame exposed to the outdoors is larger than the area exposed to the indoors. This last defect causes the inner frame to be cold, increasing the potential for condensation. The wall-roof junction is a common location for air leakage due to discontinuities between the wall air barrier and the roof membrane. The wall air barrier may or may not extend to the roof deck, and the roof membrane is seldom sealed to the wall air barrier. Rather, the membrane is often turned up at the roof edge, leaving a discontinuity in the envelope air barrier at this junction. Examples of thermal defects at wall/roof intersections are presented in the section Systems/Roofing Systems.

The connections between walls and structural columns and between different wall systems can be associated with thermal bridges and insulation defects. These connections are also associated with air leakage due to the use of air sealing systems which can not accommodate differential movements between the two different components. This situation was discussed earlier with reference to concrete block masonry walls and structural columns and spandrel beams. Also discussed earlier, the intersection of the wall and a suspended ceiling is sometimes associated with inadequate airtightness and missing insulation when materials and finishes are not carried up above the ceiling level to the floor above (Handegord, Kudder).

Other Assemblies

- Overhangs
- Soffits
- Stairwells
- Interior Partitions

There are variety of other assemblies in buildings that are associated with thermal envelope defects. Overhangs, where a heated space extends out over an exterior wall, is one such assembly where air leakage, insulation defects and thermal bridging can occur. Soffits, for example those located over an entrance, can be associated with air leakage and heat loss from the building interior into the soffit and then to the outdoors (Perreault 1980, Quirouette 1983, Turenne). Stairwells located at building perimeters can also be associated with thermal defects (Kudder). They are often enclosed in concrete block with a single coat of paint and insulation board adhered to the exterior face of the block. A single coat of paint results in substantial permeability from the stairwell to the cavity beyond the backup wall, and the insulation board on the exterior of the block will not provide a functional air barrier. The air-tightness of interior partitions, such as stairwells, elevator shafts and shafts associated with building services, is often neglected despite its importance to building thermal performance. Airflow communication between the building interior and these vertical shafts serve to connect the floors of a building in terms of airflow, thereby increasing the stack pressures across the exterior envelope and increasing infiltration rates. These stack pressures can also interfere with the effective operation of mechanical ventilation systems.

Figure 2.3.4 shows an example of an air leakage problem at an overhang involving a steel roof deck in which air leaks in through the bottom and outer edge of the overhang (Riedel). Airflow then continues over the top of the outside wall and into the roof insulation. Air is also able to move past the building wall above the deck since the deck flutes are not adequately sealed; the flutes are simply stuffed with glass fiber insulation.

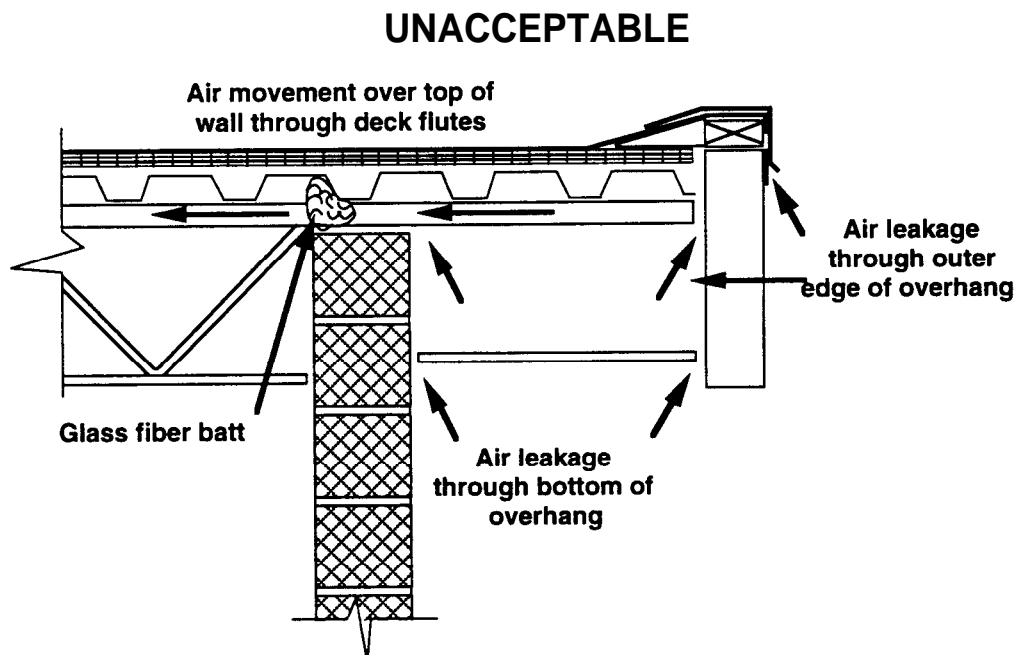


Figure 2.3.4 Connection of Wall and Roof Overhang (Riedel)

Another air leakage and moisture problem associated with a soffit, depicted in Figure 2.3.5, is described in Perreault (1980). The wall consists of a brick veneer, rigid insulation and a block backup wall, and the roof has an insulated metal deck. The overhang construction consists of a soffit enclosed on the top by an extension of the roof deck and on the back by the building's block wall. Precast concrete panels make up the sides of the soffit. The bottom consists of stucco applied to a mesh that is suspended by wires that pass through holes in the deck. Due to leakage of moist interior air into this overhang, there was severe frost on the soffit panels, the steel truss members, and the suspension wires. This leakage occurred through the roof deck flutes between the top of the block wall and the underside of the deck. These joints were filled with batt insulation but were not sealed. Air leakage also occurred through the upper flutes of the deck, and then through holes in the deck associated with the suspension wires. Perreault states that this air leakage problem could have been avoided by sealing the top and bottom of the roof deck at the wall junction with foam and caulking.

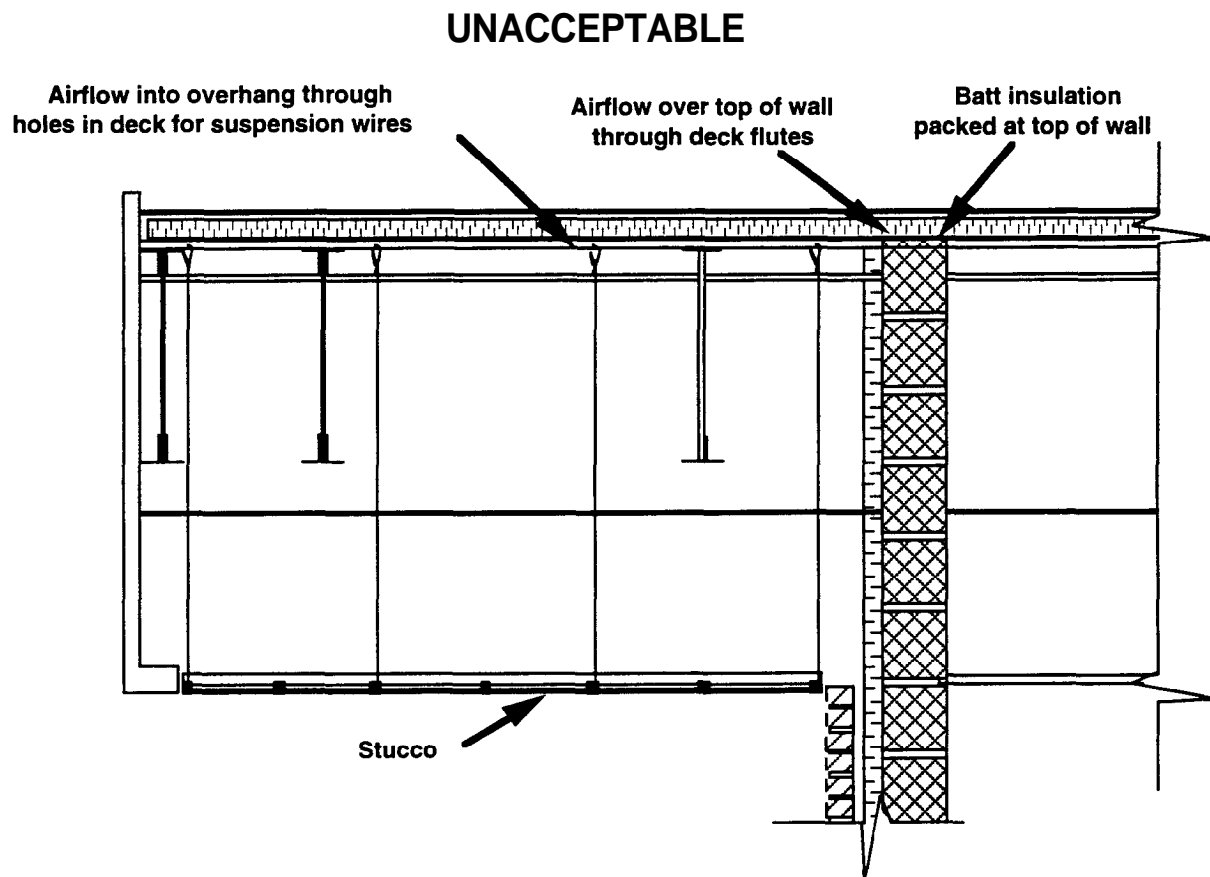


Figure 2.3.5 Connection of Wall and Soffit (Perreault 1980)

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2.4 DESIGN AND CONSTRUCTION PROCESS

These guidelines primarily consist of design guidance and details directed towards the avoidance of air leakage and insulation system defects. While the use of sound design principles and details is essential to achieving good thermal performance, their use is not sufficient without a commitment to quality and performance in the design and construction processes. This commitment must begin in the first stages of design and continue throughout the construction of the building. The design and construction of office buildings is a complex process, involving building owners, architects, engineers, consultants, builders and subtrades, and all of these people have their individual motivations, concerns and experience. The CSI Manual of Practice presents a good discussion of these participants and the various relationships that exist between them. Sometimes the motivations of these participants, conflicts among their goals, and a lack of familiarity with thermal performance issues lead to some of the envelope performance problems that these guidelines are attempting to address. This section discusses the design and construction processes and their relationship to thermal envelope performance.

Motivations and Concerns

The design and construction of an office building is a very complex process involving numerous players, each with their own particular motivations, concerns and experiences. The process and the established roles of many of these players can contribute to the occurrence of thermal envelope performance problems. While the reasons are as complex as the process, part of the problem is that thermal envelope integrity is not emphasized and recognized as a critical factor throughout the design and construction of an office building. To some designers and builders, simply requiring a certain level of insulation, or the installation of an air barrier material or a quality sealant, is all that is needed. The importance of purposefully designing the insulation and air barrier systems as integral parts of the envelope is not recognized, nor is the need for a commitment to these systems from the very beginning or the necessity to develop straightforward, buildable details in order to make these systems work. Without a strong emphasis on thermal envelope integrity, decisions will be made or not made that result in thermal defects, and it will be too late for any alternative details to be developed to correct these defects.

When the commitment to thermal envelope integrity is lacking, problems arise in many areas. For instance, the efforts of the various design disciplines (architectural, structural, mechanical, electrical) will not be coordinated with the continuity and integrity of the air barrier and insulation systems in mind. Problems in these as well as other aspects of envelope performance will arise when the activities of these separate disciplines are not considered in relation to one another. Poor communication, a segregated approach to developing design details and a lack of commitment to thermal envelope integrity in the development of these details can result in envelope system that can not be effectively insulated or air sealed (Kudder). Kudder presents an example of such a problem that concerns the edge of a floor slab, as shown in Figure 2.4.1. The structural drawing showed only the spandrel beam supporting the floor slab, but did not show the wall. The architectural drawing included the wall, but did not show the beam located just inside the wall. The structural drawing implied that there was free access for the installation of fireproofing on both sides of the beam, and the architectural drawing implied that there was free access to the wall for the installation and finishing of the drywall all the way up to the floor slab. In fact, due to the location of the beam, the drywall screws could not be installed and the drywall joints could not be taped, leading to the leakage of interior air into the wall cavity. This problem occurred because there was no commitment to an air barrier system and because of poor coordination among the design disciplines.

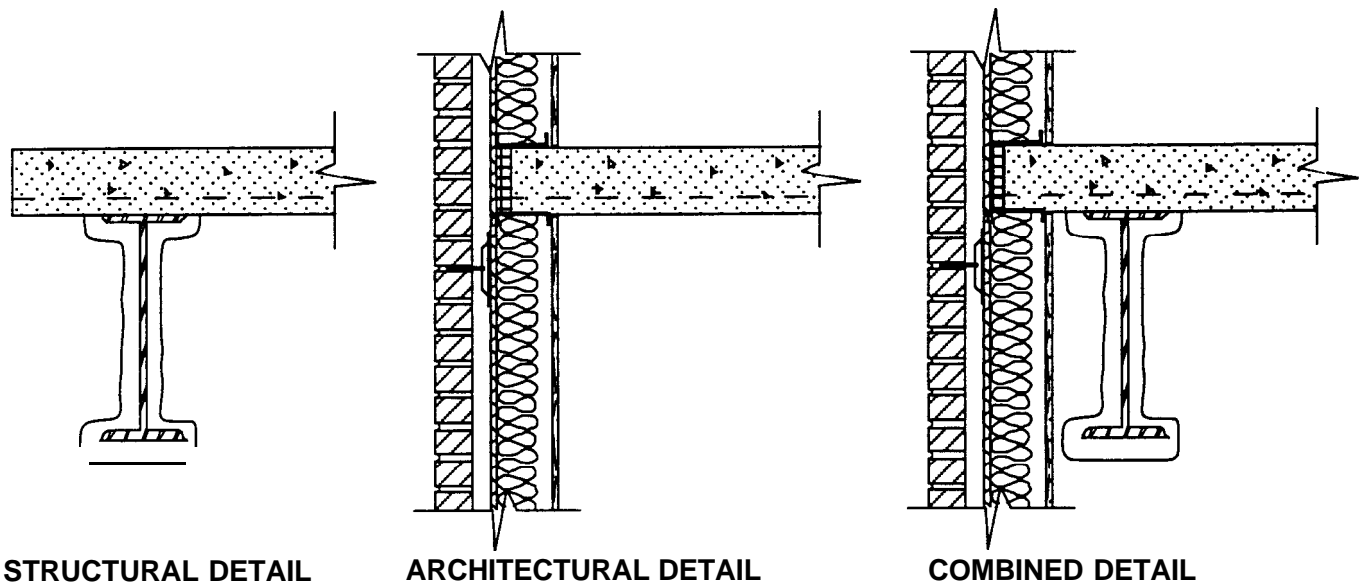


Figure 2.4.1 Example of Poorly Coordinated Detailing (Kudder)

It is important for the various participants in the design and construction process to understand each others roles, motivations, limitations and abilities. While this is more easily said than done, it is absolutely essential. Designers need to develop details with consideration of the fact that the construction workers have no design background and should not be forced to guess the designers intention or play the role of designer. The role of construction worker should be to build as carefully as the details were developed. Therefore, construction details need to be precise, easy to understand and buildable, with no guesswork left to the workers (Perreault 1980). Too often, the design process involves copying design details from previous jobs or published details that contain no air barrier system and include significant thermal bridges, as opposed to designing the envelope as a system and considering each detail in relation to this system.

Similarly, the designer needs to recognize the importance of individual envelope elements and their impact on performance, and not compromise essential requirements for aesthetic or other considerations. For example, flashing must extend beyond the face of the facade in order to function properly, despite the fact that it might conflict with certain aesthetic goals. Similarly, designers will sometimes limit the width of sealant joints without an analysis of the relevant performance factors to determine if the width they select will be effective (O'Connor). The designer must understand that these thermal envelope design considerations and requirements are critical and must be incorporated into the envelope design.

As discussed in the section on air barriers, the importance of air leakage is not always appreciated in the design and construction of buildings. As stated throughout these guidelines, the control of air leakage through the use of an air barrier system is essential to good thermal envelope performance. There is an unfortunate lack of appreciation on the part of designers, builders and material suppliers as to the importance of air leakage (Handegord). It is sometimes assumed that simply by specifying a vapor retarder or an air barrier, one has dealt with the problem. In reality, achieving airtightness requires that an air barrier system is designed into the wall from the very beginning. There is also sometimes a resignation that air leakage is inevitable and in fact desirable. To the contrary, air leakage can and must be controlled to prevent a variety of performance problems.

The AAMA manual on the Installation of Aluminum Curtain Walls is an excellent reference on communication and coordination in the design and construction process. Although much of the discussion is specific to aluminum curtain walls, the manual discusses general issues relating to the responsibilities of architects, contractors and field personnel. The architect needs to be aware of field procedures and conditions and develop clear drawings and specifications based on this awareness. The architect should work closely with the contractor in developing the details to facilitate fabrication and installation. Inspection during construction is identified as critical to insuring that the specifications and shop drawings are closely followed. Architects should clearly define maximum permitted tolerances in the alignment of the building frame, and provide for these tolerances in the wall installation. The general contractor must develop the construction schedule in consultation with the other players in the project, allowing sufficient time for other steps in the process such as the development of the shop drawings, the fabrication of custom components, and the assembly and testing of a mockup.

Air Barrier Systems

Because of the importance of including air barriers in building envelopes, and their common omission in most buildings, this section gives special attention to how air barrier systems fit into the design and construction process. Many architects and designers are either unfamiliar with air barrier systems or do not consider them to be significant relative to the many other issues with which they must deal. This lack of familiarity exists because most discussions of air barriers exist in the technical literature, not in the publications to which designers are more often exposed. Also, the promotion of most new ideas within the construction industry is largely product or sales driven. Since an air barrier is a system as opposed to a single material, it is not promoted in new product columns or by writers of architectural publications.

Designers are often unfamiliar with the importance of air barrier systems and how to incorporate them into building envelope design. Before the design process even begins, it is relevant to determine whether anyone on the design team is aware of or experienced with air barriers and able to incorporate such a system into the envelope details and specifications. If not, it probably will not happen. If such a person is part of the team, he or she still may not have sufficient influence to pursue the issue. Once the design development phase has begun, the commitment to a continuous, well-supported and buildable air barrier should already be in place. This commitment is likely to be challenged with statements such as: "We have not done this before...We have a vapor retarder, what do we need this for?...It is not in the budget." The case for an air barrier must be made strongly and clearly; its function and requirements must be explained. When a commitment has been made to an air barrier system, its compatibility with the basic envelope design, the structural system, and the thermal insulation and vapor retarder systems must be reconciled early in the design process. An air barrier that is incorporated as an afterthought can not be effectively integrated with these other systems and will not perform adequately. The compatibility of the air barrier system and the major details, e.g., wall-floor, wall-window, corners, columns and parapets, should be examined early in the process.

As the working drawings are being produced it is important that the air barrier is correctly and consistently applied to all primary and derivative details. This is particularly important for masonry walls where the working drawings are used for construction without the benefit of separate construction drawings. All members of the design team must understand the principles of the air barrier so that all details are developed consistently, and all details must be reviewed with respect to the air barrier. As the specifications are developed, it is essential that they contain a requirement for an air barrier. The requirements should specify that the air barrier be identified on shop drawings and should address the structural adequacy of the air barrier system.

During the estimating and budgeting phase, it may become apparent that the construction managers and owner's representatives do not understand the principles of air barriers. They may regard them suspiciously as something they have never done before and a waste of money. The owner and construction manager may be likely to listen to the contractor's claims that such an elaborate air barrier system is unnecessary, and that they never include them in the walls they build. If building or energy codes mandated the inclusion of an air barrier, it would certainly strengthen the case of the air barrier proponent.

An air barrier will be incorporated into the shop drawings, and therefore into the building envelope, only if a specific requirement for an air barrier system is made by the wall designer. Shop drawings are generally not submitted for masonry walls, rather the working drawings are used during construction. It is therefore very important that the masonry contract drawings and specifications are thorough so that there are no questions regarding the existence of the air barrier, its location, materials and its treatment at junctions. Since masonry contractors typically do not develop shop drawings and design details in response to performance specifications, they are relying on the designer to develop these details. In other curtain wall systems the specifications are generally performance based and the manufacturer incorporates them into the engineering and shop drawings, which become the construction drawings. The air barrier will be correctly incorporated into the construction drawings only if the designer has included the system into their drawings and included appropriate language in the specifications.

If the commitment to an air barrier has survived to the construction phase, there are two remaining issues to deal with, education and supervision. All site personnel must be educated on the air barrier system and its importance to the project. An inspection agent should be employed and an inspection program developed to insure a proper installation of the entire wall, with special attention given to items that are new to the site worker. A field mock-up of the wall is a very good way to educate the site personnel and to identify construction problems with the system as designed.

Requirements and Recommendations

These guidelines are not able to offer a redirection of the process by which office buildings are designed and constructed. However, there are several essential design principles, stressed throughout these guidelines, that need to be incorporated into the design and construction processes. These include a modification of the rules stated by Brand for evaluating envelope designs and all associated details:

- Enclose the building in a continuous air barrier.
- Provide continuous support for the air barrier against wind loads.
- Ensure that the air barrier is flexible at joints where movement may occur.
- Provide continuous insulation.
- Design copings, parapets, sills and other projections with drips to shed water clear of the facade.
- Provide the means for any water that does penetrate the facade to drain back to the outside.

Thermal envelope design must also include a recognition that wall materials are not dimensionally stable and will move differentially from each other and from the structural frame. The location and extent of this movement must be anticipated. The air barrier element at these locations, whether it is an elastomeric sealant or a flexible membrane, must be designed to accommodate the anticipated degree of movement. If such movement is not adequately dealt with, the air barrier will fail at these locations and the continuity of the air barrier system will be lost. The need for continuity of the air barrier system can not be stressed enough. This continuity must also be maintained over wall areas, including those that are not readily accessible such as above suspended ceilings and behind convector cabinets.

The distinction between the control of water vapor diffusion and air leakage must be clearly understood. By definition a vapor retarder controls water vapor transport by diffusion, but not water vapor transport that occurs due to convection. An air barrier system is required to control convective moisture transport due to air leakage. The amount of water vapor transferred by air leakage is much larger than the amount transferred by diffusion, making the installation of an air barrier essential to the control of water vapor movement.

Perreault points out the importance of the environmental conditions during construction and the effect they can have on building components. Most building materials need to be protected from sun, heat, cold, wind and rain prior to their use and after they are installed, but before the exterior cladding is erected. Many of these materials will be affected by such exposure, degrading their in-use performance. These material issues can be dealt with through proper storage of construction materials, protection of partially completed work and scheduling of construction activities.

The CMHC Seminar on High-Rise Buildings makes a very valuable point on design philosophy, i.e., the designer must always assume that some degree of imperfection will exist in wall components. The design process must involve an evaluation of the locations and potential consequences of these imperfections, such as the degree and duration of wetness at critical locations, and then assure that the performance will not be compromised by these imperfections, or if it will, modify the design to accommodate them. The aim of the designer should be to minimize gross defects in the thermal envelope integrity and to tolerate the minor defects that inevitably occur.

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3.0 DESIGN

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3.1 AIR BARRIERS

The purpose of an air barrier is too prevent airflow through the building envelope. This includes both the prevention of outdoor air from entering the building through walls, roofs and foundations, and the prevention of indoor air from exfiltrating through the building envelope to the outside. The inclusion of an air barrier system in the envelope design is essential to controlling air leakage and achieving good thermal envelope performance. Air leakage leads to excessive energy consumption, poor thermal comfort and indoor air quality, condensation within the envelope and the associated degradation of envelope materials, and interference with the proper operation of mechanical ventilation and smoke control equipment.

Even if an air barrier is not specified in the envelope, those elements which are most impermeable to airflow will be subjected to the envelope pressure differences. They will then “act” as the air barrier, most likely a poor one. The material experiencing the pressure difference, and its means of attachment, will probably not be adequate to withstand the pressure and it will be displaced. For example, rigid insulation board may be forced out of position by wind pressures when there is no air barrier system in the wall and the insulation attachment is not designed to withstand the wind pressures.

The air barrier system must be designed with full recognition that envelope materials are not dimensionally stable and that differential movements occur due to temperature effects and structural loads. The elements of the air barrier at locations where differential movement is expected to occur must be capable of accommodating this movement using systems and materials that will retain the essential performance requirements of the overall air barrier system.

Material and System Requirements

There are four basic requirements for an effective air barrier system: continuity, structural integrity, air-tightness and durability.

Continuity: Continuity throughout the entire building envelope is one of the most important requirements of the air barrier system. It means much more than the various elements not having holes; continuity requires that all of the air barrier components are sealed together so there are no gaps in the envelope airtightness. The sealing of component connections is essential to air barrier design and construction, and a common source of failures. Areas where air barrier continuity must be given particular attention are at window frames, utility penetrations, wall-roof connections and the intersections of different wall systems.

The air barrier in each envelope component must be clearly identified during the design, and the manner in which they will be sealed together at component connections must be well thought out. Air barrier continuity can also be violated at locations that are hidden by other envelope components. For example when the interior finishing (e.g. gypsum) serves as the air barrier, if it is sometimes not finished above suspended ceilings or behind convactor cabinets, there will be large gaps in the air barrier system's continuity.

Example; The sketch in Figure 3.1.1 shows a failure in air barrier continuity due to a lack of interior finishing (Kudder). In this wall the interior drywall served as the air barrier. However, due to the obstruction of the spandrel beam, the drywall could not be finished and severe air leakage occurred around the beam into the cavity behind the facade. Drywall screws were not installed behind the beam, and the joints were not taped all the way up the height of the wall.

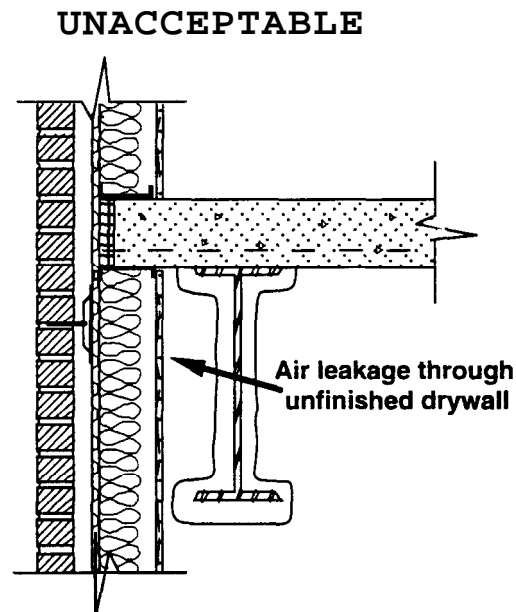


Figure 3.1.1 Failure of Air Barrier Continuity (Kudder)

Structural Integrity: All elements of the air barrier must be able to resist the imposed pressure loads or be supported by something that can resist these pressures. If the air pressure difference across the building envelope is not able to move air, it will work to displace those materials that are preventing this airflow. If the pressure exceeds the capability of the air barrier system to support this pressure load, then the system will fail, permanently destroying its ability to provide air-tightness. In more specific terms, the air barrier system must resist peak wind loads, stack pressures and (de)pressurization by ventilation equipment without rupturing or detaching from its support and must not creep away from its supports or split at joints under sustained air pressures.

Example: A case of inadequate structural support of the air barrier in a parapet wall is shown in Figure 3.1.2 (Quirouette 1989). The wall consists of a brick veneer, an insulated steel stud wall, a polyethylene sheet air barrier/vapor retarder and an interior drywall finish. The parapet consists of a brick veneer, rigid insulation, polyethylene and concrete block backup. The rigid board parapet insulation was spot adhered to the polyethylene, which ran from the top of the wall studs, past the steel beam, and up the parapet where it was sealed to the parapet top plate. Because the polyethylene was not adequately supported, it moved back and forth with the wind pressures and eventually tore. The movement of the polyethylene pulled the rigid insulation from its original location, which in turn pulled the polyethylene further out of place. The parapet air seal was rendered totally ineffective, and the effectiveness of the insulation was severely degraded.

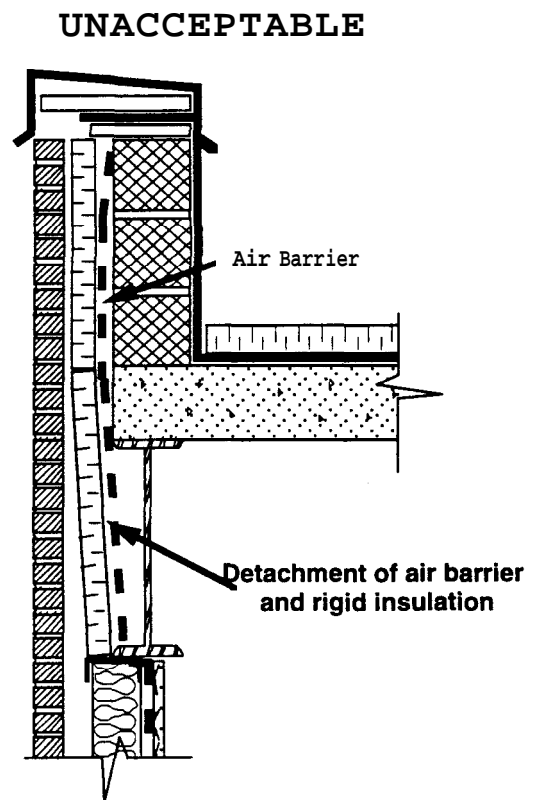
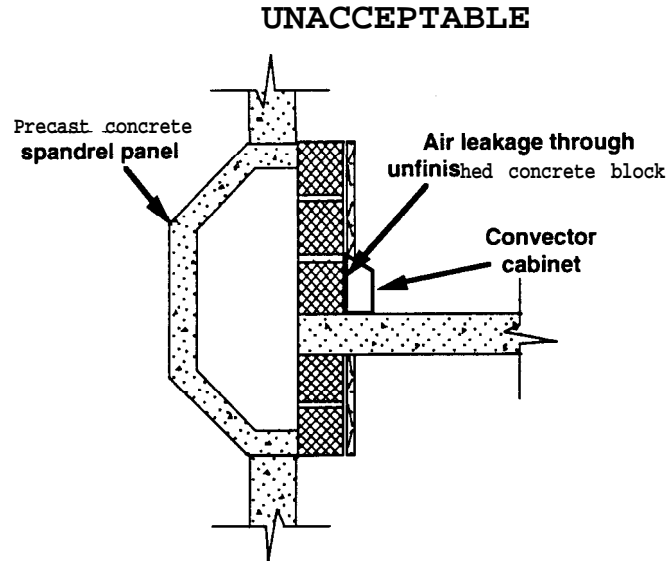


Figure 3.1.2 Failure of Air Barrier Integrity (Quirouette 1989)

Ah-tightness: The materials comprising the air barrier system obviously must be airtight, but more importantly these materials must be joined into a system such that the total assembly is equally airtight (continuity). Many building materials are clearly impermeable to airflow, e.g. glass, sheet metal and various membranes. Other materials are permeable to airflow, though this permeability is not always recognized, as in the case of a single wythe of masonry construction.

Example: The importance of air impermeability, specifically that of concrete blocks, is demonstrated by the example depicted in Figure 3.1.3 (Quirouette 1989). The figure shows a precast concrete panel wall with U-shaped column covers and C-shaped spandrel panels on a cast-in-place concrete frame with a concrete block infill wall. The blocks behind the convector cabinet were left exposed and untreated. Air passed through the blocks, into the space between the infill wall and the spandrel panel, and up behind the column covers. Severe condensation, freezing and melting problems occurred.



**Figure 3.1.3 Air Barrier Permeability
(Quirouette 1989)**

Durability: The air barrier materials and the assembly must be known to have sufficient durability and demonstrated longevity in the field. If not, the air barrier materials should be positioned in the envelope such that they can be inspected and serviced as necessary. One must recognize that durability is not an inherent material property but is a function of how the material reacts to environmental exposures, i.e., temperature, moisture, radiation (UV) and adjacent materials.

Perreault and others have pointed out the use of inappropriate materials as air barriers:

- Insulation materials do not necessarily prevent the flow of air, unless specifically designed to serve as part of an air barrier system that meets all of the above requirements.
- Mastic is often used in masonry walls as an insulation adhesive and can serve as an adequate vapor retarder, but it cannot serve as an air barrier. As Perreault points out, mastic does not have the material properties required to bridge gaps and fissures on masonry surfaces, and therefore it cannot achieve the requirement of continuity.
- Polyethylene sheet or film is an effective vapor retarder material, but because it is not strong enough to withstand wind pressures, it is not suitable for controlling air leakage without adequate structural support. Polyethylene will perform if well-supported on both sides, but it is not strong enough to bridge openings. Another material could be used to bridge these openings, but it must be sealed to the polyethylene. In addition, the long-term durability of polyethylene has been questioned.

Air Barrier Location within the Envelope

From the perspective of controlling heat transfer alone, the location of the air barrier within the envelope is not important. However, from the perspectives of constructability, durability and envelope condensation, the location is very important.

From the perspective of durability, it is preferable to have the air barrier within the exterior cladding and outward of the structural frame. Having the air barrier within the cladding protects the air barrier materials from the detrimental affects of weather, i.e., sunlight, rainwater and extreme temperature fluctuations. The preferred approach to realizing this design is the use of a pressure-equalized rain screen cladding, as discussed in the section on Rain Penetration Control. In this approach a well vented cavity behind the facade controls pressure-driven rain penetration and a well protected air barrier controls air leakage.

Keeping the structural frame of the building within the air barrier makes the air barrier system design more straightforward in terms of maintaining continuity at penetrations associated with structural elements.

In cold climates, positioning the air barrier on the interior side of the insulation protects the air barrier from outdoor temperature fluctuations. Furthermore, the envelope elements to which it is attached are similarly protected, minimizing the thermally induced movement of these elements and the resultant physical stresses on the air barrier components. In this situation the air barrier can also serve as the vapor retarder since it is on the warm side of the insulation. In warm climates, it will generally be more advantageous to locate the air barrier outside the insulation from the perspective of airborne moisture transport. If the air barrier is located interior of the thermal insulation, special care is required to avoid infiltrating water vapor from condensing on the air barrier.

As discussed in the next section on Vapor Retarders, if the air barrier is not also serving as a vapor retarder, the relative position of these two elements must be given careful consideration. Whether or not this is the case, the position of the vapor retarder should be based on an analysis of the temperature and water vapor profiles through the building envelope, using the techniques presented in the ASHRAE Handbook of Fundamentals. If the two systems are separate, i.e., the air barrier is on the low vapor pressure side of the envelope, then the water vapor permeability of the air barrier must be well above the permeability of the vapor barrier. Recommendations on the permeability ratio of the air barrier to the vapor retarder range from 5 to 20, however, each system needs to be analyzed individually for its particular climate.

Application Examples

The particular air barrier system approach employed in a building envelope necessarily depends on the specific envelope system being used. Perreault (1989) has described the various air barrier systems in use, and they are discussed below:

Accessible Drywall: In this approach, shown in Figure 3.1.4 for a brick veneer/steel stud wall, the interior (exposed) drywall is the main component of the air barrier system. This approach relies on high performance sealants (see section Design/Sealants) to seal the drywall to other materials and to accommodate the large tolerances associated with commercial construction and the large differential movements associated with long spans. There is easy access to the air barrier from the building interior, facilitating inspection and repair. This system works well with concrete structures, as shown in the figure, but its application can be quite complicated in a steel structure.

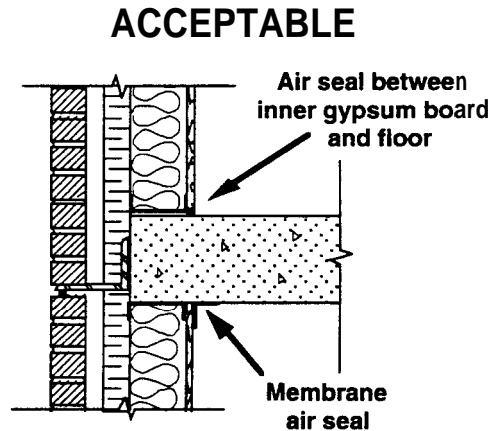


Figure 3.1.4 Accessible Drywall Air Barrier (Perreault 1989)

Non-accessible Drywall: In this approach, the exterior drywall sheathing serves as the main component of the air barrier system as seen in Figure 3.1.5. Joints between drywall boards are sealed with reinforced self-adhesive tapes, and joints between boards and other components are sealed using strips of elastomeric membranes. This system has the advantage over the accessible drywall approach of having fewer perforations of the air barrier from interior services such as electrical outlets. Because the gypsum sheathing and the air seals are inaccessible after construction, these materials must be durable and their attachment must be capable of long term performance. This approach works well in steel structures because the air barrier can be extended past steel columns and beams. The two details shown in the figure are examples of the application of this approach to a wall with a panel facade, insulation and a stud wall with gypsum board on both sides. The first case has a concrete frame and the second has a steel frame.

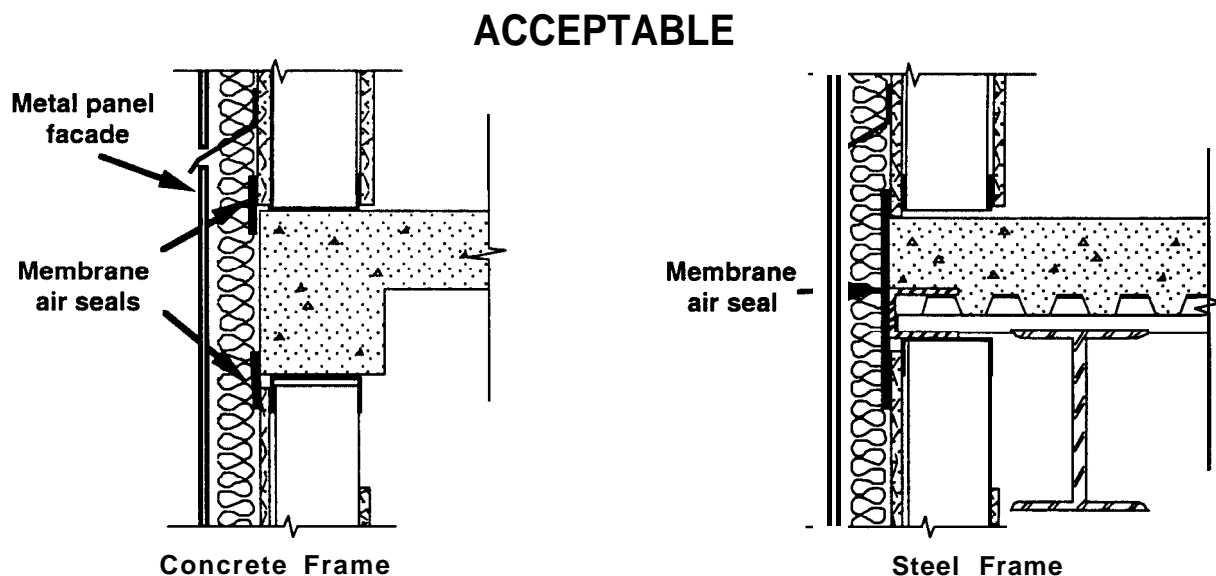


Figure 3.1.5 Non-Accessible Drywall Air Barrier (Perreault 1989)

ACCEPTABLE

Curtain Walls: In curtain walls the air barrier consists of the glass, metal pan and extrusions, insulation and sealants. Figure 3.1.6 shows the basic approach to providing an air barrier in the system. The metal pan behind the spandrel insulation and the vision glass are the major elements of the air barrier; they must both be joined to the mullion using appropriate sealants to maintain the air barrier continuity.

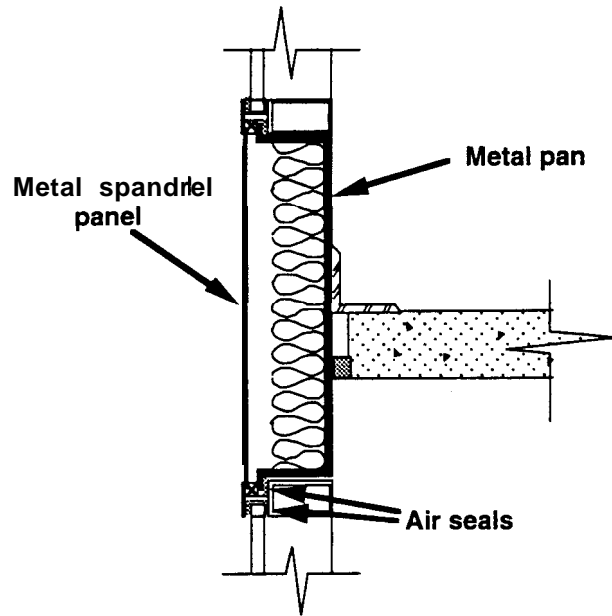


Figure 3.1.6 Curtain Wall Air Barrier (Perreault 1989)

Metal Buildings: In metal building systems, the interior sheet steel liner serves as both an interior finish and a combined air/vapor barrier. Since the metal liner is airtight, the panel joints are the critical elements in the air barrier system. Care is also required in the design of wall/roof intersections and at the bottom of the walls in these systems.

Masonry Walls: Various approaches have been used for air sealing masonry walls. Factory-made elastomeric membranes provide a reliable air barrier, with the membrane being applied to the entire surface of the masonry backup wall as shown in Figure 3.1.7. These membranes may be thermofusible or peel-and-stick. Thermofusible membranes are adhered to the backup wall by heating the membrane backing with a propane torch. Insulation can be held in place with metal clips heat welded to the membrane. A sketch of an elastomeric membrane air barrier applied to a masonry wall is shown in the figure. The membrane runs continuously past the floor slab providing good continuity. Note the gap between the top of the backup wall and the bottom of the floor slab to accommodate deflection of the floor slab or other differential movement between the backup wall and the building structure.

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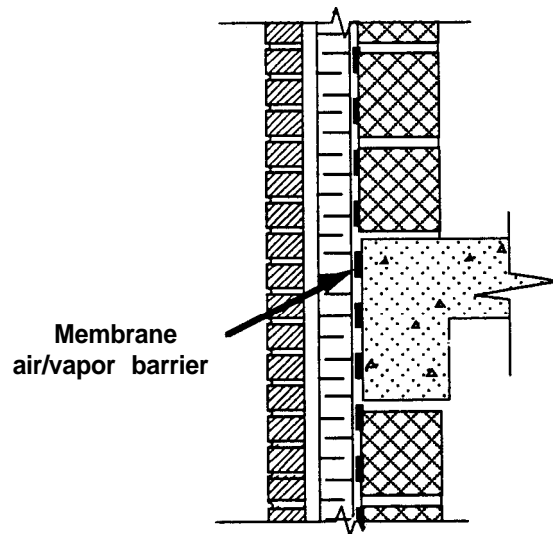


Figure 3.1.7 Masonry Wall Air Barrier (Perreault 1989)

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3.2 VAPOR RETARDERS

The purpose of a vapor retarder is to retard, or slow down, the rate of water vapor diffusion through the envelope. An effective vapor retarder decreases the potential for condensation within the envelope by decreasing the amount of water vapor that diffuses to the colder portions of the envelope. The diffusion of water vapor is analogous to heat conduction, with the vapor pressure difference corresponding to the temperature difference and the resistance to diffusion corresponding to the R-value. The rate of water vapor diffusion through a material is equal to the vapor pressure difference across it divided by the material's resistance to water vapor diffusion. The resistance of a material to water vapor diffusion is generally described by its permeance or "perm" rating. The permeance is actually the inverse of the resistance, and therefore the lower the permeance the higher the resistance to water vapor diffusion. While certain materials, with a permeance below a specific value, are generally classified as vapor retarders, all envelope materials have some resistance to water vapor diffusion. Therefore, when designing the thermal envelope and considering the vapor retarder, one must do more than select a material with a specific permeance. One must consider its resistance to water vapor diffusion in relation to that of other envelope components.

In general, condensation control requires that envelope components increase in permeance in the direction of vapor diffusion, whether or not a vapor retarder is specifically included in the system. This approach will generally prevent the air diffusing through the envelope from reaching a temperature below its dewpoint, the dewpoint being the temperature at which the water vapor will condense. Locating a low permeance material on the low vapor pressure, and generally cold, side of the envelope will slow the rate of diffusion and increase the water vapor content of the air at this point. In this situation, sometimes referred to as a "moisture dam" or "vapor trap," the dewpoint is increased, and water vapor may actually condense at this location and lead to various condensation-related problems. Whether such condensation leads to problems depends on the amount of condensation, the duration of the condensation episodes, the moisture absorptive properties of the envelope materials and the durability of these materials over wetting and drying cycles. These processes and material properties are currently being studied, and up-to-date and time-tested guidance based on the consideration of these issues is not yet available.

Vapor retarders only control water vapor transport by diffusion and do not address the larger amounts of water vapor transport caused by air leakage. It has been repeatedly pointed out that air leakage can carry several hundred times more water vapor than diffusion. The dominance of air leakage does not mean that diffusion can be ignored and vapor retarders eliminated. Rather, both diffusion and air leakage need to be considered and effective means for their control included in the thermal envelope design.

Material and System Requirements

The two primary requirements for an effective vapor retarder are a sufficiently high resistance to water vapor diffusion (low permeance) and continuity of the retarder over the building envelope. The permeance of a material is the rate at which water vapor diffuses across a unit area subject to a unit water vapor pressure difference. The SI unit for permeance is $\text{ng}/\text{Pa}\cdot\text{s}\cdot\text{m}^2$. The inch-pound unit, referred to as the “perm”, is $\text{grains}/\text{hour}\cdot\text{ft}^2\cdot\text{in Hg}$. (1 perm = $57 \text{ ng}/\text{Pa}\cdot\text{s}\cdot\text{m}^2$.) The 1989 ASHRAE Handbook of Fundamentals contains a good discussion of vapor retarder properties and their use in buildings, including a table of permeance values for many common building materials. Other material requirements for vapor retarders include mechanical strength, elasticity, fire and flammability resistance, and ease of installation. Vapor retarders include rigid materials such as sheet metal and some insulations, flexible materials such as metal foils, treated papers, coated felts and plastic films, and coatings such as mastics and paints.

A vapor retarder is sometimes considered to be any material with a permeance of less than $57 \text{ ng}/\text{Pa}\cdot\text{s}\cdot\text{m}^2$ (less than 1 perm), but actually the perm rating required for an effective vapor retarder depends on the specific envelope design and the expected vapor pressure difference across it. In some applications, a permeance much less than $57 \text{ ng}/\text{Pa}\cdot\text{s}\cdot\text{m}^2$ is required. It is also critical to consider the fact that all envelope components have some resistance to water vapor transport, even if they have not been designated as vapor retarders. The performance of the designated vapor retarder must be considered in relation to these other materials. In order to determine the adequacy of a particular vapor retarder one needs to conduct an analysis of the temperature and vapor pressure profiles within the envelope as discussed in the ASHRAE Handbook.

Another important vapor retarder system requirement is the continuity of the vapor retarder over the building envelope. As discussed below, sealing small penetrations and joints between vapor retarder elements is generally not crucial. However, the vapor retarder treatment must be installed over the entire building envelope. For example, if the vapor retarder is the interior finish of vinyl wallcovering, this wallcovering must be installed over the entire interior surface including wall areas that are hidden from view, such as above suspended ceilings or behind convactor cabinets. Exterior ceilings and soffits are other areas where vapor retarder continuity must not be forgotten.

Transport by Diffusion versus Air Leakage

Diffusion is one mechanism of water vapor transport through a building envelope, the other being air leakage. Airflow through leaks and openings in the building envelope can transport much larger quantities of water than diffusion alone, and in order to truly address the potential for condensation in the building envelope one must control air leakage. Quirouette calculated the water vapor transport through 1 square meter of an insulated stud wall with a brick veneer due to both diffusion and air leakage. For a 10 square centimeter penetration in the wall, assuming that only 10% of the moisture contained in the exfiltrating air actually condenses in the cavity behind the veneer, he found that more than 200 times as much water transported by leakage condensed in the cavity as compared to amount which would condense due to diffusion. Although air leakage can easily dominate the transfer of water vapor, it is still important to control diffusion with a vapor retarder.

Vapor Retarders versus Air Barriers

The requirements and properties of vapor retarders and air barriers are often confused. In fact, the ASHRAE Handbook of Fundamentals describes a vapor retarder as having the requirement of resisting airflow. Actually, a vapor retarder does not need to control air leakage, assuming that the envelope has a properly designed and installed air barrier system. Problems can arise when the function of a vapor retarder is confused with the requirements of an air barrier system, principally an air barrier's requirements for continuity and structural adequacy. For example, polyethylene sheet or aluminum foil are not strong enough to withstand wind pressures. Also, it is extremely difficult to seal these sheet materials around penetrations.

An air barrier system is required in the building envelope for air-tightness, and the air barrier system must be designed and installed to meet all of the requirements. If the air barrier will also be serving as a vapor retarder, or if it has a low permeance to diffusion, then its position within the building envelope must be carefully considered in relation to the other envelope components.

Position within the Building Envelope

The general rule regarding the positioning of the vapor retarder within the building envelope is that the permeance of envelope materials should increase in the direction of vapor flow. Therefore, the vapor retarder should be located on the high vapor pressure side of the envelope. In climates dominated by heating this means the vapor retarder should be towards the interior of the envelope, and in cooling climates towards the exterior. While these general rules are useful, it is still appropriate to conduct an analysis of each envelope system. This analysis should consider climate and indoor humidity levels in determining temperature and water vapor profiles through the envelope system and assess the condensation potential within the system. The important factor to determine in such a calculation is whether and where the temperature within the envelope system will fall below the dewpoint temperature. The ASHRAE Handbook of Fundamentals describes the steps in such a calculation, and presents an example. The Moisture Control Handbook, recently published by Oak Ridge National Laboratory, discusses the positioning of vapor retarders for heating, cooling and mixed climates and discusses moisture transport for several different residential envelope designs.

If a high vapor permeance material is positioned on the low vapor pressure side of the envelope, the result can be an envelope with two vapor retarders, a so-called vapor trap. A vapor trap causes problems when water vapor is able to move into the wall on the high vapor pressure side but is unable to pass through the vapor retarder on the low vapor pressure side. Rules of thumb exist stating that if vapor retarding materials are to be used on opposite sides of a wall, the water vapor resistance of the high vapor side should be from 5 to 20 times the resistance on the low vapor side. However, rules of thumb are no substitute for a careful analysis of the temperature and vapor pressure profiles within the building envelope.

Summary: Problems in Practice

Most vapor retarder problems stem from considering the envelope vapor transmission properties of the vapor retarder in isolation from the rest of the building envelope and the particular environment to which the envelope will be exposed.

A vapor retarder is not just a material with a permeance below a specific value, it is a material/system that has been considered in relation to the entire envelope system regarding its ability to retard the diffusion of water vapor to locations where it may condense.

A good vapor retarder is not necessarily a good air barrier. And if the air barrier is distinct from the vapor retarder, the water permeance of the air barrier must be considered.

Vapor retarder continuity is not as essential as air barrier continuity. Small discontinuities in vapor retarders at joints, intersections and penetrations will not generally have serious effects due to their small areas, but they should be avoided. Neglecting the installation of the vapor retarder over large areas may result in more serious condensation problems.

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3.3 THERMAL INSULATION

Thermal insulation serves several purposes in building envelopes: controlling heat flow, serving as a component of the condensation control system, contributing to the maintenance of thermal comfort by controlling interior surface temperatures, reducing thermally induced movement of structural elements, and protecting envelope materials from temperature cycling. The ASHRAE Handbook of Fundamentals discusses the fundamentals and application of thermal insulation.

The discussion of thermal insulation in these guidelines does not address the determination of appropriate levels of insulation, but rather the manner in which this insulation is incorporated in the thermal envelope at the design and construction stages. There are two key issues regarding thermal insulation systems, the first being the insulation material. The other issue is how the insulation is positioned and attached to obtain effective and long-lasting performance.

Materials

There are a variety of materials used as thermal insulation, each with advantages and disadvantages in application within particular envelope systems. The Insulation Contractors Association of America (ICAA) manual describes the various types of insulation and provides the relevant specifications for each. Most of the material in this section is based on this document as well as Chapter 20 of the ASHRAE Handbook of Fundamentals, Thermal Insulation and Vapor Retarders - Fundamentals and Brand. Additional information on the various insulation materials and systems is available from the relevant industry associations listed in the Appendix C of these guidelines.

Insulation materials used in commercial construction include inorganic fibrous and cellular materials such as glass and rock wool, perlite and vermiculite. Organic fibrous and cellular materials are also used, such as cellulose, foamed rubber, polystyrene, polyurethane and other polymers. Metallic or metallized organic reflective membranes are also available, and are used as radiant barriers with air or gas-filled spaces. Insulation materials are available in a variety of forms including loose-fill, flexible and semi-rigid, rigid and foamed-in-place. All insulation materials have advantages and disadvantages, and their application must be considered with regard to issues of thermal resistance, degradation over time, shrinkage or settling, compatibility with adhesives and other proximate materials, and environmental concerns of recycling and offgassing.

Batt or blanket type mineral insulation is often used in stud walls for heat and sound control, and to be effective it must completely fill the cavity being insulated. When installing this insulation, the pieces should be as long as possible to minimize end joints, and where they do occur the material should be butted tightly together to avoid gaps. The batt should extend the full height of the cavity, butting flush at the top and bottom, again to avoid any gaps. When the batt is held by friction, it must be slightly oversized to prevent sagging and the associated gaps. When the cavity is more than about 2.5 m (8 feet) high, or it does not completely fill the cavity, additional mechanical attachment is necessary. Various mechanical fasteners are available, but it is important that they do not compress the insulation.

Insulation is also available in rigid boards consisting of mineral fibers, extruded polystyrene, expanded polystyrene, polyurethane, polyisocyanurate and light-weight cementitious composite materials. Mineral fibers boards should not be held up with adhesive alone since the fibers tend to come loose at the point of contact; some means of mechanical attachment is required. Mineral boards are advantageous when applied to rough surfaces, such as concrete masonry, because they are flexible enough to conform to the surface without leaving air spaces between the insulation and the backup. Rigid plastic boards have the advantage of rigidity and greater thermal resistance per thickness. They can be held in place mechanically or with adhesives. When rigid board insulation is applied in a cavity, the design must account for the exposure of the insulation to water. The insulation boards themselves should not be considered as a waterproofing material; a separate waterproofing system is required.

Various materials are available in the form of sprayed insulation, including mineral fibers, cellulose and foamed plastics. Sprayed insulation can be used in a variety of applications including exterior walls and can provide continuous coverage that is free of voids and cracks. When using sprayed insulation, there are several important jobsite issues to be considered, including proper preparation of the surface to receive the insulation, job scheduling to avoid damage to the completed work and temperature conditions at the time of the installation. Some spray insulation materials, including foamed plastics, can provide an air and water tight barrier. The insulation may need to be supplemented by flexible seals at interfaces between envelope components in order to accommodate differential movements.

Position in the Envelope

The position of the thermal insulation within the envelope needs to be based on several considerations including condensation control, ease of installation, the maintenance of insulation system continuity, and the relation to elements of the structural frame. In reference to water vapor transport, the insulation position needs to be based on consideration of the total envelope system, the means of water vapor transport control and climate. Basically the insulation should be positioned such that the temperature of low permeance materials are kept above the dewpoint of the interior air in heating climates and above the dewpoint of the outdoor air in cooling climates. The interactions of the vapor retarder and the insulation positions are discussed in the section Design/Vapor Retarders and in the ASHRAE Handbook of Fundamentals.

The position of the insulation within the envelope is also an issue with respect to interaction with other envelope elements. Positioning the insulation outside of the structural frame makes it easier to maintain the continuity of the insulation system and protects the structural elements from outside temperature swings. This protection in turn reduces thermally induced movements of the structural frame and the need to accommodate these movements in other envelope elements. However, when the insulation is located in the outer areas of the envelope, it will more often be exposed to water, and the material selection and attachment must account for this exposure. On the other hand, locating the insulation within the structural frame makes installation, inspection and repair of the insulation easier. However, it is difficult to deal with the interruptions of the insulation system caused by the structural elements while maintaining the continuity of the insulation, i.e., minimizing thermal bridging of the insulation system.

Design and Installation Requirements

While these guidelines do not address the design issue of how much insulation is required, there are many other critical design and construction issues relevant to the performance of the thermal insulation system. One particularly important issue is selecting the insulation material and the means of attachment based on the environment to which it will be exposed. Issues of drainage, adjacent materials, and compatibility with adhesives all need to be explicitly considered. The role, or roles, that the insulation will play also need to be considered. While the insulation is being used to control heat flow, it may also be serving as a vapor retarder or an air barrier. Such a dual role may be intentional. If it is not, problems can arise. If the wall does not have an adequately designed and installed air barrier system, the insulation may experience the air pressure difference across the wall. Unless the insulation and its attachment mechanism is designed for this pressure, the insulation may be displaced from its intended position, reducing its thermal effectiveness and perhaps leading to other serious consequences.

Another design and construction issue relevant to thermal insulation is the need to avoid convection around and through the insulation material. As discussed in Brand, if the insulation is applied or ends up in a position that allows air to circulate around it or behind it, convection currents will be set up that can reduce the insulating value of the insulation system as a whole. For example, if an air space exists between a masonry backup wall and a layer of cavity insulation in a heating situation, the air will be warm and will tend to rise within the cavity. As it rises, cold air from outside the insulation will be drawn into the air space and be warmed. The effectiveness of the insulation system will be quite poor, and heat transfer through the wall will be well above that determined based on material R-values alone.

While some envelope designs intentionally include air spaces that serve an insulating role, such as with radiant barriers, these air cavities need to be well-sealed and carefully designed and installed for optimal performance. Undesirable air spaces that lead to convection around and through insulation occur when a design incorporates ill-considered air spaces into the envelope and when the insulation is attached to an irregular surface. These spaces also arise when the insulation is repositioned over time due to air pressures or forces arising from differential movements of envelope elements. Irregularities in exterior walls, especially masonry backup walls, make insulation attachment a critical issue for the avoidance of air spaces. In cavity walls the insulation attachment system should be able to accommodate surface irregularities and hold the insulation tight to the air barrier. The attachment of rigid insulation boards by adhesive alone is more problematic because some adhesives do not have the tensile strength to hold the boards close to an irregular surface. Also, some insulation materials are too stiff to conform to these irregularities. Attachment of insulation with dabs of adhesive can make the situation worse due to air spaces between the dabs.

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3.4 CONTROL OF RAIN PENETRATION

While the relation between rain penetration and heat, air and water vapor transfer through the building envelope is indirect, it is still an important envelope performance issue. In fact, when most people in the field of building envelope design and construction discuss leakage, they are referring to rain penetration and not air leakage. Rain penetration is important to the discussion in these guidelines because, like all envelope design concerns and subsystems, the means for controlling rain penetration must be integrated into the building envelope so that all the various subsystems can function effectively.

The control of rain penetration is primarily an issue of keeping water away from building materials whose performance will suffer if wetted, and preventing water leakage to the building interior. Water leakage can lead to dimensional changes in envelope materials, rust and corrosion, decay of materials due to molds and fungi, deterioration of paint and other finishes, efflorescence, disintegration of materials, and dislodging of envelope components due to freezing (Brand). In addition to leakage into the building envelope, the flow of rainwater across the building surface must be controlled to prevent dirt-marking and staining of facade materials and etching of glass.

Rain Penetration Mechanisms and Control

There are four forces that move water through walls: gravity, capillary action, kinetic energy and air pressure differences (Brand). Gravity will move water through any opening or along any element, such as a brick tie, that slopes downward. Capillary action draws water into small cracks and pores in building materials and can account for the leakage of large amounts of water, particularly in masonry construction. Kinetic energy refers to water leakage into and through walls due to the force of wind-driven raindrops impinging on openings in the wall. Water will also penetrate a wall when there is an air pressure difference between the wetted side of the wall and the opposite side.

There are two basic approaches to controlling rain penetration, eliminating the openings and controlling the forces acting across these openings. Both approaches are used in different systems, but before considering either approach it is important to stress the control of rain water that flows down the facade of a building. Even the most well designed and carefully constructed system will have trouble preventing water leakage if the facade is constantly exposed to a stream of rain water runoff. In order to keep rain water off the face of the building, the facade must have properly designed drips at copings, ledges, sills, balconies, window and door heads, and other facade features. The design of drips is covered in many construction guides including Architectural Precast Concrete from PCI. Robinson and Baker also present a thorough discussion of wind-driven rain and the control of runoff.

The control of rain penetration by plugging the holes on the facade is sometimes referred to as the face-seal approach. This involves the use of various sealants at panel joints and other interfaces. The problem with this technique is that the sealant is exposed to severe conditions of sunlight and ultraviolet radiation, temperature cycling, water exposure and the differential movement of facade components. These conditions place very severe material requirements on the sealant and the technique of the sealant installer. For these reasons it is very difficult, some would say impossible, to achieve long-term success with the face seal approach without significant maintenance efforts. Any gaps or holes that arise over time, or occur at the time of installation, will leak water since no effort is made to control the forces transporting water across the facade. The first costs may be lower than in other approaches, but the costs to maintain performance can be high.

Controlling the forces that cause rain penetration involves designing and constructing joints and other envelope elements to deal with each of the four mechanisms referred to above (Brand). Gravity is controlled by sloping all openings to the outside so that water runs out instead of into the envelope. This is essentially the approach taken with flashing and weepholes in masonry construction and the use of sloping joint designs in precast concrete panels. Capillary action is generally more of a problem in masonry systems than in other systems and can be controlled by obtaining a good bond at the unit-mortar interface as discussed in the section Systems/Masonry. To control capillary action, intentional openings should be wide, at least 10 mm (3/8 inch). Rain penetration due to kinetic energy can be controlled by shielding openings with cover battens, splines and internal baffles. Air pressures across the envelope can be controlled by designing openings into the facade such that the cavity behind the facade is equalized to the outside surface pressure. The so-called pressure-equalized rain screen approach has been advocated for many years (Garden) and is used in different forms in many wall systems, as discussed below.

There are essentially three approaches to water leakage control: face-seal, two-stage seal and the pressure-equalized rain screen. The first two approaches attempt to seal the facade to rain penetration and air leakage, while the third approach attempts to control the forces of rain penetration including the elimination of air pressure differences across the joint.

The face seal approach employs a single line of defense against rain penetration and air leakage by employing a field-installed elastomeric joint sealant (see section Design/Sealants). A simple one-stage joint is shown in Figure 3.4.1. This is the lowest initial cost option and can perform well for several years, given good joint design, good sealant materials, careful installation and nominal joint width and movement. However, as mentioned above, the sealant is fully exposed to the degrading effects of sunlight, ultraviolet radiation, water and temperature cycling, increasing the material requirements on the sealant material. Over time the performance of these sealants will decrease, increasing maintenance costs. Also, any defect in the sealant, even a small gap in the sealant adhesion, will lead to both water and air leakage.

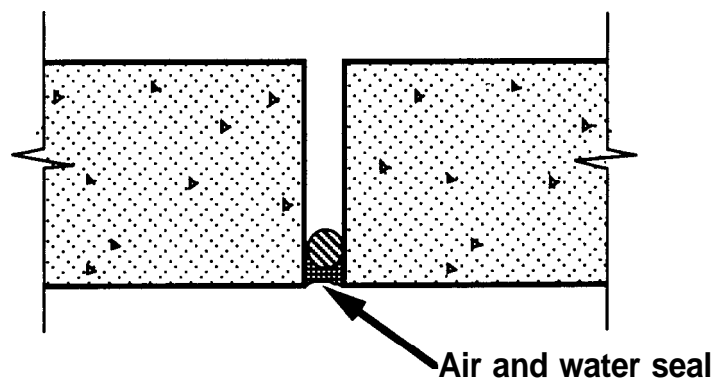


Figure 3.4.1 Section of Vertical, One-Stage Joint

Two-stage joints employ an outer seal to control water leakage and an inner seal for air-tightness, as shown in Figure 3.4.2. These joints are sloped downward to prevent gravity-driven flows into the joint and are wide enough to reduce capillary action. The outer rain seal serves to control kinetic energy. Any rainwater that does penetrate the rain barrier drains to the outside, well before it is able to reach the air seal. The inner air seal is now in a less severe environment, being protected from water and ultraviolet radiation, placing less severe requirements on the sealant material.

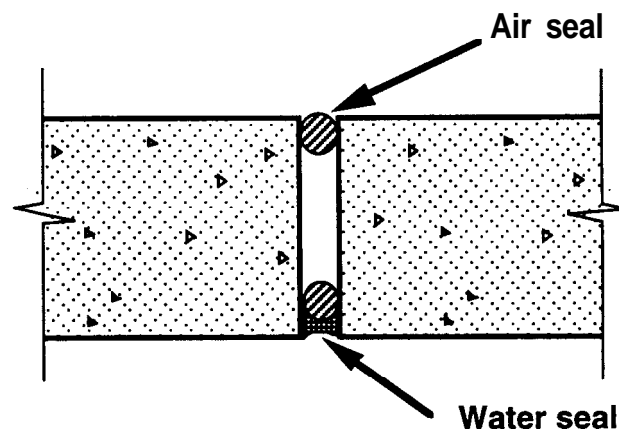
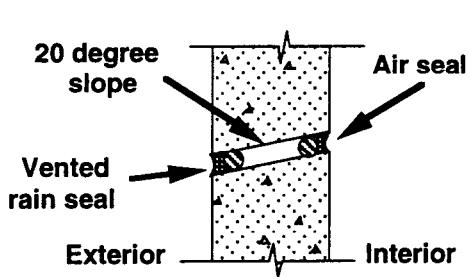
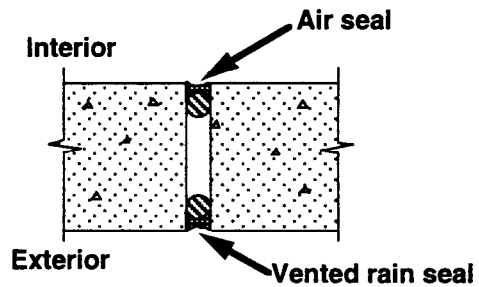


Figure 3.4.2 Section of Vertical, Two-Stage Joint

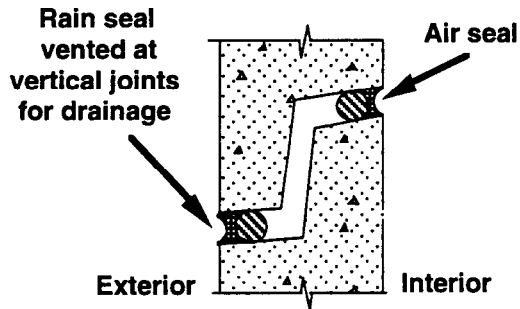
The two-stage joint approach can be used in a pressure-equalized rain screen joint design to further improve performance. In this approach, vents are purposely provided in the rain seal and a pressure equalization chamber is provided between the rain and air seals. The vents and the chamber provide for rapid equalization of the outdoor air pressure and the chamber air pressure, reducing the pressure-driven flow of water past the rain seal. Figure 3.4.3 shows two-stage, pressure-equalized joints from Architectural Precast Concrete (PCI). These joints are sloped downward to control gravity, wide enough to control capillary action and equipped with baffles of some kind to control kinetic energy. For this joint system to work it is important that any water that does penetrate the rain seal is drained to the outdoors and that good airtightness is achieved at the air seal. A disadvantage of this approach is the higher initial cost compared to the face seal approach, but lower maintenance costs and better performance can compensate. Achieving the desired performance requires careful design and construction, including intensive supervision of the work since inspection of the completed installation is difficult. The most common construction errors in this approach are not sealing the air seal completely and making the rain seal airtight.



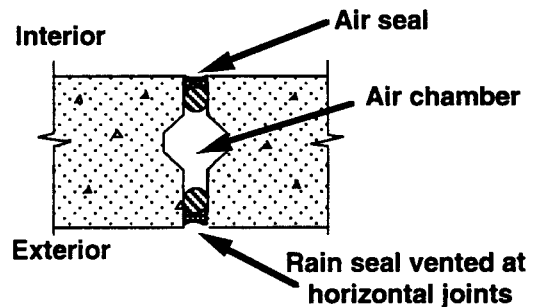
Section of Horizontal Joint



Plan of Vertical Joint



Section of Horizontal Joint



Plan of Vertical Joint

Figure 3.4.3 Two-Stage Pressure Equalized Joints (PCI 1989)

The pressure-equalized rain screen approach can also be applied to the whole wall systems by incorporating a cavity behind the facade. Figure 3.4.4 shows the essential features of a pressure-equalized rain screen wall adapted from AAMA. Vents in the facade equalize the cavity pressure to the outdoor pressure, decreasing the pressure-driven rain penetration into the cavity. These vents must be designed to prevent rain penetration due to gravity, capillary action and kinetic energy. The air barrier within the backup system, capable of withstanding the pressure due to wind loads, is absolutely essential to achieving pressure equalization. Ideally this air barrier is located behind the insulation, protecting the air barrier and associated seals from outdoor temperature swings. The cavity must be well drained to the outside in order to remove any water that does penetrate. This is essentially the approach being used in a brick veneer wall when there is a true air barrier incorporated into the backup wall.

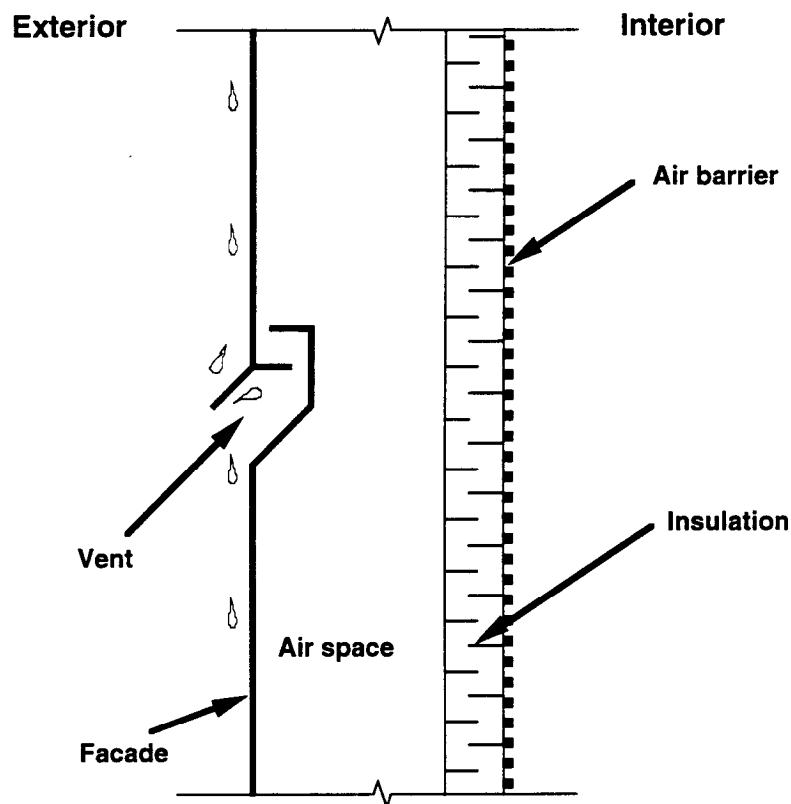


Figure 3.4.4 Pressure-Equalized Rain Screen Wall (AAMA)

While the pressure-equalized rain screen approach appears to be simple, its application requires careful design and consideration of several important issues (AAMA). When applying this approach in large buildings, one must partition the pressure-equalization cavity over the facade of the building to prevent water transport horizontally and vertically within the cavity. This is because the exterior air pressures on the facade of the building vary significantly, with larger variations in tall and wider buildings. Also, projecting elements such as mullions and column covers may have air pressure differences across them. The design of these systems sometimes suffer from a lack of recognition of the need for a continuous and structurally adequate air barrier system. The design and installation of adequate flashing within the cavity is essential to remove any water that does penetrate the facade.

Design Examples

This section discusses the control of rain penetration in specific wall systems, specifically brick veneer with concrete masonry and steel stud backup, precast concrete panels, metal building systems, glass and metal curtain walls and exterior insulation finish systems.

Brick Veneer

Given that even the best brick veneer will leak water, a drained cavity wall approach is necessary in these systems. Figure 3.4.5 shows such a system with a steel stud backup wall. As with all wall systems, water is kept off the facade with well designed drips at copings, sills and elsewhere. That water that does penetrate the veneer is directed back outside by properly designed and installed flashing at all required locations. A continuous air barrier is installed behind the cavity insulation to control air leakage and to make pressure equalization of the cavity possible. The pressures acting on the exterior of the facade and within the cavity are equalized through vents in the veneer at weepholes. The critical elements to achieving pressure equalization in this system are a continuous and tight air barrier, adequate flashing and weepholes, a wide enough cavity, and keeping the cavity and weepholes clear of mortar droppings.

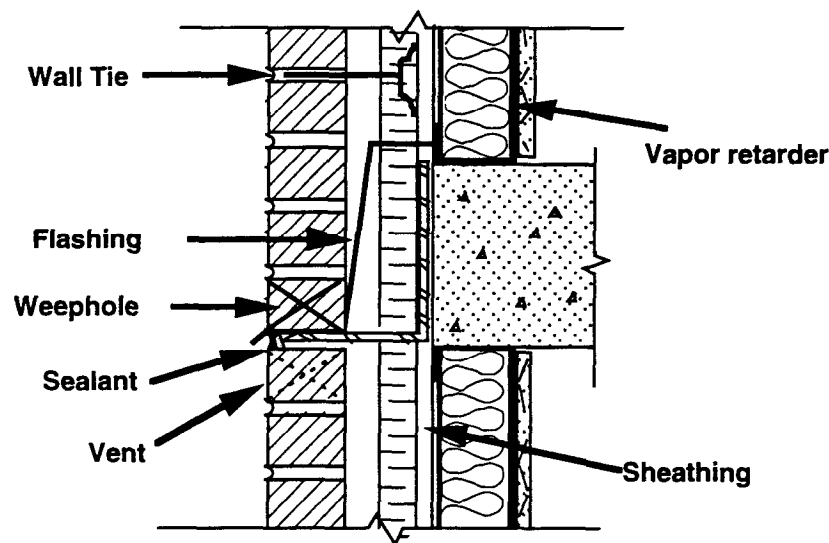


Figure 3.4.5 Brick Veneer / Steel Stud Backup Wall (CMHC)

Figure 3.4.6 shows a brick veneer wall with a masonry backup. This approach and the critical design elements are similar to the steel stud backup system.

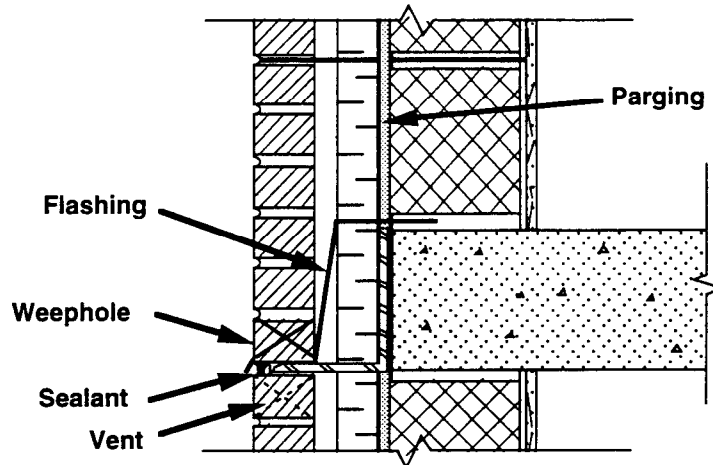


Figure 3.4.6 Brick Veneer / Concrete Masonry Backup Wall (CMHC)

Precast Concrete Panels

Because uncracked precast concrete panels are watertight, the design and construction of the panel joints are critical to the control of rain penetration in these walls. As discussed above, the design of panel joints can employ one-stage, two-stage and pressure equalized designs. In addition, the entire wall can be designed using a pressure equalized cavity behind the facade. The design of sealant joints is discussed in the section Design/Sealants. Most guidance on the design and installation of sealant joints concerns simple horizontal and vertical joints and does not generally address the intersections between horizontal and vertical joints and other complexities. An adequate joint design must include details for all joints, intersections between joints and locations where joints terminate at other envelope components.

Figure 3.4.7 shows a simple one-stage joint in a precast panel wall system from Rousseau. In the so-called face seal approach, a single line of defense is employed against both rain penetration and air leakage. Although this approach has low first costs, the sealant is fully exposed to the degrading effects of sunlight, ultraviolet radiation, water and temperature cycling. Over time the performance of these sealants will decrease, increasing maintenance costs.

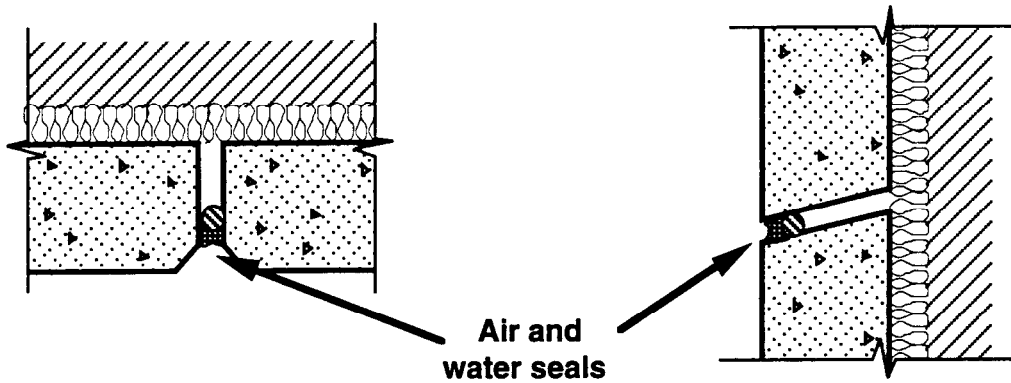


Figure 3.4.7 Precast Concrete Panel - One-Stage Joints (Rousseau)

A two-stage joint in a precast panel is shown in Figure 3.4.8. The outer rain seal serves to control water leakage due to kinetic energy. Any rainwater that does penetrate the rain barrier drains to the outside, before it is able to reach the air seal. The inner air seal is in a less severe environment, being protected from water and ultraviolet radiation, easing the material requirements on the sealant.

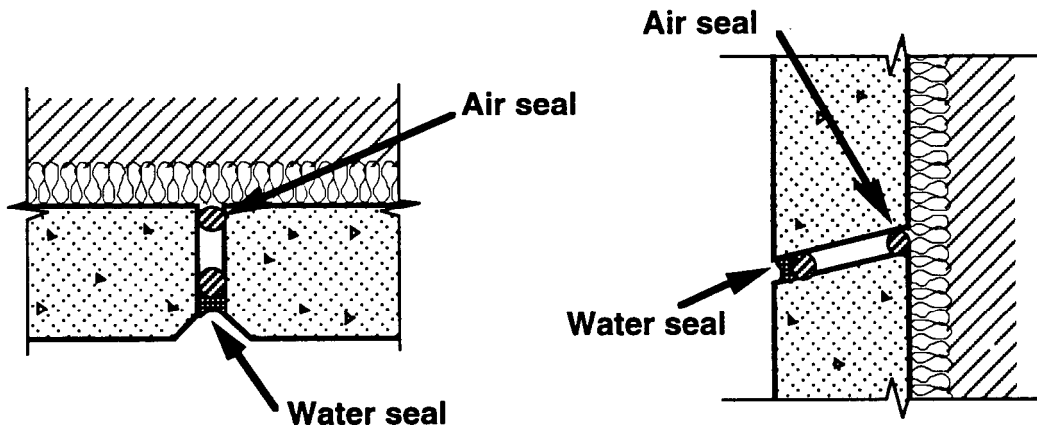


Figure 3.4.8 Precast Concrete Panel - Two-Stage Joints (Rousseau)

A two-stage joint can be designed as a pressure-equalized rain screen joint to further improve performance, as shown in Figure 3.4.9 (PCI). In this approach, vents are purposely provided in the rain seal to achieve pressure equalization in a chamber between the rain and air seals. The joints are sloped downward to control gravity driven leakage and are wide enough to control capillary action. The joints are also equipped with baffles to control water leakage from kinetic energy.

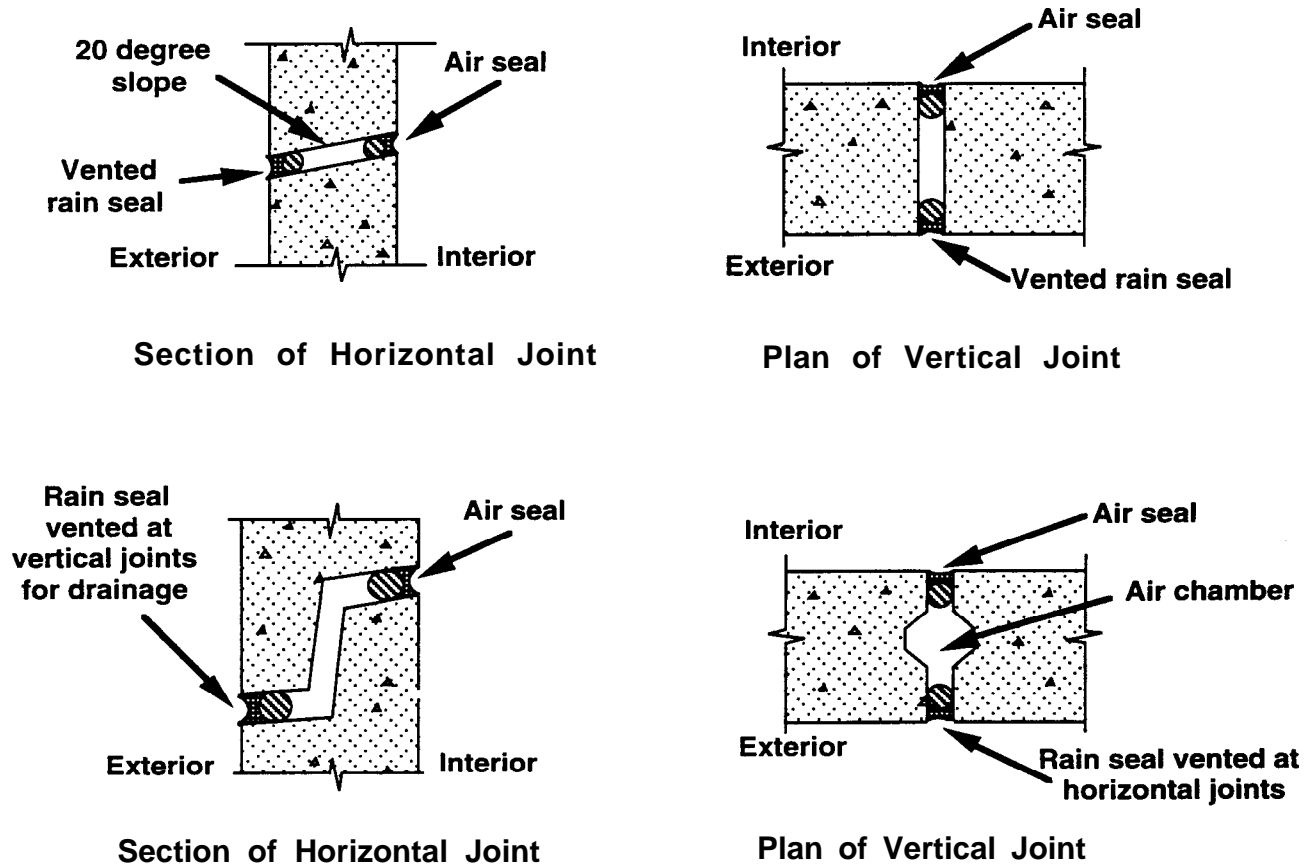


Figure 3.4.9 Precast Concrete Panel - Two-Stage Pressure Equalized Joints (PCI)

The pressure-equalized rain screen approach can also be applied to whole wall systems by incorporating a cavity behind the facade, as shown in Figure 3.4.10. The panel joints are opened to pressurize the cavity and are sloped downward to control gravity-driven rain penetration. The cavity is equipped with flashing at appropriate locations to provide drainage. An air barrier is installed behind the insulation, with the air-tightness of this element being critical to the performance of the system.

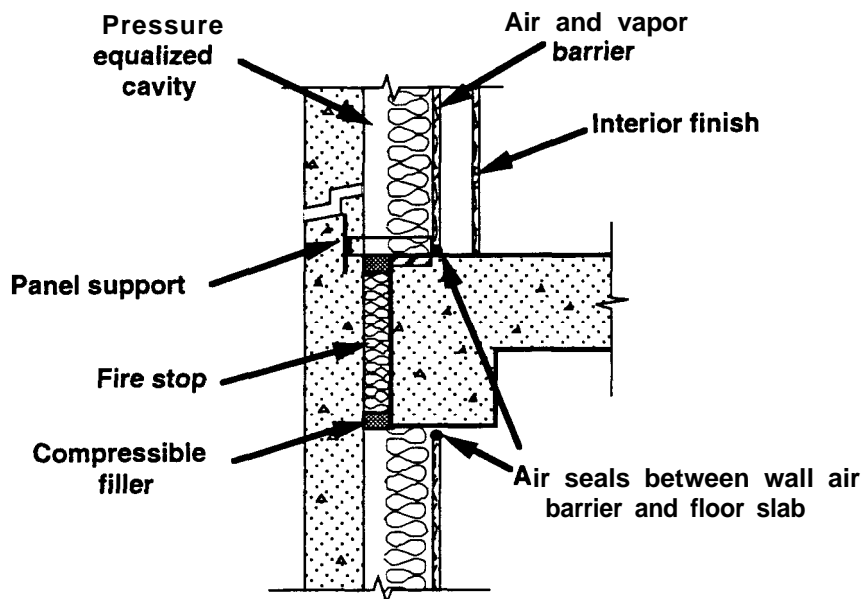
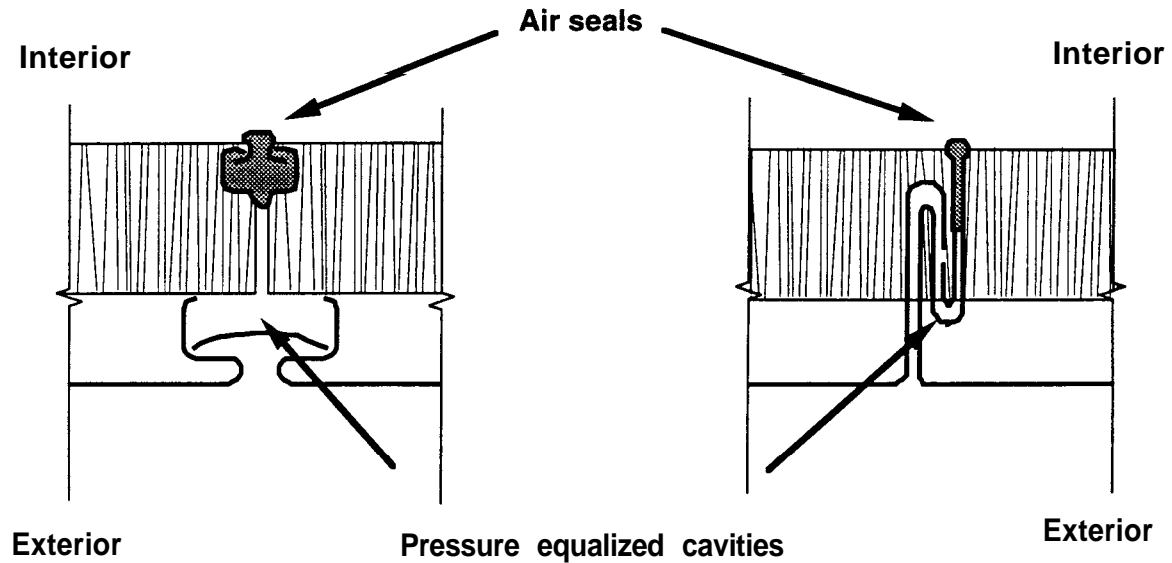


Figure 3.4.10 Precast Concrete Panel - Pressure Equalized Rain Screen (Rousseau)

Metal Building Systems

Figure 3.4.11 shows two examples of insulated panel joints in metal building systems (AAMA). Both joints employ pressure-equalized cavities with an outer rainscreen and an inner air seal. Various arrangements of the joint are used to prevent water intrusion due to gravity, capillary action and kinetic energy.



**Figure 3.4.11 Pressure-Equalized Joints
in Insulated Metal Panels (AAMA)**

Curtain Wall Mullions

Pressure equalization is also applicable to mullions in glass and metal curtain walls and other panel systems. Figure 3.4.12 shows an example of a pressure equalized mullion design (Ganguli). As in all pressure equalized systems, the inner air seal is critical to performance.

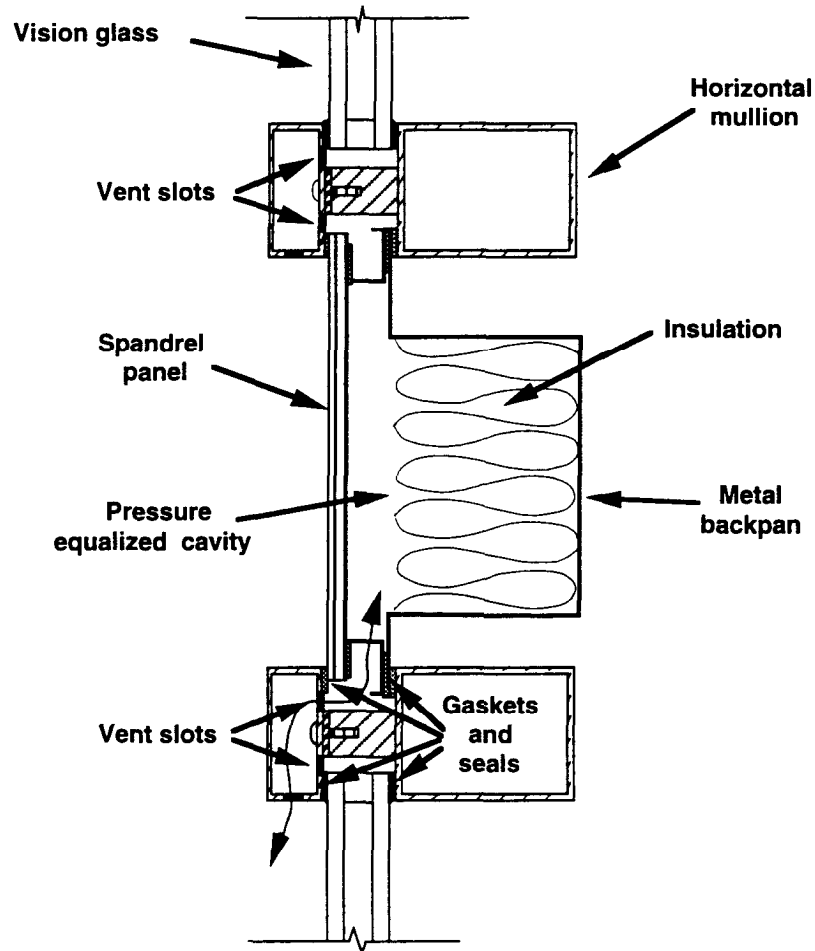


Figure 3.4.12 Pressure Equalized Curtain Wall Mullions (Ganguli)

Exterior Insulation Finish Systems

EIFS systems employ the face-seal approach to the control of both air leakage and rain penetration. Water-tightness is very important in EIFS systems to prevent the degradation of system components, particularly the exterior gypsum sheathing in the case of a steel stud backup system. The finish coat, as see in Figure 3.4.13, serves as both the air and water seal. Leakage can occur at panel joints, locations where the finish has delaminated and at voids in the finish coat when they are exposed to moisture for extended periods of time. The latter problem of exposure can occur at joints that are not designed to drain well and at other facade articulations. It is very important in this system that roof edges, window sills and other articulations are designed to shed water away from the facade.

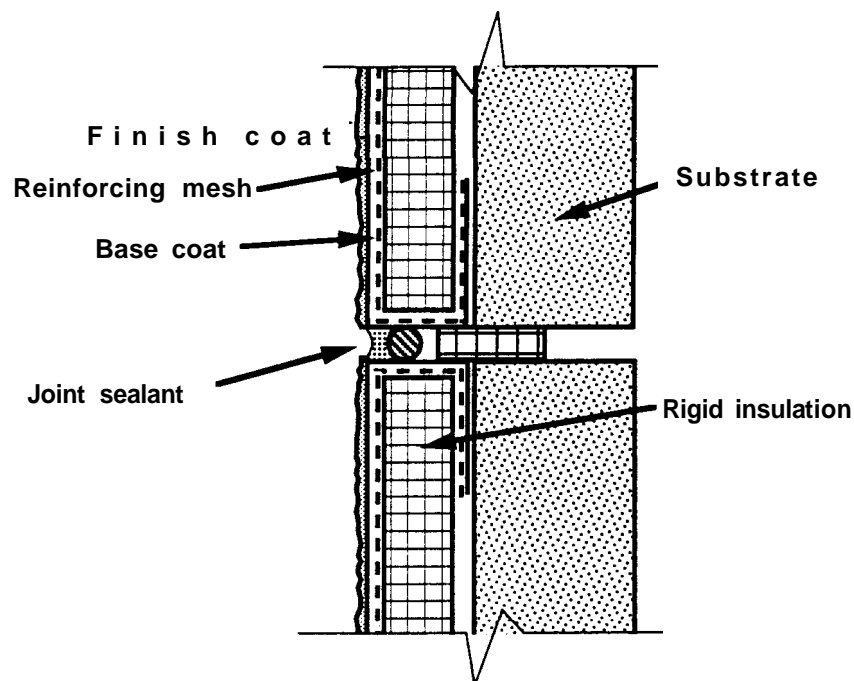


Figure 3.4.13 Exterior Insulation Finish System (Williams)

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3.5 SEALANTS

Sealants are used to prevent the passage of air, moisture (both vapor and liquid), dust and heat through joints and seams. A variety of different materials are used as sealants including viscous liquids, mastics, pastes, tapes and gaskets. These materials are used in applications such as panel joints, expansion and control joints, roofs, and glazing systems. The selection of a particular sealant is based on the application and the conditions to which it will be subjected in use. The Sealant, Waterproofing & Restoration Institute (SWRI) guide to sealants is an excellent reference on joint design, sealant materials, applications and the preparation of specifications. The book on construction sealants by Panek and Cook is also very good, and is a source of much of the material in this section. ASTM Committee C-24 on Building Seals and Sealants has developed many standards on sealants and sponsored two symposia. The proceedings of these symposia are published in ASTM STP 606 Building Seals and Sealants and ASTM STP 1069 Building Sealants: Materials, Properties and Performance.

This section is concerned primarily with the elastomeric sealants that are commonly used to prevent rain penetration and air leakage through joints in exterior claddings. In the face seal approach to controlling rain penetration, they constitute the primary seal against both rain and air penetration. While sealant materials and design methodologies exist that provide adequate levels of performance in these applications, joint sealant problems do exist. Part of the reason for these problems is that although sealants play a crucial role in building envelope performance and must function under demanding circumstances, they are only a small portion of the total envelope design and construction. And because sealants are often perceived as only a minor percentage of the project, they can be subject to careless specification, inappropriate substitution and poor application. In addition, joint design and sealant selection can be influenced by aesthetic considerations to the point where performance problems result.

When sealant joints do fail, the consequences of the resultant air leakage and rain penetration can be serious. Sealant failures take a variety of forms including the failure of the sealant to adhere to the substrate (adhesive failure), the tearing apart of the sealant itself (cohesive failure), discoloration of the sealant or substrate and hardening or cracking of the sealant. Warseck presents a very thorough discussion of sealant failure, and states that the basic reason for sealant failure is a lack of attention to detail in the sealant joint design, specification and installation. The fact of the matter is that sealants are generally installed under a variety of conditions, on many different substrates, by persons with varying degrees of interest, ability and supervision, and are subjected to severe deformation and harsh environmental conditions, i.e., temperature, water and sunlight. Successful sealant joints require a careful design of the joint geometry, the selection of appropriate and compatible backup and sealant materials, and proper installation practice.

Sealant Materials

A variety of sealant materials have been used over the years, and very good materials are available today for a variety of applications including exposed expansion and control joints, joints between cladding panels, the perimeters of wall and roof openings such as windows and doors, and corrugated metal walls and roofs. Depending on the application and conditions to which the sealant will be exposed, there are a variety of performance criteria that must be considered. These include stability in storage and in the application pot, mixing, curing time, modulus of elasticity, elongation, recovery, hardness, temperature limits of application and performance, color and color retention, resistance to chemicals, ozone and ultraviolet radiation, bond durability and applicability. ASTM C 920, Standard Specification for Elastomeric Sealants, provides classifications for the various properties of elastomeric joint sealants and identifies the relevant ASTM test methods. In addition to these performance criteria, sealants should be selected based on their offgassing properties as they affect indoor air quality. Research is currently in progress on the emission characteristics of sealants and their impact on the indoor environment, and these results will make it easier to consider indoor air quality in the specification of sealants.

Sealant materials can be classified by a variety of characteristics including their application, i.e., pourable, gun-applied, tapes and cured gaskets. Sealants may also be classified as non-hardening or hardening, and rigid or nonrigid. Some advantages and disadvantages of different sealant materials are presented below. This information is based on material in Panek and Cook and is not intended to be exhaustive. More thorough discussions of specific sealants are found in Panek and Cook and in ASTM STPs 606 and 1069.

Polysulfides

Polysulfide sealants were the first elastomeric sealants used in modern curtain walls, starting in the early 1950s. They have movement capabilities as high as 25%. Following the introduction of urethanes and silicones, with their better ozone and ultraviolet resistance, the use of polysulfides declined. They still constitute a major part of the insulating glass market, but are otherwise used only in limited applications due to their poor recovery compared with urethanes and silicones.

Silicone Sealants

Silicone sealants have very high recovery, are unaffected by ultraviolet radiation and ozone, and have movement capabilities from 25% to 50%. Because of their high recovery, they are used in structural and stopless glazing systems. Other advantages include excellent workability and color stability, durabilities of over 20 years, and the fact that they are one-component sealants. Disadvantages include cost, dirt pick-up, odor, short tooling time and some problems with obtaining primer-less adhesion to aluminum, wood and concrete surfaces.

Urethane Sealants

Urethane sealants were developed in the early 1970s and are the most used sealants for building joints followed by silicones, with polysulfides a distant third. They have movement capabilities of about 25%. The advantages of urethanes include excellent recovery, long work life, negligible shrinkage and good resistance to ozone and ultraviolet radiation. The disadvantages of urethane sealants include poor water immersion resistance, so they are not recommended for wet joints. One-component urethanes have limited stability and take a long time to cure.

Solvent-Based Acrylic Sealants

This general class of sealants is described as semi-elastomeric, with movement capabilities from 7.5% to 12.5%. They adhere well to many surfaces without primers, are generally one-component, have good ultraviolet and chemical resistance, and have durabilities of over 20 years. On the negative side, they cannot be used in joints greater than about 20 mm (3/4 inches) wide, have poor recovery and water resistance, and are associated with strong odors.

Butyl Caulks

Butyl caulks are characterized as low cost, very stable, non- or slow curing, and are widely used as caulks and adhesives in concealed rather than exposed locations. They are not recommended for large movement applications, based on their maximum movement capabilities of 7.5%. Therefore, they do not compete with polysulfides, urethanes or silicones in high movement applications.

Latex Sealants

Latex sealants are a general class of sealants employing several different materials and used for a range of applications. Latex sealants employing acrylics as their chief materials, have movement capabilities of 7.5% and are used outdoors. Sealants employing vinyl acrylic and polyvinyl acetate are used indoors where the temperature gradients and movements are smaller. Latex sealants are one-component, gun-grade materials, with fair flexibility, little recovery, and high shrinkage. They clean up easily and are commonly used in light construction.

Oil- and Resin-Based Caulks

These materials are nonelastomeric, with movement capabilities of only 2% to 5%, and are used in joints with little or no movement. The advantages of these low-cost, one-component caulks include easy application and tooling, durabilities greater than 10 years, no handling or storage problems, and no requirements for joint cleaning or priming. Their disadvantages include no recovery, little flexibility, as much as 20% shrinkage, and low movement capabilities.

Specialty Sealants

Numerous other sealants have been developed for their unusual properties and as slight modifications of existing sealant materials. Chlorosulfonated polyethylene sealants (CSPE) are flexible, one-component sealants that are impervious to water, have good ultraviolet, ozone and chemical resistance, and have movement capabilities of 12.5%. On the negative side, CSPE sealants cure slowly and are characterized by high cost, high shrinkage and poor package stability. Neoprene sealants are one-component, gun-grade materials that cure slowly. Their major advantage is that they are one of the few sealants that are compatible with asphaltic concrete, bitumen and neoprene gaskets. Other advantages include low cost, good water resistance and movement capabilities of 12.5%. Disadvantages include high shrinkage, slow curing and availability in only dark colors. They are not recommended for dynamic movement joints. Other specialty sealants include polymercaptan, styrene-butadiene rubber (SBR), nitrite rubbers, epoxy resins, polybutene and polyisobutylene caulks, and roofing caulks.

Preformed Sealing Tapes

These are permanently tacky materials that are used in metal buildings to seal overlapping metal panels. They are also used in glazing systems as a sealant and a resilient filler. Sealing tapes are composed of either cured butyl or modified butyl for varying degrees of hardness and tackiness.

Preformed Gaskets Seals

These sealants include dense rubber or cured sponge and are characterized by a variety of compositions, shapes and hardnesses. They are also referred to as compression seals since they are placed in joints under compression and rely on the interface pressure to maintain a tight seal. Their prime application is in glazing systems, though they are also used as seals in exterior panels and structural gaskets. The gaskets are made from neoprene, EPDM, butyl, silicone, urethane and SBR.

Design Issues

The performance of sealant joints depends on several design issues including the configuration of the joint itself and the selection of the sealant and backup materials.

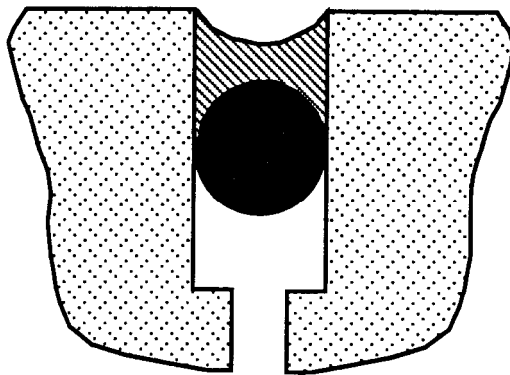
Joint Design

The basic objectives of building joint design are to provide a seal that prevents rain penetration, excessive heat flow, water vapor migration, and air leakage. As discussed in the section Design/Rain Penetration, rain penetration can be prevented with a perfect seal, i.e., the face seal approach. Creating such a perfect seal in the often harsh environment of the building skin is difficult, and in fact it is not necessary. Instead, the joint can be designed to control the forces causing rain penetration using a pressure-equalized joint design. This latter approach actually prohibits the use of an air seal at the wetted plane. An air seal is still necessary to control air leakage, but it is located inward of the wetted plane so that air pressure, the major force causing rain penetration, can be controlled. Locating the air seal inward from the exterior also protects the sealant from environmental stresses. Heat flow at joints is generally small due to the small cross-sectional area involved and can be reduced using a dead air space or some insulation material. Water vapor diffusion can generally be ignored, especially if there is no exterior seal at the joint. In heating climates, however, severe vapor condensation can occur if interior air leaks into cold spaces in the joint. In cooling climates, condensation can occur if humid exterior air leaks through the joint and contacts cold interior surfaces.

The two basic considerations in sealant joint design are the determination of the expected dimensional movement of the joint, and the geometry and configuration of the joint. The basics of sealant joint design and movement are covered well by O'Connor. This document describes the various performance factors that must be considered in joint design and provides three sample calculations of joint width. For aesthetic reasons, designers may prefer to limit the width and number of sealant joints without proper consideration of whether the resultant joint design will be effective. In some cases the joints are made excessively wide to make up for their insufficient number, or there are enough joints but they are made as small as possible. In either case, the joint design will be inadequate and, as a result, the building will create more joints by cracking or worse, i.e., walls will bend, joints will be crushed, or curtain wall fasteners or masonry ties will be sheared. In order to design a sealant joint, one must determine the expected movement of the joint given the numerous factors affecting this movement. O'Connor discusses these factors, including thermally induced movement, structural loading and construction tolerances, and how they must be considered in designing sealant joints. Basically, one must consider each of the various performance factors and determine the required joint width and expected range of movement.

The geometry of a sealant joint determines its cohesive and adhesive strength. A concave, or hourglass, shape is widely recognized as optimal for sealant beads, with a width to depth ratio of about 2. The desired shape is achieved through the use of a backer rod and the proper tooling of the exposed side of the sealant. Figure 3.5.1 shows an example of a properly designed sealant joint from Schroeder and Hovis in ASTM STP 1069. The joint is wide enough to accommodate movement, and is sawed deep enough to allow placement of the backer rod and sealant. A proper backer rod is used and installed, and the sealant is tooled 6 mm (1/4 inch) below the surface. A properly shaped bead will deform under expansion such that most of the strain will occur in the central portion of the bead where the cohesive strength is good.

ACCEPTABLE



Wide enough to accommodate movement
Sawed deep enough for backer rod placement
Proper backer rod
Sealant tooled 6 mm (1/4 inch) below surface

Figure 3.5.1 Good Joint Design (Schroeder and Hovis)

If the joint width is too narrow, the sealant will be forced out of the joint when the joint is under compression as seen in Figure 3.5.2 (based on Warseck in ASTM STP 1069). When the building contracts, the extruded sealant is no longer in the joint, resulting in leaks. 6 mm (1/4 inch) has been suggested as a minimum joint width. On the other hand, if the joint is too wide, sealant may sag out of the joint. In addition, in order to maintain a 2 to 1 width-to-depth ratio in a wide joint, a deep sealant bead is required, and such a deep bead is less capable of stretching.

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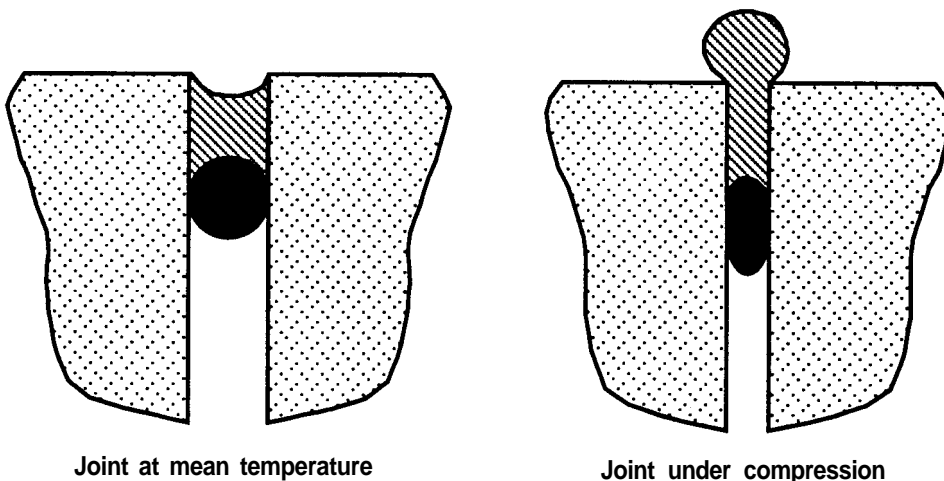
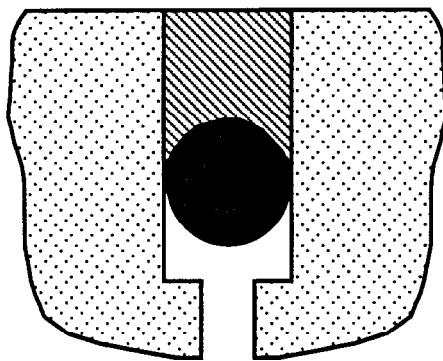


Figure 3.5.2 Sealant Extrusion in Narrow Joint (Warseck)

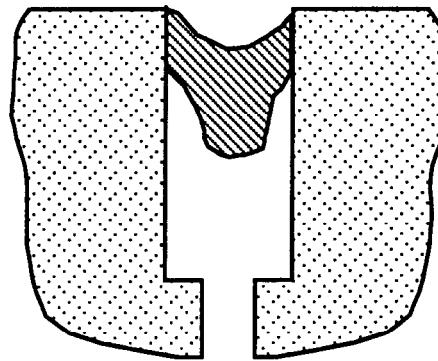
Figure 3.5.3 shows three examples of poor joint design. In the first case the sealant is not tooled to the proper depth, the sealant bead is too thick and the bead width-to-depth ratio is too low. In the second example, there is no backer rod, no support to tool the sealant against, and the bead is too thick. In the third case there is no backer rod so the sealant is bonding against the back of the joint, resulting in so-called three-sided adhesion. This will result in cohesive and/or adhesive failure of the sealant.

The location of the sealant joint within the wall is an important design and installation consideration. Locating the sealant joint at the exterior subjects the sealant to the most extreme environmental conditions and the largest differential movements. If the sealant joint is located inward, it is protected from most of the environmental extremes and is subjected to smaller differential movements. Also, interior sealants can be installed from inside the building simultaneously with erection of panels on upper floors and under more severe weather conditions than exterior sealant application. The application of an interior sealant can be complicated by the location of columns, beams and floor edges, and these interferences must not be overlooked in the design phase.

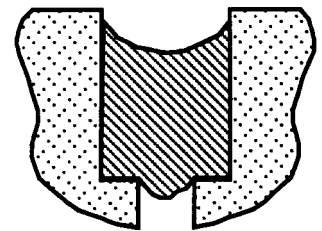
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Sealant not tooled properly
Sealant bead too thick
Wrong width-to-depth ratio



No backer rod
Sealant bead too thick
No support to tool against



No backer rod
Sealant bonding to back of joint
Joint cut too shallow

Figure 3.5.3 Poor Joint Designs (Schroeder and Hovis)

Most guidance on the design and installation of sealant joints contained here and elsewhere concerns simple horizontal and vertical joints and does not generally address more complex joint configurations. These include intersections of horizontal and vertical joints, doglegs and other transitions. The lack of adequate design details for these complexities are a common source of performance problems due to the unusual stresses and movements that occur at these locations. An adequate joint design must include details for all joints, intersections between joints and locations where joints terminate at other envelope components. Without the provision of design details at all locations, the sealant installation at irregular joints is left to the mechanic in the field.

Sealant Materials

The primary criteria for the selection of a sealant material is the ability to accommodate the anticipated movement under the expected environmental conditions and to maintain an adequate level of performance over time. Sealants at exterior joints are subjected to environmental factors that can accelerate their deterioration: extreme temperatures, solar and ultraviolet radiation, large differential movements, frequent wetting, and physical abuse. Other performance factors include adhesive and cohesive properties, weather resistance and durability, workability at different temperatures, compatibility with the substrate and puncture resistance. Panek presents a brief and up-to-date discussion of sealants materials and their properties. ASTM STP 606, published in 1976, also contains a thorough discussion of many different sealant materials.

Warseck points out that the most common sealant design failure is the selection of a sealant with insufficient movement capability, pointing out that sealant "performance" is not a well-defined quantity. This leads to confusion when selecting and comparing sealants. Other sealant selection problems are due to incompatibility of sealants with materials in close proximity including substrates, primers and other sealants.

Another point raised by Warseck is the use of sealants with insufficient recovery. A sealant with poor recovery may stretch adequately, but will not easily return to its original shape, so-called stress relaxation. As shown in Figure 3.5.4, the sealant bead assumes a distorted shape, and when the joint reopens the sealant will fail.

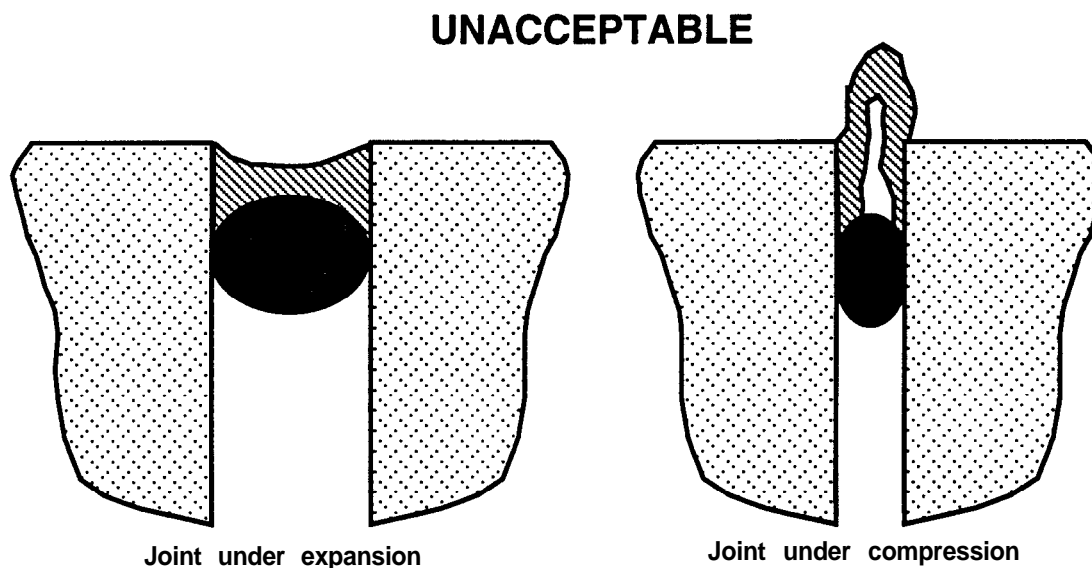


Figure 3.5.4 Stress Relaxed Sealant (Warseck)

Other sealants remain bulged after compression and will not restretch, so-called compression set, as shown in Figure 3.5.5. In this situation, the joint sealant will fail cohesively when the joint reopens.

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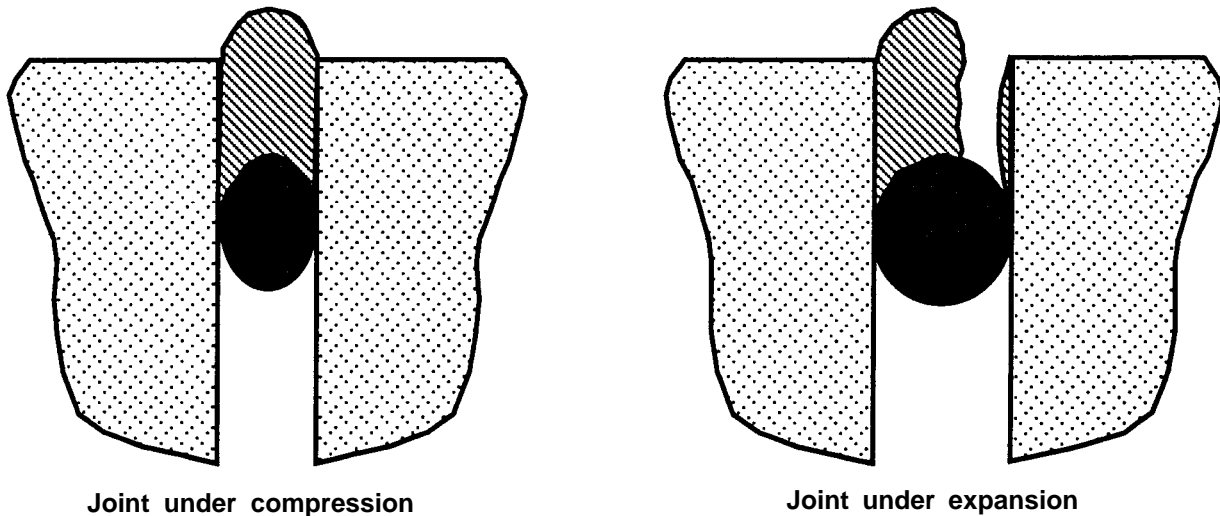


Figure 3.5.5 Compression Set Sealant (Warseck)

Backup Materials

The selection and sizing of backup materials, often a backer rod, is another crucial aspect of sealant joint design. General discussions of sealant backup materials are presented by Balliet and Panek in ASTM STP 606 and by Schroeder and Hovis in ASTM STP 1069. The purpose of a sealant backup is to limit the depth of the sealant bead, to enable the proper shaping to the sealant by providing support to tool against, and to act as a bondbreaker to prevent back-side adhesion of the sealant. In order to provide adequate performance, backup materials must not absorb water, must not offgas and cause bubbling within the sealant, must remain flexible at low temperatures, and must be compatible with the sealant material. Because it may be many months between the installation of the backup and the sealant application, the backup material must be able to perform as a temporary seal during this period of time. Closed-cell backer rods are a common backup material, though offgassing can be a problem with the slow-curing sealants in use today. If the backer rod is punctured or somehow damaged during installation, the gas emitted from these ruptured cells can be pumped into the uncured sealant by thermally-induced cycling of the backup. Gas bubbles in the sealant can degrade the cohesiveness of the sealant and lead to performance problems. New developments of backup materials that do not offgas when ruptured are described by Schroeder and Hovis in ASTM STP 1069. In addition to proper backup material selection, the sizing of the backer rod relative to the joint width is important. The backer rod should be sized such that it is held in place by compression in its final position and remains in place through the dimensional changes in the joint width. Warseck recommends that the backer rod be sized about 30% greater than the maximum expected joint opening.

Installation Issues

Many sealant problems are associated with installation practice including joint cleaning, primer application, joint tooling, and material substitution. This section discusses many of these installation problems, with most of the material based on the article by Warseck in ASTM STP 1069.

Most adhesion problems are caused by a dirty and/or wet substrate when the sealant is applied. Specifically, this occurs when the substrate is not cleaned at all, a dirty or contaminated solvent is used, the wrong solvent is used, the rags or brushes are contaminated, and the rag contains lint. In some cases the envelope design causes the joint to be inaccessible for cleaning. Adhesion problems can also be associated with the primer application, i.e., no primer, too much primer, the wrong primer or not allowing the primer to dry before applying the sealant. The weather conditions during the sealant application are also critical. If it is too cold, the joint is at its widest dimension and the increased viscosity of the sealant makes it difficult to apply without gaps and difficult to tool. In warm weather the joint is at its narrowest dimension, and the warm sealant may sag or flow out of the joint.

Another important installation issue concerns the tooling of the sealant bead. Tooling should compress the sealant and push it against the backing, assuring good contact with both sides of the joint, eliminating air pockets and achieving the desired hourglass shape for the bead. If tooling does not eliminate air pockets, they will expand in hot weather. A bead deformed by improper tooling may not stretch as easily as desired and may rupture. Or the bead may not have sufficient bond area to prevent adhesive failure.

Other installation problems can arise from the unauthorized substitution of the specified sealant or the improper preparation of multi-component sealants. Spillage of one of the components on the site can often result in incorrect mix ratios. Mixing at too high a speed can result in air being introduced into the sealant. Also, if too much sealant is mixed at one time, the sealant may begin to cure before it is applied.

ASTM Standards

ASTM Committee C-24 on Building Seals and Sealants has issued many standard specifications and test methods. The following list contains several of these standards, which are found in Volume 04.07 of the Annual Book of ASTM Standards.

- C 509, Standard Specification for Cellular Elastomeric Preformed Gasket and Sealing Material
- C 510, Standard Test Method for Staining and Color Change of Single- or Multicomponent Joint Sealants
- C 542, Standard Specification for Lock-Strip Gaskets
- C 570, Standard Specification for Oil- and Resin-Base Caulking Compound for Building Construction
- C 603, Standard Test Method for Extrusion Rate and Application Life of Elastomeric Sealants
- C 679, Standard Test Method for Tack-Free Time of Elastomeric Sealants
- C 711, Standard Test Method for Low-Temperature Flexibility and Tenacity of One-Part, Elastomeric, Solvent-Release Type Sealants
- C 716, Standard Specification for Installing Lock-Strip Gaskets and Infill Glazing Materials
- C 717, Standard Terminology of Building Seals and Sealants
- C 719, Standard Test Method for Adhesion and Cohesion of Elastomeric Joint Sealants Under Cyclic Movement (Hockman Cycle)
- C 790, Guide for Use of Latex Sealants
- C 920, Standard Specifications for Elastomeric Joint Sealants

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4.0 SYSTEMS

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 - Design and Construction Issues
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 - Roof Penetrations
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4.1 GLASS AND METAL CURTAIN WALLS

The airtightness of glass and metal curtain walls is provided by the glass and metal panels and the aluminum or steel tubes that comprise the system. Figure 4.1.1 shows the basic components of a curtain wall system employing a pressure equalized cavity to control rain penetration and to protect the air seals. The thermal insulation system consists of the insulation behind spandrel panels, sealed double glazed windows, and thermally broken mullions. Continuity of the air barrier is maintained at the mullion air seals and the interfaces between the curtain wall and other envelope systems. The design of thermally-broken mullions are crucial elements in maintaining the continuity of the insulation system.

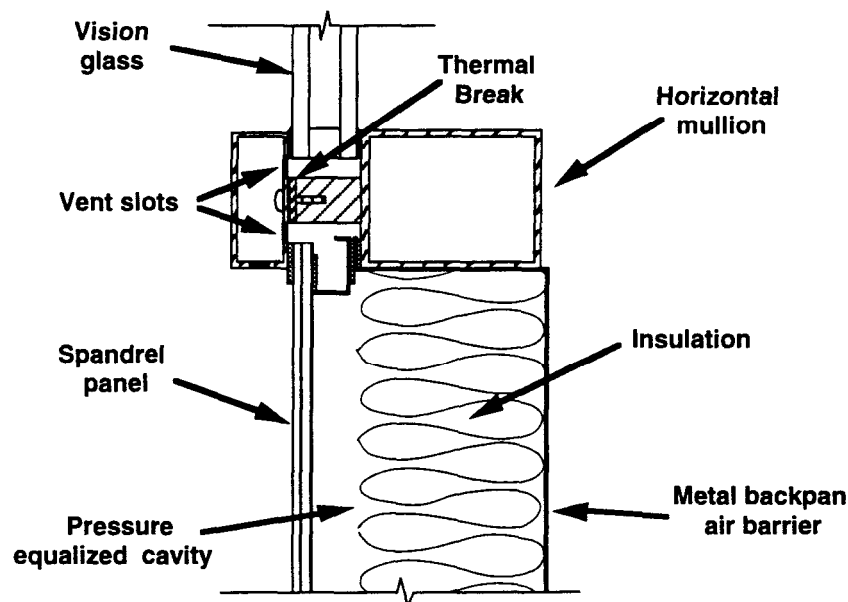


Figure 4.1.1 Glass and Metal Curtain Wall (Ganguli)

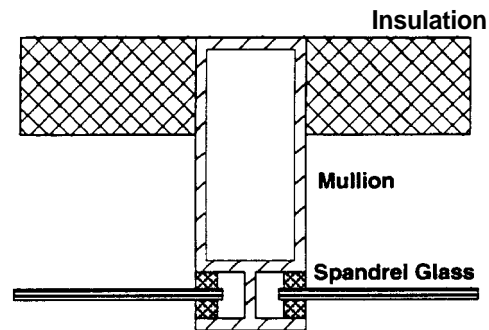
Curtain wall systems have both advantages and disadvantages over other envelope systems, many of which relate to the thermal performance of these systems. The advantages include the following: weather conditions have relatively little effect on construction, most systems are self-weeping, they generally have a high quality appearance and relatively fast erection, and much of the engineering can be done by the curtain wall supplier. The disadvantages include: a high level of exterior maintenance is required for cleaning, condensation can result on cold parts of the system if adequate thermal breaks are not included and a relatively high cost. The American Architectural Manufacturers Association (AAMA) has developed numerous manuals on curtain wall design, installation, testing and performance requirements. The performance and testing requirements addressed by the AAMA documents include air leakage, water penetration, condensation resistance, thermal transmittance and structural performance. While curtain wall system design is a well developed area, the thermal performance of these systems can be compromised by discontinuities in the air barrier and thermal insulation systems at mullions and at interfaces with other envelope systems.

Mullion Design

The design of curtain wall mullions is crucial in achieving air barrier and insulation system continuity. Figure 4.1.1 showed a generic representation of a thermally broken mullion. Effective mullion designs must include thermal breaks and a means of pressure equalization and drainage. Pressure equalization removes the wind forces that would otherwise force water through the outer seal, protecting the inner air seal from deterioration due to exposure to water. Weepholes provide for the drainage of water that does penetrate the pressure equalization cavity and must be shielded against the penetration of wind-driven rain. The AAMA Window Selection Guide contains a detailed discussion of mullion and window frame design, with numerous examples of mullion designs.

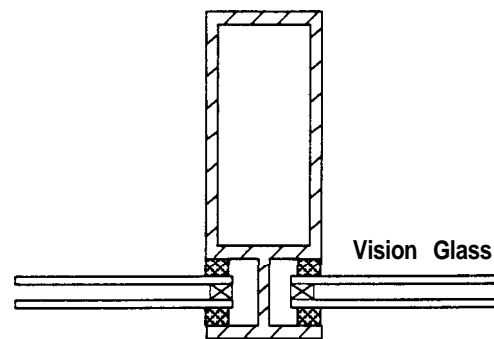
Figure 4.1.2 shows generic, thermally-unbroken mullion designs for three different applications: a vertical mullion at an insulated glass spandrel, a vertical mullion at vision glass and a horizontal mullion at the intersection of vision glass with a glass spandrel. All of these systems suffer from the same basic problem, thermal bridging at the aluminum web connecting the main mullion section to the exposed surface of the mullion. This thermal bridging results in increased heat loss through the mullion, as well as an increased potential for condensation on interior surfaces under heating conditions. Airtightness is related to the air seal materials used and their ability to accommodate differential movement at this location.

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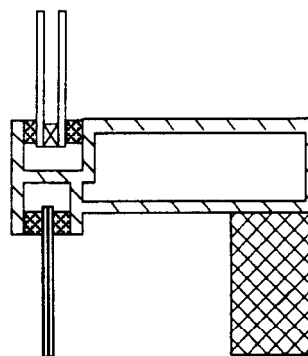
Vertical Mullion at Insulated Glass Spandrel

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Vertical Mullion at Vision Glass

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Horizontal Mullion at Vision/Spandrel Interface

Figure 4.1.2 Thermally Unbroken Mullions

Most guidance on mullion design contained here and elsewhere concerns straightforward horizontal sections and plans sections, and does not generally address more complex configurations. These include intersections of horizontal and vertical mullions, doglegs and other transitions. The lack of adequate design details for these complexities are a common source of performance problems due to the unusual stresses and movements that occur at these locations. An adequate design must include details for all mullions, intersections between mullions and locations where curtain walls meet other envelope systems. Without the provision of design details for all locations, the installation at these irregularities is left to the mechanic in the field.

A variety of alternate mullion designs have been developed to provide a thermal break while meeting the structural performance requirements of these elements. Five alternative designs are presented below: Structural or Stopless Glazing, Poured-in Place, Screw-on-Face with Snap-On Cover, Internal Slide-In Spacer, and Structural Neoprene Gaskets

Structural Silicone Glazing

Structural or stopless systems are considered the best design for thermal performance since there are no exposed mullion surfaces. As shown in Figure 4.1.3, both the vision and spandrel glass are fixed to the metal support system with structural silicone adhesive sealant. The design of such a system must insure that there are no exposed metal surfaces that will provide a thermal conduction path from the exterior to the interior. In heating climates, a vapor retarder is sometimes applied to the interior of the insulation to prevent condensation in the cavity behind the spandrel glass. For this vapor retarder to be effective, it must also control air leakage from the building interior into the space behind the spandrel panel. The application of the structural silicone requires great care with regard to cleanliness, temperature conditions and curing without stress on the silicone. These requirements lend this system to the factory assembly of large panels and on-site erection. ASTM STP 1054 contains several articles on structural silicone glazing systems, though not from the perspective of thermal performance. These articles cover design considerations, performance properties of the adhesives, methods for calculating joint dimensions and other issues.

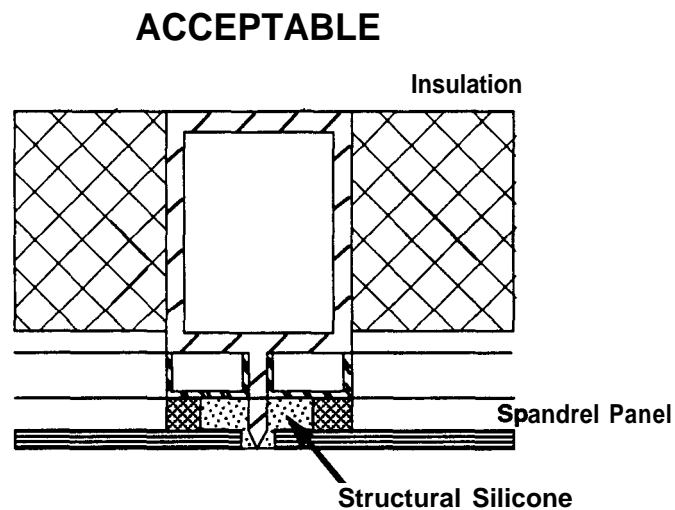


Figure 4.1.3 Structural Silicone Glazing

Poured-in-Place

Poured-in-place mullion systems have been widely used in less expensive curtain wall systems for a long time. These systems employ mullions which are fabricated in the shop. As shown in Figure 4.1.4, the system is based on a poured-in-place spacer which serves as a thermal break as well as a structural element. A receiver pocket is extruded into the framing system, which later receives a hot molten plastic. After the plastic is cured, a portion of the metal pocket is machined out to eliminate the metal-to-metal connection between inside and out. Due to structural considerations, this system is not recommended for use in "high performance" curtain walls where severe wind loads are expected. The plastic spacer must transfer all loads applied to the exterior face into the structural framing. These materials can become brittle in very cold temperatures and soft under hot temperatures. Thus, material selection is a very important issue. The framing must be designed so that the plastic filler forms a continuous thermal break. Sometimes spandrel filler beads, shown by the dashed line in the figure, bridge the thermal break and such designs should be avoided. Another issue with this system is that many architects prefer only about 60 mm (2 1/2 inches) of exposed framing, and that is not enough to achieve adequate structural performance. 80 mm (3 1/4 inches) is a preferable minimum dimension.

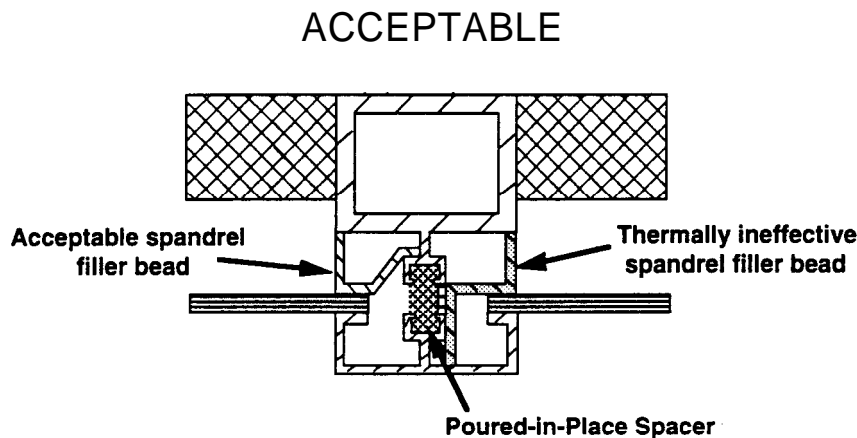


Figure 4.1.4 Poured-in-Place Mullion

Screw-on-Face with Snap-On Cover

This is a fairly standard system offered by most curtain wall manufacturers. As shown in Figure 4.1.5, the thermal break is provided by a low-conductivity spacer, usually made of vinyl or rigid PVC. The design of the spacer is critical in terms of material selection and its long term ability to seal out water. The exterior extrusions are attached with screws, whose size, type and spacing is based on structural considerations. In designing these systems, the bridging caused by spandrel glass adapters must also be reviewed. The figure shows a nonbridging adapter on the left; the dashed line on the right shows an adapter that conducts heat.

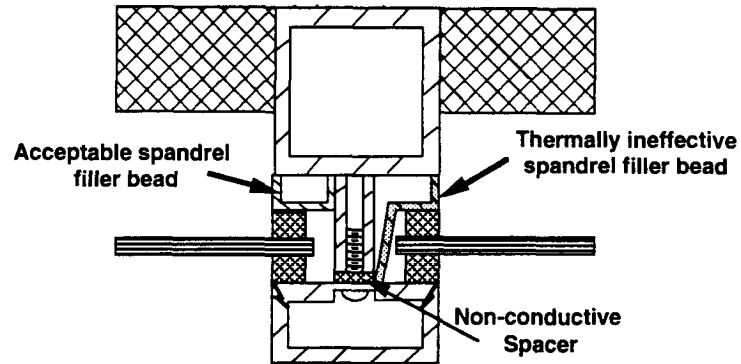
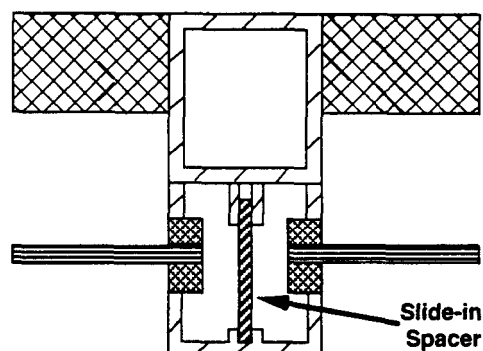
UNACCEPTABLE**Figure 4.1.5 Screw-On Face Mullion****Internal Slide-In Spacer**

Figure 4.1.6 shows a schematic of this system in which the interior and exterior metal is separated by a plastic, slide-in separator. These spacers often consist of extruded PVC and are designed to transfer the structural loads to the interior framing. The plastic spacer is slid into the framing at the fabrication shop. This system is common in medium commercial curtain walls. The structural properties of the plastic material are key to this system.

ACCEPTABLE**Figure 4.1.6 Slide-in-Spacer Mullion**

Structural Neoprene Gaskets

In structural, or zipper, gaskets, an extruded neoprene gasket that incorporates glazing pockets is attached to a metal support system. This system, shown in Figure 4.1.7, is simple and the thermal performance is generally excellent. In specifying this type of system, one must consider its visual appearance, the structural support system, the size of the gaskets and the anticipated building movements. It is usually used in small to medium scale buildings of limited height to create strip systems or vertical ribbon systems. Maintenance of this system is critical as the neoprene is exposed to the elements; concerns have been expressed about the life expectancy of the neoprene.

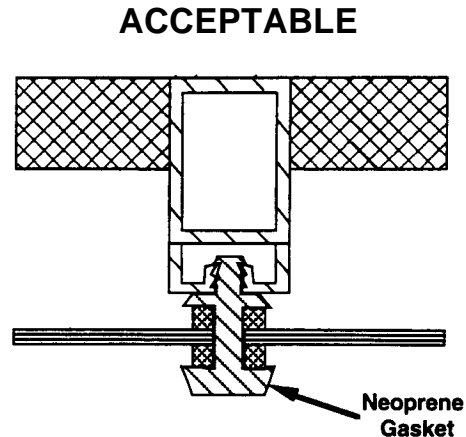


Figure 4.1.7 Structural Neoprene Gasketed Mullion

Interfaces with Other Envelope Systems

Intersections between curtain wall systems and other envelope systems are key locations where air barrier and insulation system continuity must be maintained. Quirouette and Brand have identified several such interfaces and have described appropriate designs where continuity is maintained by a structurally adequate air barrier that is secured between the curtain wall and the appropriate element in the other component. A rigid air barrier material is suggested for this application so that insulation can be brought into intimate contact with its surface. All of these designs are for heating climates, therefore the insulation is located on the outside of the air barrier. In all of these details, the air barrier is also serving as the vapor retarder.

Parapet

Figures 4.1.8 and 4.1.9 contain two presentations of a parapet with a metal curtain wall exterior. When the curtain wall system is brought up the outside of the parapet, it is exposed to colder temperatures, leading to potential condensation problems from the exfiltration of moist interior air. The exposure of the parapet to extreme temperature cycling can lead to structural concerns as well.

In Figure 4.1.8 (Quirouette), the curtain wall is connected to the parapet with an insulated air barrier, in this case a flexible membrane. This membrane runs from the shoulder of the top mullion and is sealed to the base flashing at the top of the parapet. The air barrier is kept warm by insulation under the metal coping and within the wooden parapet. The air barrier material and its means of attachment must be strong enough to carry the strong air pressures that exist at parapets from the wind and stack effect.

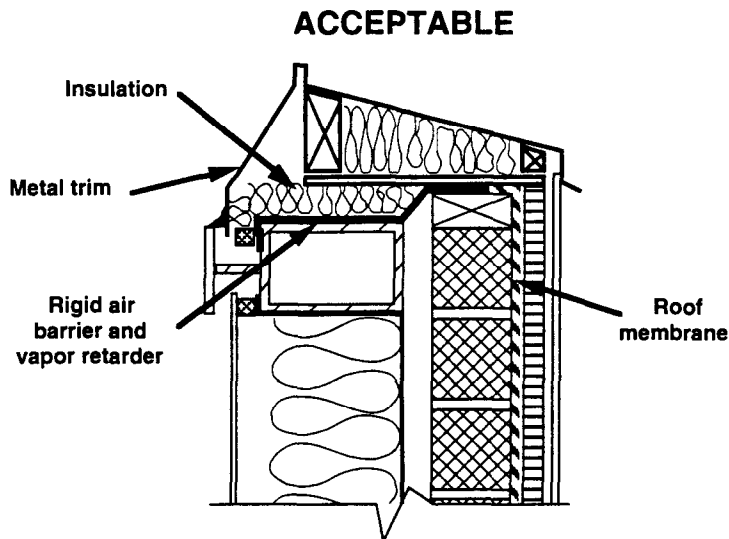


Figure 4.1.8 Curtain Wall Parapet (Quirouette)

Figure 4.1.9 shows another version of the intersection of a vertical curtain wall and roof at a parapet (Brand). A flexible membrane air barrier runs from the top mullion and over the parapet. It is insulated with glass fiber insulation under a metal cap that serves as a rainscreen. An insulated wooden parapet assembly keeps the air barrier warm.

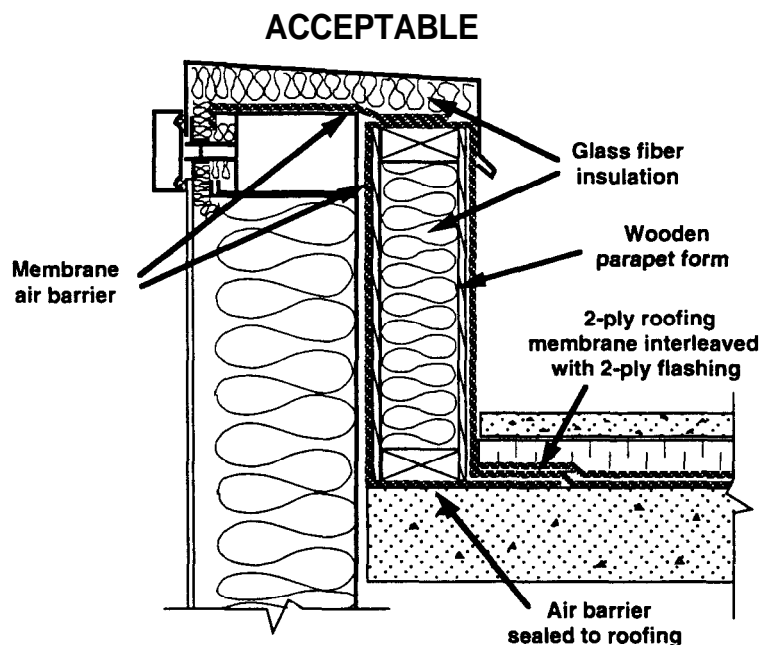


Figure 4.1.9 Curtain Wall Parapet (Brand)

Corners

When two sections of curtain wall meet at a corner, an air barrier must be fabricated to connect the two sections. Such a connection is shown in Figure 4.1.10. The air barrier and its attachment must be structurally adequate to carry the wind pressure loads. The air barrier can be fabricated of sheet metal, with consideration given to the corrosive potential of dissimilar metals. In a heating climate, the air barrier must be insulated on the outside with the insulation in intimate contact with the air barrier and in line with the mullion thermal breaks. The decorative cap outside of the insulation serves as a rainscreen and must not be sealed airtight to the mullions.

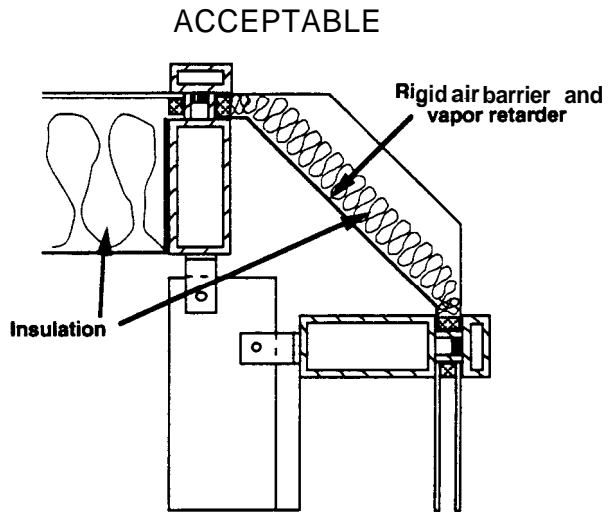


Figure 4.1.10 Curtain Wall Connection at Corner (Quirouette)

Grade Connection

Figure 4.1.11 shows two curtain wall connections to grade, one with poor thermal performance and an improved alternative. The connection between a curtain wall and grade is particularly sensitive to rain penetration and air infiltration. The first detail violates the requirements for both air barrier and insulation system continuity. The insulation under the mullion is out of line with the mullion thermal break, and the air seal under the mullion is out of line with the mullion air seals. In addition, cold air infiltration past the flashing and into the insulation creates the potential for condensation on the interior of the mullion. Rainwater accumulation in the cavity between the wall section and the floor will deteriorate the floor-to-mullion air seal. The alternate detail maintains the continuity of both the insulation and air barrier systems. The insulation is located to control condensation on the interior of the air barrier. A sealant is used at the base of the air barrier to create a sloped edge or water dam to control rain penetration. Flashing is installed under the mullion cap to ensure that water draining from above is directed to the outside of the cavity.

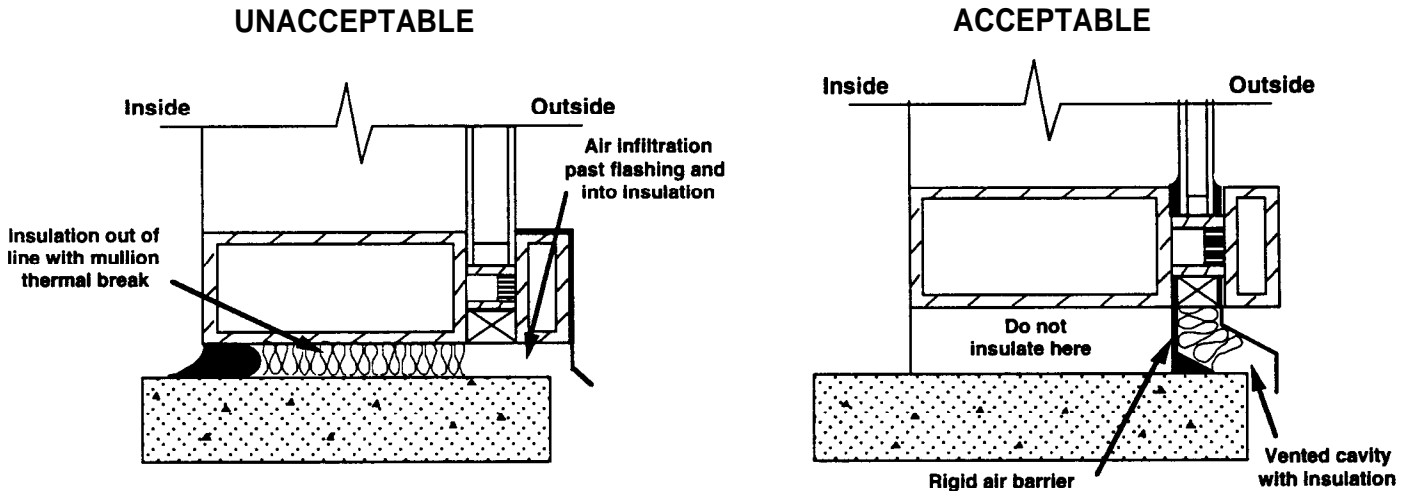


Figure 4.1.11 Curtain Wall-Grade Connection (Quirouette)

Wall-Foundation Connection

Figure 4.1.12 shows the intersection between a curtain wall and foundation, in which the wall is cantilevered beyond the face of the foundation wall. A flexible membrane air barrier is sealed to the bottom mullion of the wall and heat welded to the foundation waterproofing. The insulation at the bottom of the cantilevered section is clad with aluminum panels bolted to furring channels, supported by Z sections that are perforated to reduce the area of metal conducting heat through the insulation.

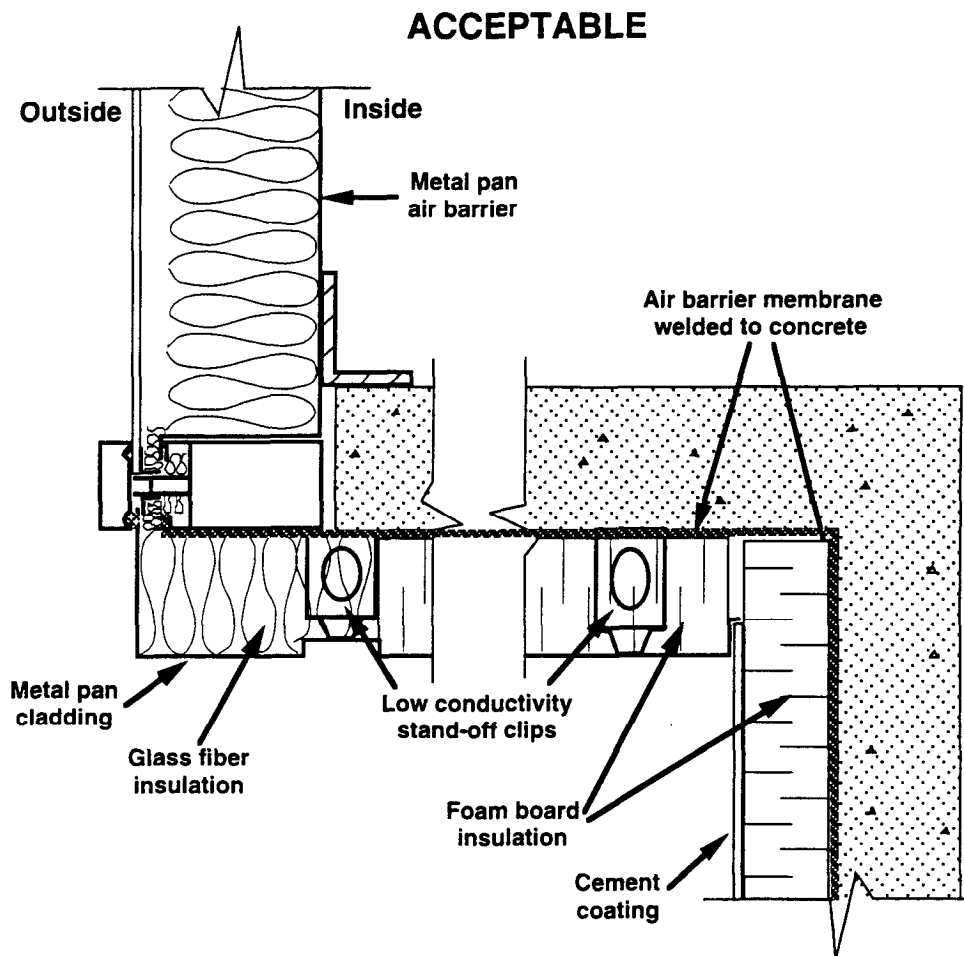


Figure 4.1.12 Curtain Wall/Foundation Connection (Brand)

Precast Panel Interface

Figure 4.1.13 shows the intersection between a precast concrete panel and a curtain wall. The space between the panel and mullion is insulated to maintain the continuity between the panel insulation and the mullion thermal break. An air barrier runs from the mullion shoulder, between the mullion and this insulation, and is connected to the air barrier in the insulation system behind the panel.

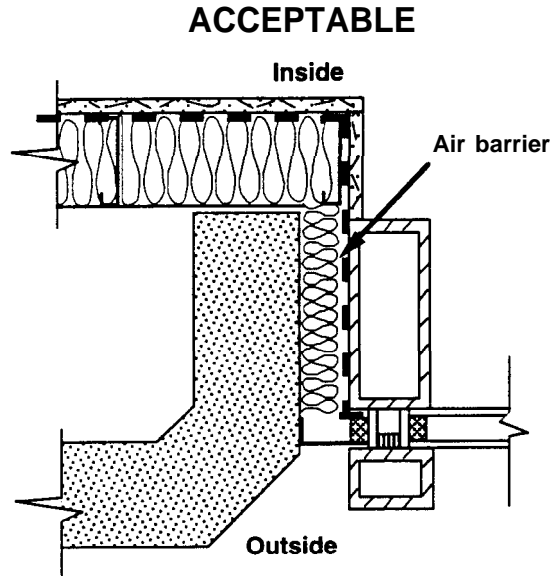


Figure 4.1.13 Curtain Wall/Precast Concrete Panel Connection (Quirouette)

Heated Soffit

Figure 4.1.14 shows the connection between the base of a curtain wall and the bottom of a heated soffit. A rigid metal air barrier runs from the lower shoulder flange of the mullion face to the air barrier on the inside surface of the soffit floor. Insulation is placed outside this air barrier under the mullion, extending past the edge of the soffit floor insulation.

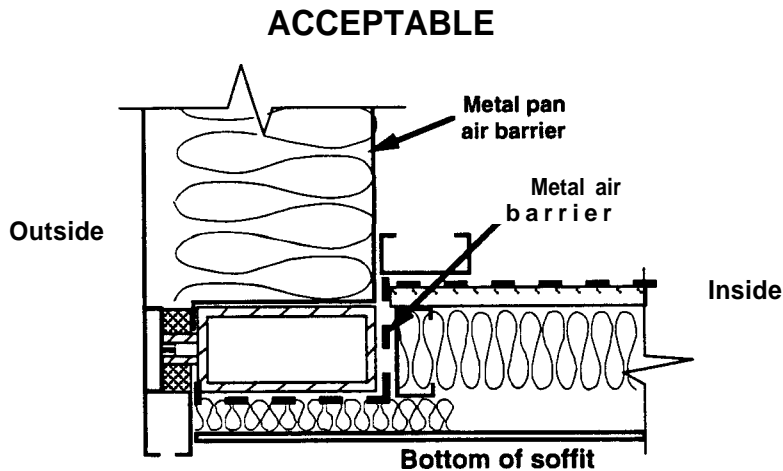


Figure 4.1.14 Curtain Wall/Heated Soffit Connection (Quirouette)

Design and Constructions Issues

Good curtain wall performance, thermal and otherwise, requires careful design, fabrication and installation. Achieving this goal in practice requires good communication and coordination between all of the parties involved in each of these steps. The AAMA manual on the Installation of Aluminum Curtain Walls is an excellent reference on these issues. In this document, curtain wall systems are described as highly-engineered, factory-made elements with close tolerances installed in a field-built structure with a significantly lower degree of dimensional accuracy. The curtain wall performance is dependent on how well the curtain wall and structural systems are matched, and these issues of tolerances and clearances in the building frame alignment are major issues in the AAMA installation manual.

The AAMA manual discusses these and other installation issues in relation to the responsibilities of the architect, the general contractor, the curtain wall contractor and the installation contractor. The architect needs to be aware of field procedures and conditions and then develop clear drawings and specifications based on this awareness. The architect should work closely with the curtain wall contractor in developing the details to facilitate fabrication and installation. Inspection during construction is another key role for the architect to insure that the specifications and shop drawings are followed. Architects should clearly define maximum permitted tolerances in the alignment of the building frame, and provide for these tolerances in the curtain wall installation. The general contractor must develop the construction schedule in consultation with the other players in the project, allowing sufficient time for the development of the shop drawings, the fabrication of custom components, and the assembly and testing of a mockup. A realistic schedule must be developed to enable a quality installation while controlling costs and delays. The curtain wall contractor is responsible for the fabrication of the wall elements and sometimes also their installation. In either case, the contractor must work closely with the architect during the design stage to give advice as the details are being developed.

As mentioned above, a key issue in curtain wall installation is keeping the deviations in the building frame within the tolerances specified in the design. If this is not done, the curtain wall cannot be installed without the potential for compromising its performance. The tolerances, or limits on the dimensional deviations, must be clearly established by the architect and closely followed in the erection of the frame. Adequate clearances between adjacent elements must also be provided to accommodate the tolerances and provide the necessary working space.

The AAMA manual also covers other important installation issues of layout and alignment of curtain wall elements, handling and storage of materials, protection of work during construction and installation problems during cold weather.

References

AAMA, "Installation of Aluminum Curtain Walls," Aluminum Curtain Wall Series 8, American Architectural Manufacturers Association, Des Plaines, Illinois, 1989.

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Parise, C.J., Ed., Science and Technology of Glazing Systems, ASTM STP 1054, American Society for Testing and Materials, Philadelphia, 1989.

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4.2 MASONRY

This section discusses wall systems in which a wythe (or wythes) of masonry constitutes the major component of the wall. There are many systems, which may appear to be quite different, that can be included under the general category of masonry walls. Such systems can range from a single wythe with no exterior or interior finish to a double wythe cavity wall with brick veneer and an interior finish of furring and gypsum. In general, most of the masonry walls of interest in commercial buildings fall into two categories. First, there are single wythe masonry walls with one of several different exterior and interior finishes. These exterior finishes include metal siding, stucco or paint, while the interior finishes can range from furring and gypsum wallboard to just paint. The second category of masonry walls are brick veneer walls which consist of a brick veneer, an air space, an inner wythe of masonry, and an interior finish. A great deal of design and construction information is available for brick veneer wall systems. This section does not cover brick veneer steel stud walls, as these are covered in the next section.

Guidance on the design and construction of masonry systems is available from a variety of sources including the Brick Institute of America (BIA), the National Concrete Masonry Association (NCMA), the Masonry Advisory Council and the Portland Cement Association (PCA). The BIA Technical Notes, the NCMA TEK series and the PCA Concrete Technology Today series provide very practical information. While these materials do cover some issues of thermal integrity and envelope airtightness, they tend to concentrate on material properties, structural issues, rain penetration and construction techniques. While these issues are relevant to achieving good thermal performance in masonry walls, these guidance documents do not emphasize the prevention of air leakage and other thermal defects.

General Design Information

There is a great deal of design information available for masonry walls in publications such as the NCMA manual of construction details by Elmiger and the PCA Concrete Masonry Handbook by Randall and Panarese. These and other publications provide information on masonry units, mortar, properties of masonry walls, finishes and construction techniques. Other sources of general design information include BIA Technical Notes 21 and 21B. Grimm published a literature review on the durability of brick masonry in 1985 that discusses the agents and mechanisms that cause deterioration and how to increase durability through design, material selection, construction and maintenance.

In most of these masonry design references, the discussions of thermal issues are generally not extensive and do not stress problems of air leakage and thermal defects. While there is some discussion of insulation systems and thermal bridging, air barriers are rarely mentioned. Some of the guidance they provide is relevant to our discussion, including the issues of materials, crack control, water leakage, and construction technique. This section on design information contains brief discussions of materials and crack control, followed by a discussion of brick veneer walls since they constitute a significant portion of commercial building masonry construction.

Materials

The materials of masonry construction have been studied for many years, and the properties necessary for good performance are well established (see BIA Technical Note 21, NCMA-TEK No.85 and the PCA Concrete Masonry Handbook for more information). Quality materials are necessary to achieve good performance, and even the best design and construction will be compromised by poor materials. The materials of concern include the masonry units, mortar, coatings, ties and anchors, flashing, shelf angles, and joint materials. Specifications for many of these materials have been developed by ASTM and other organizations. Masonry unit specifications include strength, durability and water absorption, and provide guidance on the selection of units based on climate and anticipated loads. Specifications for masonry units are provided in ASTM C 55 (concrete building brick), C 90 (hollow load-bearing concrete masonry), C 129 (non-load-bearing concrete masonry) and C 145 (solid load-bearing concrete masonry). The important material properties of mortars include workability, water retentivity, strength, adhesion and durability. The various types of mortars and their properties are described in ASTM C270 and C476 for nonreinforced and reinforced masonry respectively. Additional material requirements exist for clear or opaque coatings used to provide watertightness or water resistance. The materials properties of ties, anchors, shelf angles, flashing and joint materials relate to strength, durability and corrosion resistance.

Crack Control

Cracking of masonry walls obviously impacts water and air leakage, and can lead to more serious problems of structural integrity for facades or whole walls. Grimm published a literature review of masonry cracking in 1986; the issue is also covered in BIA Technical Note 18 and NCMA TEK No.3 and No.53. Cracking occurs when the inevitable movement of building materials is restrained by the material itself or by adjacent elements. Such movement is caused by a variety of forces including temperature expansion and contraction, changes in moisture content, and structural loads. The differential movement of building components can be anticipated and must be accommodated for in design, otherwise cracking will result. Cracking can be controlled by the specification of materials that limit moisture-induced movement, the use of reinforcement such as bond beams, and the use of control joints or other devices to accommodate movement. In masonry veneer walls, the design of shelf angles that can accommodate movement is of particular importance and is described in Grimm and elsewhere. Crack control must be a part of the design of masonry walls, otherwise cracks will develop and both water leakage and air leakage will increase. As discussed in the section on water leakage, some fine cracking is inevitable, e.g. at mortar-unit interfaces, and adequate means must be provided for the drainage of the water that leaks through these cracks.

Brick Veneer Walls

Brick veneer walls employ a two-stage approach to the control of rain penetration. Figure 4.2.1 is a schematic of a brick veneer wall, showing the major components of the system. In this design approach, the veneer is intended to shed most of the rain water, at the same time acknowledging that some water will penetrate into the cavity. The veneer must still be designed and constructed to provide wind and water resistance so that the water-tightness of the backup wall is not continuously tested. If the veneer is not at all watertight, then the backup wall really constitutes a single stage system. The cavity must be flashed at appropriate locations so that any water that does penetrate the veneer is drained to the outdoors. Ideally, the veneer should serve as a pressure-equalized rainscreen in which openings in the veneer keep the cavity pressure close to the outdoor pressure, preventing pressure driven rain penetration into the cavity. These openings must be designed to limit rain penetration due to capillary and gravity-driven flows. For the pressure-equalized rainscreen approach to be effective, the backup wall must be airtight.

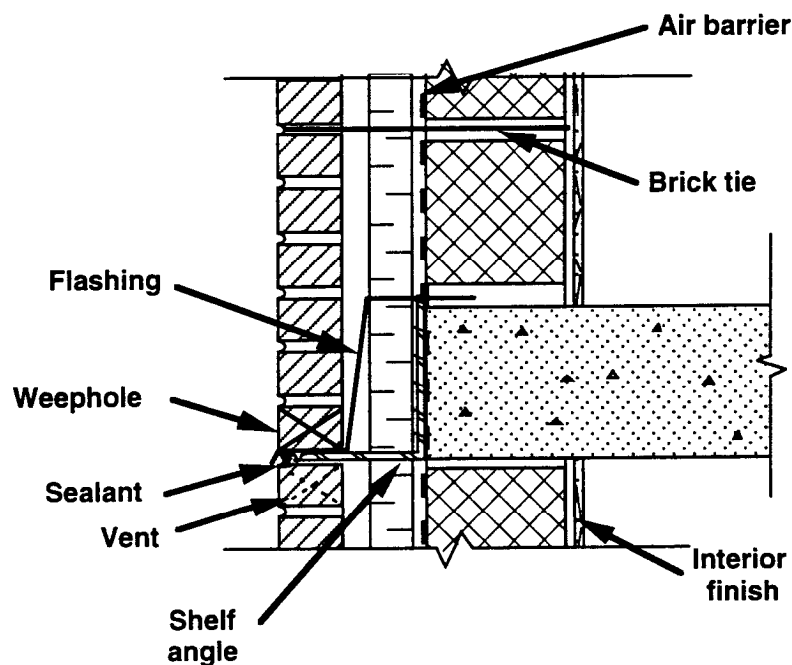


Figure 4.2.1 Brick Veneer Wall (CMHC 1989)

The design and performance of brick veneer walls is covered in BIA Technical Notes 21 and 21B, the Canada Mortgage and Housing Corporation (CMHC) Seminar on Brick Veneer Wall Systems, NCMA-TEK No.62 and No.79, and the PCA Concrete Masonry Handbook. The information in these documents concentrates on materials, structural issues and water leakage control. BIA 21B emphasizes structural issues and includes details of anchorage, expansion joints, foundations and window connections. Except for the CMHC document, design issues related to thermal envelope integrity are not emphasized in many of these guidance documents.

Water Leakage

While water leakage does not relate directly to air-tightness and thermal performance, the interactions between the elements intended to control water and those intended to control air leakage and heat transfer must be addressed. Also, water leakage can lead to the deterioration of the elements controlling air leakage and heat loss.

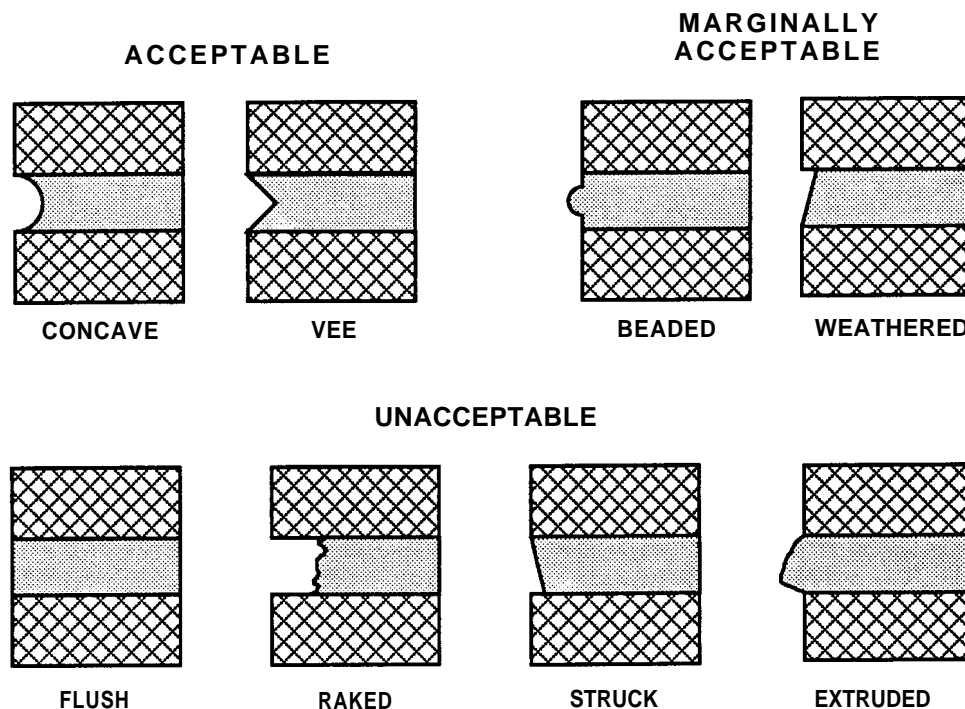
Rain penetrates masonry walls through cracks at mortar-unit interfaces, unfilled mortar joints, movement and shrinkage cracks, and interfaces of the masonry wall with other wall components. The impact of raindrops directly on cracks is not a major contributor to water leakage, rather water running down the face of the masonry leaks through cracks due to capillary action and air pressures across the wall. Gravity can also be an important factor in larger openings that slant inwards. It is important to keep water off the wall through the use of properly designed drips on copings, ledges, sills and balconies, because any wall will leak if it is continuously flooded with water.

For a solid masonry wall, or any masonry wythe, to be watertight the masonry units and mortar must be compatible, the mortar joints must be completely filled and properly tooled, and the wall must be sufficiently thick. Compatibility between the units and mortar is necessary to achieve a good bond, otherwise there will be unbonded areas and cracks will be more likely to develop. In addition, the mortar joints need to be properly tooled in order to compact the mortar against the units and to close capillary cracks. If a masonry wall is sufficiently thick, then the water that does penetrate the facade will generally not reach the interior face before it is able to dry out. This is the approach that controlled rain penetration in older masonry construction, and it worked well in these very thick walls. In modern construction, masonry walls are generally not load-bearing and are therefore thinner and less forgiving of water leakage. In order to control water leakage in modern, masonry walls, industry guidance on mortar and joint tooling should be followed, but given the miles of mortar-unit interface it is unrealistic to expect to be able control all of the water leakage. Therefore, good masonry construction for rain penetration should be supplemented by the use of a facade or veneer that provides a second line of defense combined with a drainage system to remove the water that penetrates the facade. Design for the control of water leakage requires an understanding of how the cavity wall system is supposed to perform plus achieving the following key performance elements: the brick veneer should be as watertight as possible, flashing must be properly installed at all required locations, the cavity must be well drained and the backup wall must be airtight and watertight.

ASTM E 514 provides a test method for determining a masonry wall's resistance to water penetration subject to wind driven rain. This procedure involves a wall installed in a test chamber, as opposed to a field test.

Mortar Joints

Given compatibility between the mortar and the masonry unit, the joint must be full and properly tooled to control water leakage. Construction issues related to joint tooling are discussed below, but the type of mortar joint is key at the design stage (see NCMA-TEK 85 and the PCA Concrete Masonry Handbook). Figure 4.2.2 shows acceptable and unacceptable mortar joints for water leakage control. Concave and vee joints are generally recommended when the joint is exposed to rain. There is less consensus on beaded and weathered joints, with both reports of their providing adequate performance and recommendations against their use. Therefore they are labelled as marginally acceptable. Flush, raked, struck and extruded joints are not suitable unless weather-tightness is not an issue, such as in interior construction. They should not be used on the exterior face of the inner wythe of a cavity wall.



**Figure 4.2.2 Mortar Joints for Water Leakage Control
(Randall and Panarese)**

Drainage and Flashing

Since it is practically impossible to make a watertight masonry wall, one must provide the means for the drainage of water that penetrates the facade. This design feature is recognized in the design of cavity walls, but drainage is also necessary in other masonry wall systems. Flashing is necessary at a variety of locations to direct this water flow to the outdoors through weepholes or some other such device. Good drainage requires the maintenance of an adequate space behind the facade, through which water can easily flow downward. Construction technique is important for keeping the cavity free from mortar droppings and installing the flashing such that it performs effectively, and these are covered in the section on construction. Many of the design aspects of drainage, flashing and weepholes are covered in available design guidance documents. Some of the key design requirements are outlined below, based on material contained in BIA Technical Note No.21 B, NCMA-TEK No.13A and the PCA Masonry Construction Handbook.

Flashing is required anywhere water might otherwise accumulate or tend to enter the building interior. These locations include the following: above wall openings such as window heads, below wall openings such as window sills, where the wall structure rests on the foundation, at shelf angles, at wall-roof intersections and at parapet copings. A flashing material of good quality must be specified in the design, based on the following qualities: impervious to moisture penetration, resistant to corrosion from the atmosphere or caustic substances in mortar, strong enough to resist puncture, abrasion and other damage during installation, and both easily formed into the desired shapes and able to retain these shapes in use. Preformed copper sheet flashing, with soldered joints and expansion provisions, provides good performance. Galvanized sheet steel, aluminum and lead can be corroded from substances in the mortar and must have protective coatings. The flashing design must maintain continuity of the flashing at corners and other interfaces, and dams must be employed where flashing terminates such as beyond window jambs. In order to achieve the required continuity, flashing installations need to be carefully detailed at all interfaces such as windows, corners and columns. Adjoining pieces of flashing should be overlapped and properly sealed to each other. Potential interferences with other envelope elements that might damage or puncture the flashing, such as shelf angle bolts or ties, must be avoided. In cavity walls, the flashing should be carried up into a mortar joint of the inner wythe. And perhaps most important of all, the flashing must extend beyond the exterior face of the building. Aesthetic considerations are sometimes allowed to prevent this essential extension of the flashing, defeating its effectiveness.

Flashing will not be effective unless there are an adequate number of weepholes through which accumulated water can drain, located immediately above the flashing. Recommendations for the spacing of weepholes range from 400 to 600 mm (16 to 24 inches) on center. Weepholes can be provided by leaving mortar head joints open, using removable oiled rods or sashes, or installing plastic or metal tubes in the head joints. Weepholes can become plugged with mortar during construction, thereby losing their ability to drain. Construction techniques exist to prevent this problem, and these are described below in the section on Construction Requirements. Other weephole deficiencies include their complete omission or inadequate spacing or number.

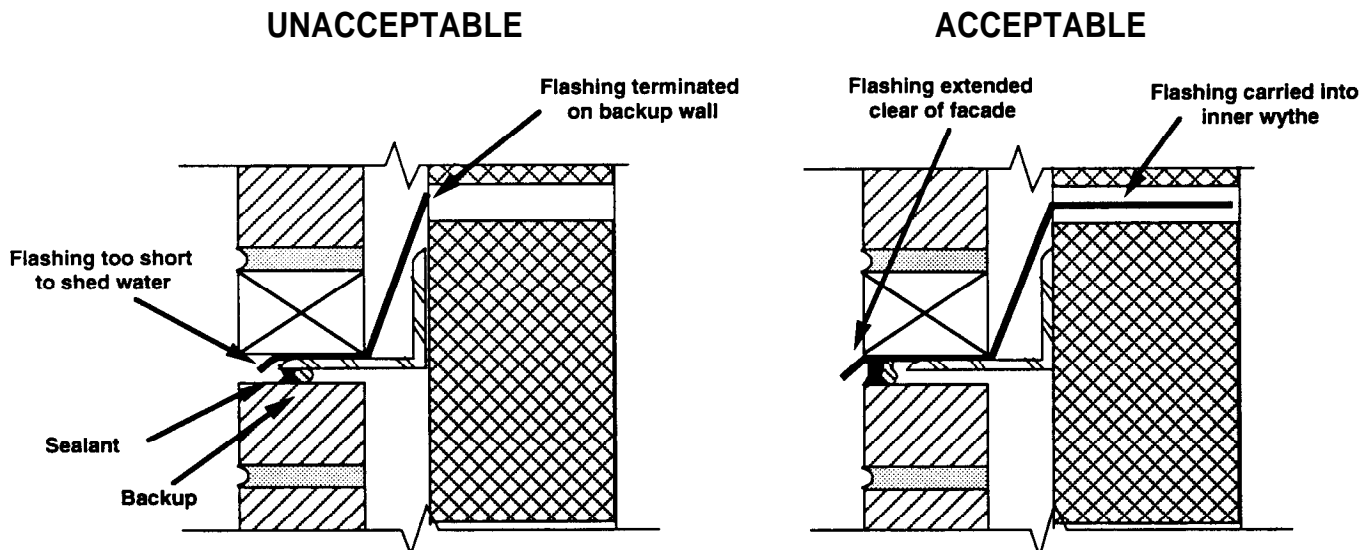


Figure 4.2.3 Unacceptable and Acceptable Flashing and Sealant Details (CMHC 1989)

Figure 4.2.3 shows unacceptable and acceptable flashing details at horizontal shelf angle joints. In the unacceptable case, the flashing is not extended beyond the face of the brick veneer, decreasing its ability to drain water to the outdoors. In the acceptable detail, the flashing is extended well beyond the face of the brick and is positively sloped to the outdoors. The flashing must not be terminated on the shelf angle because that will allow water to drain behind the sealant and into the cores of the brick veneer. Nor should the flashing be terminated against the inner surface of the backup wall, since water draining down the cavity will be able to get behind the flashing. Instead, the flashing must be carried up over the shelf angle and anchored at least 20 mm (8 in.) into the first course of the inner wythe. The relative positioning of the flashing and the anchor bolt must be considered to avoid puncturing the flashing. The flashing is sometimes placed in the second veneer mortar joint above the shelf angle for this reason. A compressible filler (e.g. neoprene) is placed under the shelf angle to keep debris, especially mortar, out of this space. If mortar does get under the shelf angle, differential movements result in unacceptable loads being imposed on the veneer.

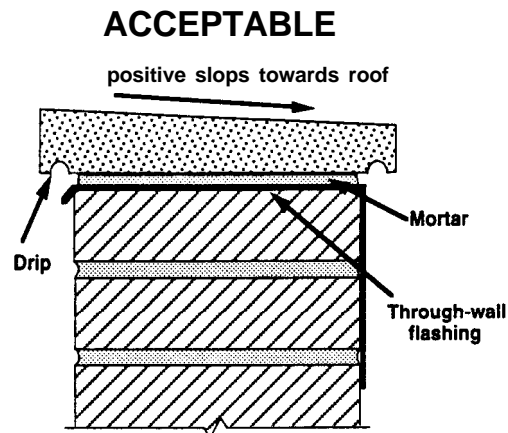


Figure 4.2.4 Flashing at Coping (CMHC)

Parapet flashing is extremely critical because of the exposure of these elements. In order to keep water out of the parapet and to prevent it from running down into the wall, through-wall flashing is required below copings and near the base of the parapet. Figure 4.2.4 shows such through-wall flashing below a pervious or segmental coping. Note that drips are included in the coping on both sides of the parapet, and that the coping slopes towards the roof to prevent water from running down the outer facade.

Figure 4.2.5 shows metal cap flashing over the top of a parapet and the through-wall flashing at the roof line. Figure 4.2.6 shows the flashing at a flashed curb at a roof edge.

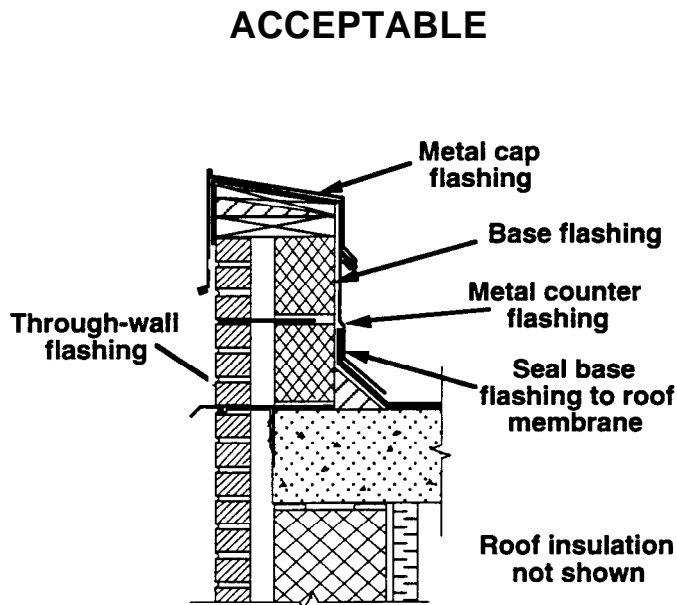


Figure 4.2.5 Parapet Flashing (CMHC 1989)

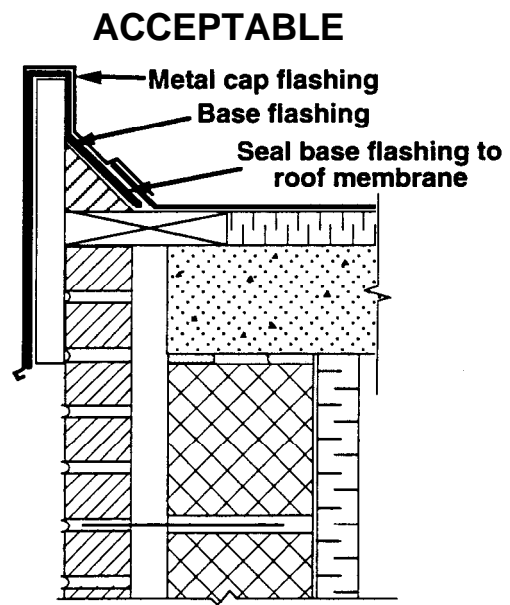


Figure 4.2.6 Flashed Curb (CMHC 1989)

The consequences of flashing deficiencies are well recognized, and as noted in the CMHC Advisory Document on Exterior Wall Construction these deficiencies may arise from several causes. First, flashing may not be called for in the design due to an oversight. In other cases, flashing is included in the design but is inadvertently omitted during construction. In some designs, the flashing is carried up a vertical surface to be tucked and sealed into a reglet or notch in the concrete structure or in a raked-out mortar joint. If this reglet is missing, the flashing may also be omitted or else not sealed properly, resulting in ineffective performance. Deficient flashing performance also results when the flashing is damaged during construction by wind or rough handling. A major cause of poor performance is insufficient flashing details that are oversimplified and neglect interference with other building elements. For example, flashing may interfere with the shelf angle bolt if the cavity is too narrow. Detailing problems also occur when flashing intersections with columns and other contiguous elements are ignored.

Coatings and Sealants

A wide variety of coatings are available for waterproofing masonry walls, as discussed in NCMA-TEK No.10A and the PCA Concrete Masonry Handbook. It is generally recognized that these coatings alone will not prevent water leakage, although they are necessary when a single wythe of concrete masonry constitutes the exterior facade. The other aspects of design and construction for controlling water leakage discussed in this section, i.e., surface drainage, mortar joints and flashing, must also be employed and in some cases can preclude the need for any surface coating. If these control measures are not taken and the wall does not adequately control cracking, then coatings alone will not prevent water leakage.

Surface coatings can be classified as opaque and clear. The opaque coatings can actually provide waterproofing because of their higher content of solids. Clear coatings tend to be less effective than opaque coatings, and are referred to as water repellents. Clear coatings employ a variety of materials, and work by changing the capillary angles of the pores in the masonry (see BIA Technical Note 7E). They will not normally fill cracks in masonry walls, and it is these cracks that are associated with most water leakage. Clear sealants do have their applications, but the inappropriate use of such materials can lead to problems. The performance limitations of clear sealants include an inability to stop moisture penetration through cracks and incompletely filled joints, the potential for contributing to spalling and/or disintegration of units; the inability to stop staining and efflorescence followed by interference with its removal; and making the wall almost impossible to tuck point. BIA recommends against their use except under very specific circumstances. Before considering their use for controlling water leakage, BIA recommends a careful inspection of the wall to investigate other potential sources of water leakage. Such an inspection should include the design and current condition of caps, copings, flashing, weep holes, sealant joints, and mortar joints. Any defects should be corrected, and these actions may control water leakage without the use of a coating. BIA Technical Note 7E provides a thorough checklist to use in determining the appropriateness of using a clear sealant. Many of these BIA limitations on the use of clear coatings also apply to opaque coatings.

Thermal Insulation

The key aspect of thermal insulation system performance is maintaining continuity over the entire building envelope. This involves placing and attaching the insulation so that there are no gaps between insulation elements, and between the insulation and its substrate. Thermal bridges must be avoided, and the insulation must remain in position over time. BIA Technical Note 21A discusses insulation of cavity walls, covering topics of materials and their properties, and points out two general criteria for cavity insulation. First, the insulation must allow the cavity to perform its function of providing a barrier to rain penetration and allow moisture to drain back to the outdoors. Also, its insulating properties must not be degraded by moisture in the cavity. Two other important issues regarding insulated cavity walls are the manner in which the insulation is attached and the position of the insulation, inside or outside the inner wythe.

The debate on whether to place insulation within the cavity or on the inside of the inner masonry wythe has been going on for decades. Both alternatives have advantages and disadvantages as discussed below. An advantage of interior insulation is that the insulation (and often the vapor retarder and air barrier) can be installed from the floors after the masonry work is complete. The installation can then be easily inspected and any defects repaired. One disadvantage of interior insulation is that the entire building envelope, and perhaps elements of the structural frame, are outside of the insulation and subjected to the full range of outdoor temperature fluctuations. This exposure increases the associated dimensional changes and places more severe requirements on materials. Also, the insulation (and again often the vapor retarder and air barrier) are not continuous over the building envelope but are interrupted by floor slabs, beams, columns and partition walls. These interruptions act as thermal bridges and require very careful attention in order to maintain the continuity of the air barrier system. Finally, when services such as electrical are installed they can end up being cut into the insulation and the air barrier.

Interior insulation often involves friction-fit batts installed between furring strips or studs. If this approach is used, the batt must fill the entire space to restrict any airflow, since airflow through or around the insulation will severely degrade its effectiveness. To this end, the spacing between the furring or studs must be kept uniform so that the batts are held securely. The insulation must be continuous over the entire interior surface, with no gaps at the floor or ceiling. If there is a dropped ceiling, the insulation must be carried past the ceiling to the slab above.

Cavity insulation also has advantages and disadvantages. On the plus side, the insulation can be applied over the entire backup wall, uninterrupted by floors, beams, columns and other elements, greatly reducing thermal bridging. The structural frame and the inner wythe are now separated from the outdoors by the insulation, providing a more stable temperature environment. The concern about electrical services, chases, ducts, etc. penetrating the insulation, vapor retarder and air barrier are eliminated. One disadvantage of cavity insulation is that since the insulation and masonry go up together, it is more difficult to inspect the work and repair any defects. The installation must be applied from a staging, and weather conditions can interfere with construction and affect the quality of the work. Also, the insulation must be worked around the veneer ties in a manner that does not compromise the insulation system effectiveness. Care is required in developing the flashing and insulation details so that they do not interfere with each other.

When insulation is placed in the cavity, a secure means of attachment is critical. The insulation within the cavity is subjected to outside wind pressures, and if it becomes displaced, it can interfere with the drainage of water from the cavity and lose its effectiveness as an insulator. In addition, there must not be any air gaps behind the insulation, otherwise air will then be able to flow around the insulation, severely degrading its effectiveness. Rigid insulation boards are often used as cavity insulation, and in order to be effective, these boards must be fixed tightly to the outside surface of the backup wall. Depending on the condition of the backup wall surface, it may be necessary to parge the backup wall to provide a flat surface for application of the insulation. Rigid insulation can be attached to the backup wall with adhesives, mechanical fasteners or a combination of both. When using adhesives it is important that the surface of the backup wall is clean and smooth. The back of the board must be fully buttered with adhesive, since spot adhering will result in air gaps behind the board. Weather conditions may restrict the use of some adhesives. One must also address their compatibility with the insulation and their long term stability and effectiveness with regards to aging, attack from biological organisms, and temperature and humidity cycling. Mechanical attachment using the brick ties or screw and washer assemblies has advantages over adhesives since they can be used under any weather conditions. Rigid, fibrous insulation is sufficiently flexible that mechanical anchors will pull the insulation into close contact with the backup wall.

When cavity insulation is used, the cavity must be wide enough to allow for the cleaning of any mortar droppings from the cavity. One can use insulations specifically designed to fill the cavity and allow for drainage, such as semi-rigid glass fiber boards. Such an approach also has the advantages of preventing mortar droppings since the insulation is in place when the veneer is installed.

In the case of rigid insulation boards, achieving secure attachment requires a solid surface for affixing the insulation and a means of attachment that can withstand the environment to which it will be subjected. Figure 4.2.7 shows an insulation adhesion failure caused when the brick ties prevented the insulation from achieving full contact with the backup wall. As a result, very little of the asphalt adhesive on the back on the rigid insulation actually contacted the block. Air moving through the block wall, due to the lack of an air barrier system, was free to move through the spaces on both sides of the insulation. In this case, severe condensation resulted on the outer surface of the backup wall. This problem could have been avoided through the use of an air barrier system and an alternative means of attaching the insulation.

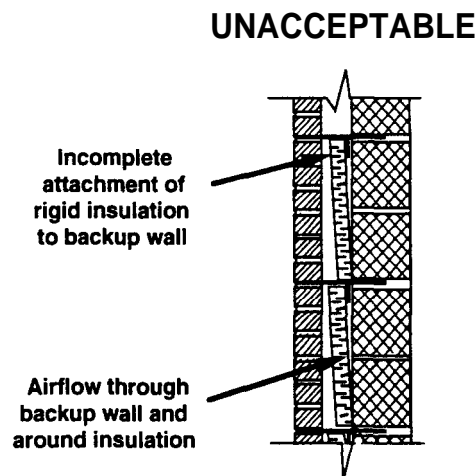
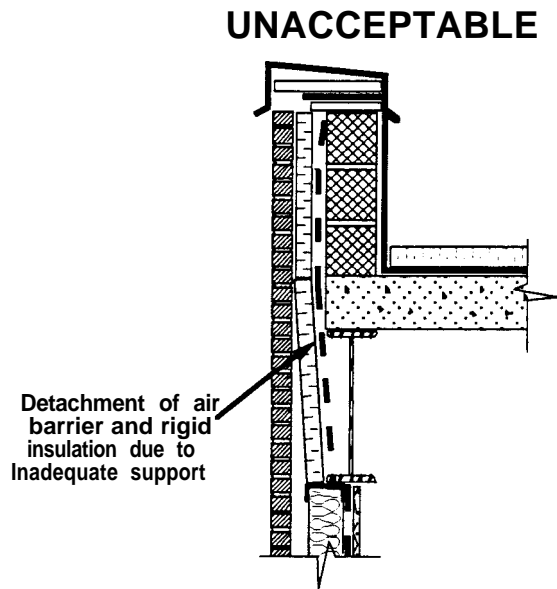


Figure 4.2.7 Insulation Attachment Failure

Figure 4.2.8 shows another case of insulation attachment failure (Quirouette 1989). In this case, the insulation was simply spot adhered to the polyethylene air barrier/vapor retarder which was attached to the top of the wall studs and the top of the parapet top plate. The insulation/polyethylene was not adequately supported to withstand the wind pressures, and eventually it was displaced and tore.



**Figure 4.2.8 Insulation Attachment Failure
(Quirouette 1989)**

Given a well-attached insulation material, the concern over thermal bridges remains. Thermal bridging is not given much attention in existing construction guidance documents. In fact, these documents contain many examples of thermal bridges in their recommended design details. NCMA-TEK No. 151 is an exception, showing several examples of thermal bridges in masonry walls and pointing out the advantages of cavity insulation for avoiding such problems. Thermal bridges are discussed below in the section Examples and Details.

Air Barriers and Vapor Retarders

Masonry walls require air barrier systems to control air leakage as discussed in the section Design/Air Barriers. Similarly, the design and installation of vapor retarders for masonry walls needs to follow the guidance given in the section Design/Vapor Retarders. To make a masonry wall airtight, one must reduce the permeability of the masonry wall itself and address the intersections between the masonry and other building elements. Mortar joints can not be made airtight because differential movements caused by temperature, moisture, shrinkage of blockwork and movement of other building elements inevitably lead to cracks in mortar joints. Since masonry itself is ultimately permeable to airflow, an air barrier material must be employed to seal the small openings at the unit/mortar joints. Air barrier materials used in masonry construction include layers of mortar, plaster, heavily textured paint or mastic, sheet material, interior gypsum board and various sealants. In order to achieve a continuous air barrier system, seams and joints must be meticulously sealed. Air barrier elements are also required at the interfaces between the masonry construction and other envelope components and must be able to accommodate the differential movement at these locations.

The following figures show air leakage defects in masonry construction, pointing out some of the key points in achieving an effective air barrier in masonry wall. Figure 4.2.9 shows a situation where air leakage occurred because the air barrier was omitted behind the convector cabinets (Quirouette 1989). Because the block behind the convector cabinets was left unfinished, interior air flowed through the unfinished block into the cold space behind the precast concrete spandrel panels and the column covers, resulting in severe condensation, freezing and melting problems. This case shows the importance of applying the air barrier continuously over the entire wall.

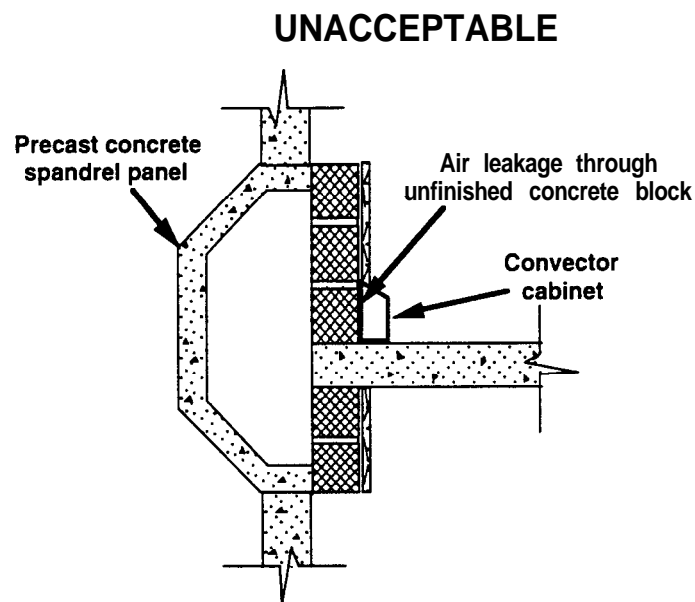
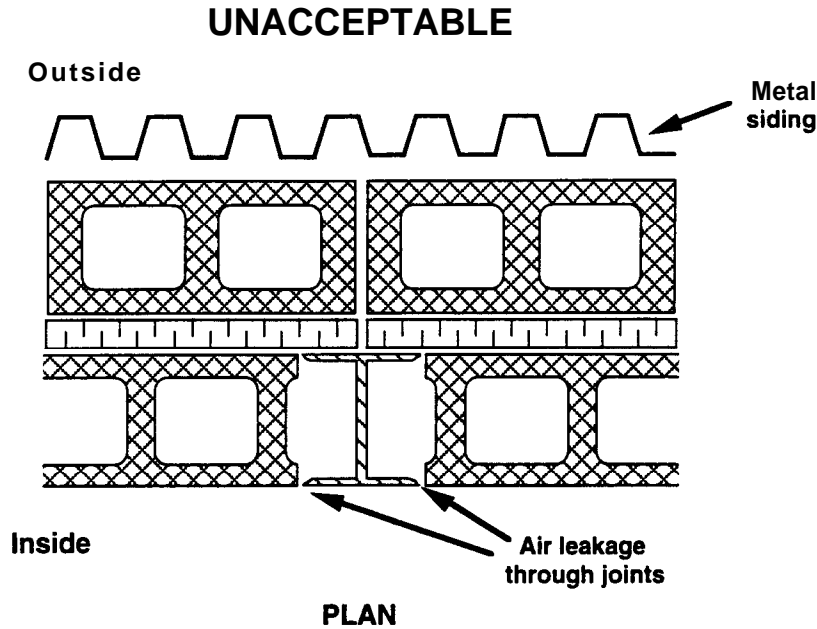


Figure 4.2.9 Air Leakage Through Unfinished Block (Quirouette 1989)

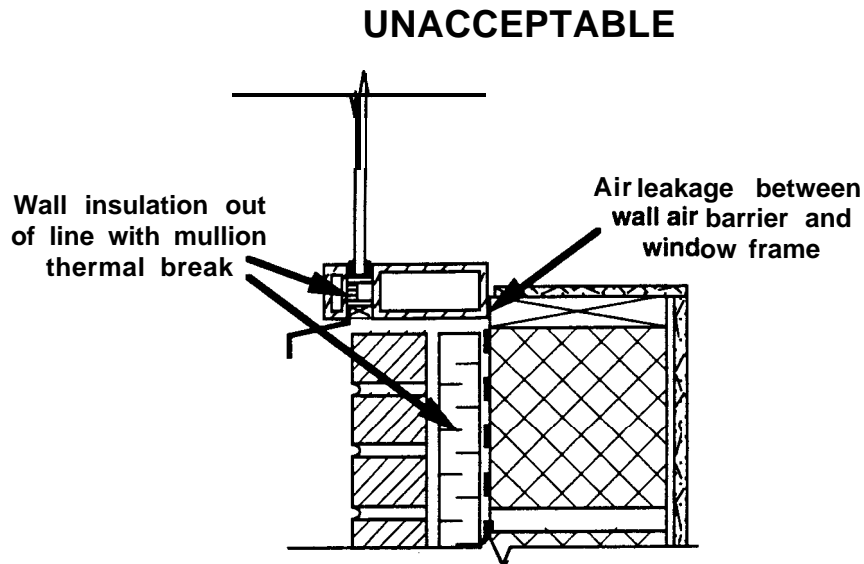
Figure 4.2.10 shows air leakage at the interface of steel columns and concrete block. The exfiltrating interior air eventually condensed on the cold metal siding, resulting in severe crumbling of the block at the outer wythe. This case points out the need to provide an appropriate air barrier at the intersection between steel columns and masonry. The air barrier element must be able to compensate for construction tolerances, differential movement of the block wall and the structural elements, and block shrinkage. The intersection between masonry walls and other envelope elements is a key area for achieving air barrier continuity.



**Figure 4.2.10 Air Leakage at Block / Column Joint
(Quirouette 1983)**

Figure 4.2.11 shows an example of an air barrier discontinuity at a window/wall interface (Quirouette 1983). In this case the wall air barrier and the window air seal are not in line with one another, resulting in a major discontinuity in the air barrier. Similarly, the wall insulation is out of line with the window thermal break. Quirouette points out that this design has been found to result in condensation on the inside mullion surface and efflorescence on the outside surface of the brick veneer.

As in the case of thermal insulation, the air barrier in a cavity wall can be placed either inside or outside of the backup wall and the insulation. The advantages of an inner air barrier include accessibility during construction and the associated ease of inspection and repair. In addition, if the air barrier and associated seals are positioned inside of the insulation then they are protected from outdoor temperature fluctuations, reducing the differential movement to which they are subjected and easing the material requirements on the sealants. The disadvantages of an interior air barrier involve the detailing required to seal the wall air barrier around columns, floor slabs and other structural members. The advantages of positioning the air barrier outside of the backup wall include having a continuous surface over which to apply the air barrier without having to work around interruptions from structural members. Whether the air barrier is inside or outside the insulation will determine the temperature environment to which it is subjected, affecting the material requirements for the air barrier.



**Figure 4.2.11 Air Leakage at Window/Wall Interface
(Quirouette 1983)**

Vapor retarder design for masonry walls must follow the guidance in the section Design/Vapor Retarders. The vapor retarder need not be absolutely continuous like the air barrier, but it must be applied to all portions of the envelope. Areas that are sometimes neglected include walls above suspended ceilings and behind convector cabinets. The position of the vapor retarder within the wall depends on the climate and the placement of the thermal insulation, and needs to be considered on a case by case basis as described in the section Design/Vapor Retarder. In some designs the air barrier is also intended to act as the vapor retarder, and in these cases the same analysis of vapor transport needs to be conducted.

There are several different options for providing a vapor retarder in terms of location and materials. The CMHC Seminar on brick veneer wall systems describes options for heating climates. First, the vapor retarder can be part of the interior finish, a necessity when the insulation is placed inside of the backup wall. Appropriate materials include oil or alkyd paint over gypsum board, polyethylene over the insulation, and impermeable insulation itself. If the insulation is positioned in the cavity, the vapor retarder can be located on the inside face of the backup wall using paint or other vapor retarding materials. A membrane on the exterior face of the backup wall can also serve as a combination vapor retarder and air barrier. Self-adhesive and torched-on membrane materials are effective. Since the membrane is serving as an air barrier, it must be continuous, able to accommodate movement cracks and remain firmly attached over time despite air and vapor pressures. When rigid insulation is applied to the external face of the backup wall, the mastic adhesive will serve as a vapor retarder. To be effective, a full bed of mastic must be applied and joints between insulation boards must be fully buttered.

Construction Requirements

There are several key requirements for building a masonry wall with good thermal and airtightness performance and with the ability to control water leakage. The following construction requirements are from the CMHC Seminar on brick veneer wall systems:

- Mortar joints must be completely filled and tooled on the exterior face to be resistant to rain penetration.
- Mortar joints on the backup wall must also be filled and properly tooled since it also forms part of the wall's moisture resistance.
- Mortar droppings within the cavity must be minimized and weepholes must be kept open.
- Securely anchor undamaged flashing to backup wall with properly lapped joints and extend sufficiently to clear the exterior face of veneer.
- Shelf angles must not tilt backwards. Sealant and backer rod must be installed below shelf angles to prevent water from entering the top of the veneer and cavity.
- Ties must not provide a path to carry water to the backup wall. Seal perforations of exterior components of backup wall caused by ties.
- Ensure that cavity insulation is fastened tightly to the backup wall.
- Avoid gaps between insulation units and gaps between wall insulation and insulation in other wall components.
- Maintain continuity in the insulation and air barrier systems, including intersections with other building components.
- Follow manufacturer's instructions for specified sealants
- Do not substitute any materials without approval of designer.
- Protect work in progress from damage due to weather and construction activities by other trades.

Several of these requirements are applicable to all wall systems. Those concerning mortar joints, mortar droppings, weepholes, flashing, shelf angles and ties are specific to masonry walls, and many of these are covered in industry guidance documents. Proper techniques for placing masonry units and tooling mortar joints are contained in BIA Technical Note 21C, the PCA Concrete Masonry Handbook and the PCA Concrete Information IS220.01M. These include minimizing the movement of the unit after placing in contact with the mortar, carefully filling head joints, covering newly erected masonry with a tarpaulin at the end of the day, and wetting exposed mortar joints for four days after filling or covering them with plastic.

Two key construction issues are keeping the cavity clean and reducing the impacts of weather on construction. The referenced construction guidance documents describe procedures to keep the cavity clean of mortar droppings and other foreign materials. Mortar within the cavity will create bridges that allow water to be carried across the cavity to the backup wall, preventing effective drainage of the cavity. Mortar droppings can also plug weepholes. Mortar droppings can be prevented by keeping a board in the cavity below the mortar application and progressively pulling the board up as the work is done. This technique is described in detail in the referenced documents. The impact of weather conditions on masonry construction are also covered in these guidance documents since both hot and cold weather impact material properties. These documents provide specific guidance on storage and handling of materials, and the construction of temporary enclosures to protect walls during construction.

Construction also impacts the integrity of masonry construction when time schedules and cost are allowed to compromise quality. As pointed out above, good construction technique is required to ensure maximum resistance to rain penetration and other aspects of performance, and good technique must not be sacrificed for speed. The use of good design and quality materials can not overcome excessively fast masonry construction.

Examples and Details

This section presents several examples of masonry construction with good thermal and air leakage performance, in some cases accompanied by examples of thermally defective designs. These examples involve the intersections between masonry walls and other envelope components, e.g., floors and windows. The connection between walls and roofs is covered in the section on Roofing Systems

The connection between walls and floors is a location that can be associated with discontinuities in the thermal insulation and air barrier system. Figure 4.2.12 shows an example of a thermal bridge at this intersection in which the concrete floor slab penetrates the wall insulation (Grot). The steel beam supporting the slab is insulated on the outside, but the beam still interrupts the insulation layer. Heat flux transducer measurements on these beams revealed that this insulation was not effective, if it was even installed. This detail also suffers from significant air leakage at the intersection of the floor and wall because there is no air seal at this location. This design, i.e., the floor slab penetrating the wall insulation, is a very common thermal bridge and appears in many design guidance documents without any acknowledgement of the thermal consequences.

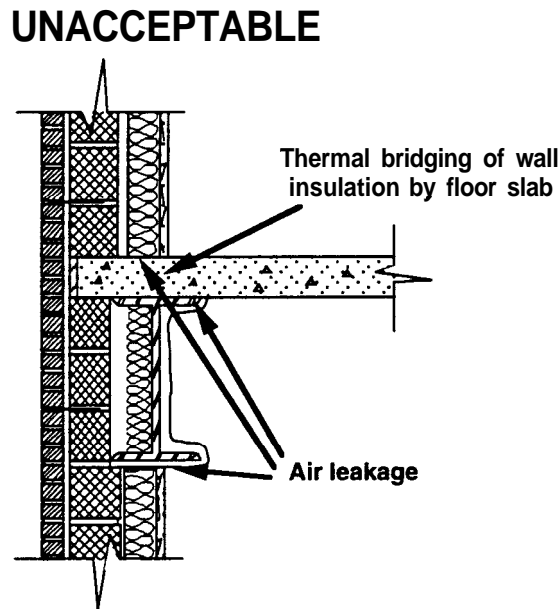


Figure 4.2.12 Wall-Floor Connection (Grot)

Figure 4.2.13 shows a typical floor/wall connection that suffers from thermal bridging and air leakage. In this design an insulated stud wall is located inside the masonry backup, and the studs act as thermal bridges through the insulation. There is no air barrier system in the wall to control air leakage. The slab bridges the wall insulation, and the shelf angles add to the heat loss effects. In addition, the “truss” type brick ties serve as an additional thermal bridge between the outside and the backup. An improved design is shown in Figure 4.2.14. Rigid insulation is added between the backup and the stud wall to reduce the thermal bridging from the studs. An air barrier is installed on the exterior side of the backup wall to control air leakage. “Pintel” type ties are used to reduce thermal bridging. The edge of the slab is insulated to reduce the thermal bridging effect of the slab, although discontinuities in the insulation system remain. Finally, high density plastic shims are used at the shelf angles to reduce the thermal bridging at this location.

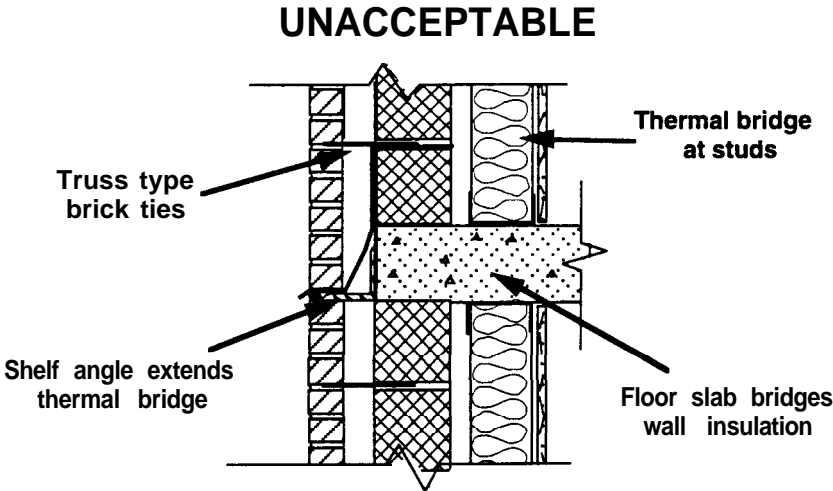


Figure 4.2.13 Wall/Floor Connection

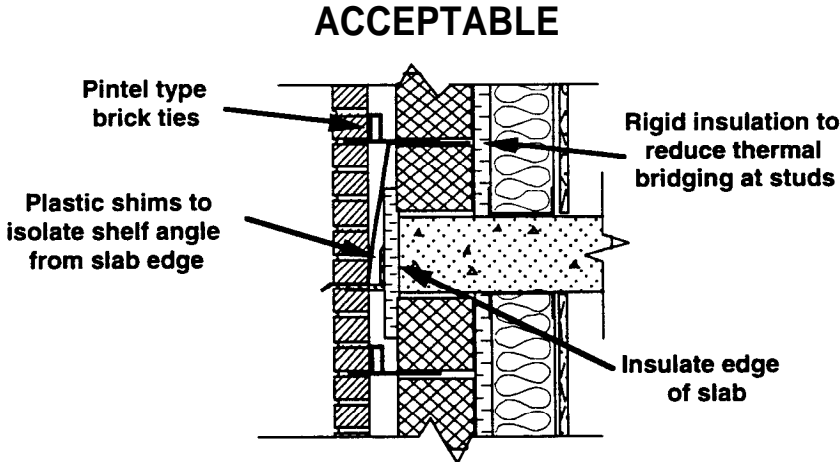


Figure 4.2.14 Wall/Floor Connection

A variety of thermally improved designs of floor/wall connections can be used to avoid the thermal bridging and the associated air leakage at this location. Additional alternatives are presented for concrete frame and steel frame buildings in Figures 4.2.15 and 4.2.16 respectively (Brand and Turenne). In both cases the insulation is positioned in the cavity to provide a continuous layer wall insulation with no thermal bridging by the floor slab. In addition, an air barrier is included in the wall to control air leakage. In the case of the concrete frame, the seal at the bottom of the floor slab and the masonry must be flexible to accommodate movement, and sufficient clearance must be provided at this location. In the steel frame case, the air barrier across the spandrel beam is supported by gypsum board on metal studs. The connection of the air barrier at the bottom of the beam must be flexible to accommodate movement, and sufficient space must be provided below the beam for deflection. The beam can also be set back from the backup wall, in which case the masonry is carried up to the floor slab. In this case the air barrier is installed similarly to the concrete frame case.

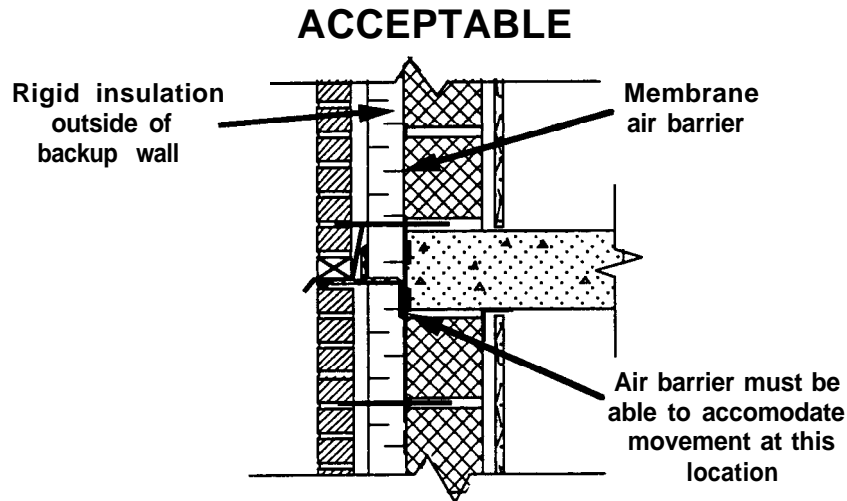


Figure 4.2.15 Wall/Floor Connection - Concrete Frame (Brand)

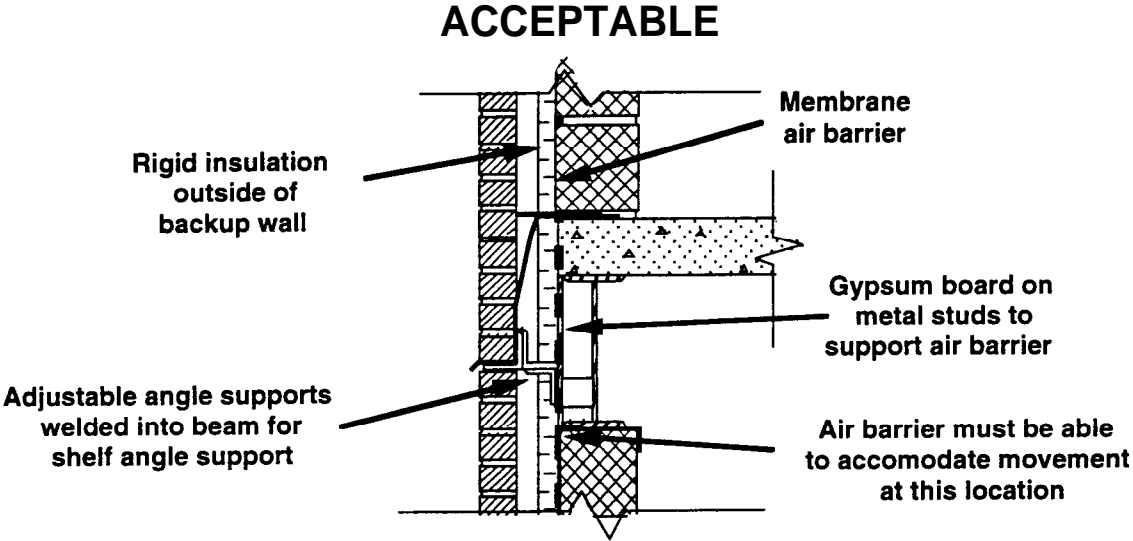


Figure 4.2.16 Wall/Floor Connection - Steel Frame (Brand)

The thermally defective design in Figure 4.2.11 pointed out the need to maintain continuity of the air barrier and insulation systems at window/wall intersections. Figure 4.2.17 shows an acceptable connection between the wall and the window head (Brand). The flashing above the windows is essential to control water leakage, and it must be straightforward to install to get good performance. The flashing is carried behind the insulation and sealed to the flexible membrane air barrier. In order to keep the frame close to the indoor temperature, it is positioned interior of the insulation. The wall air barrier is sealed to the window frame to maintain continuity. Compressible foam insulation is used to keep the air barrier warm between the wall insulation and the window frame.

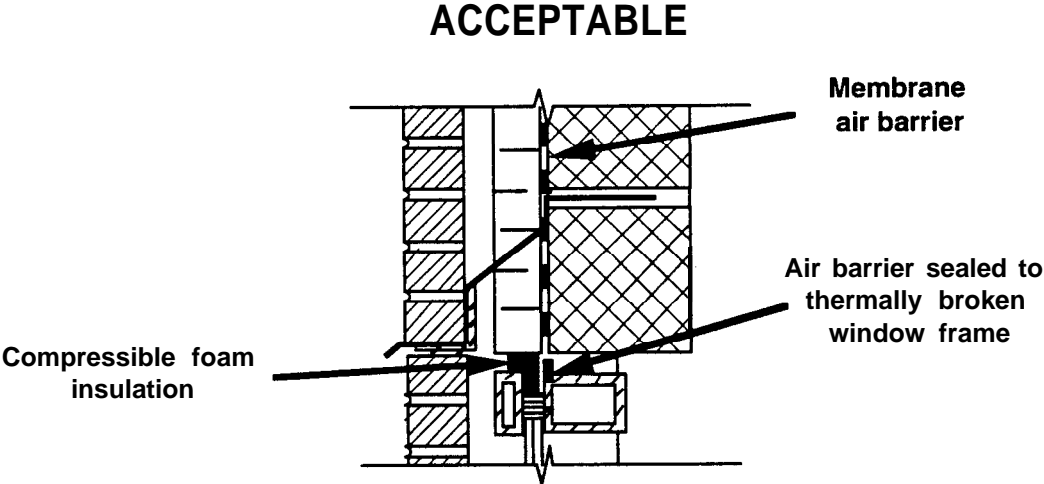


Figure 4.2.17 Wall/Window Head Connection (Brand)

Figure 4.2.18 shows a typical window jamb connection that suffers from thermal bridging and air leakage. This wall contains an insulated stud wall inside of the masonry backup and has no air barrier system. The cavity behind the veneer connects directly to the insulated stud space. Thermal bridging occurs at the studs, the “truss” type brick ties and the window frame. An improved design is shown in Figure 4.2.19. Rigid insulation is installed between the stud wall and the backup, and this insulation is carried to the window frame thermal break. Compressible gasketing is installed within the cavity to stop air movement from the cavity to the window frame. Also, “pintel” type brick ties are used to reduce thermal bridging across the cavity.

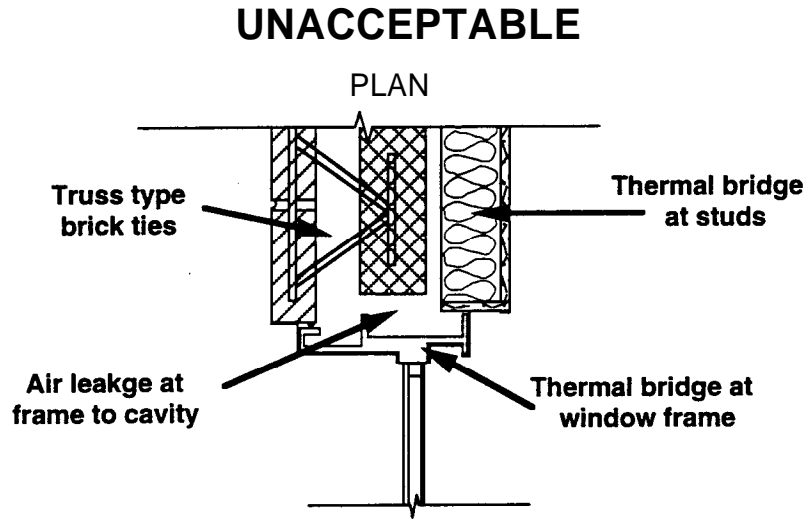


Figure 4.2.18 Wall/Window Jamb

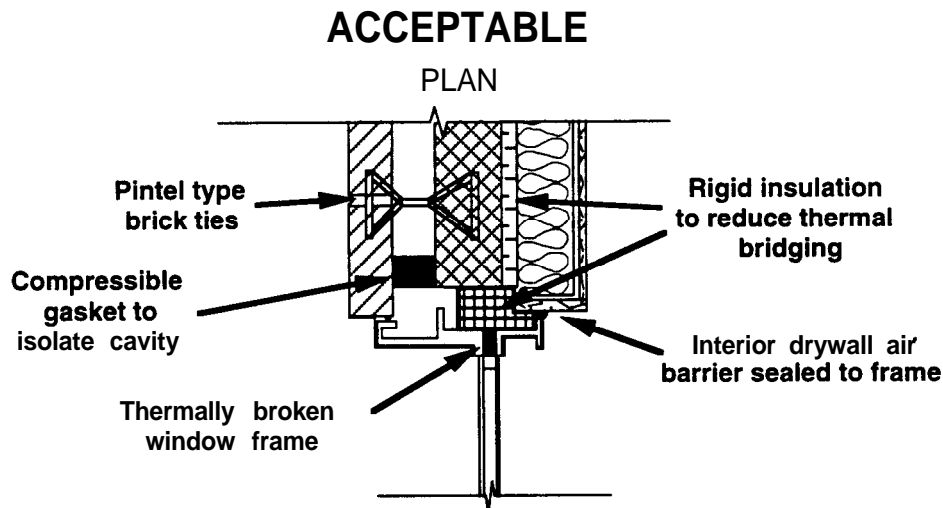


Figure 4.2.19 Wall/Window Jamb

Figure 4.2.20 shows another window jamb/wall connection (Brand and Turenne). In this detail the window thermal break is in line with the wall insulation. To maintain continuity of the insulation system, compressible foam insulation is applied behind the return bricks. This insulation also keeps the air barrier above the dewpoint temperature under heating conditions. This insulation must be held very close to the barrier to be effective.

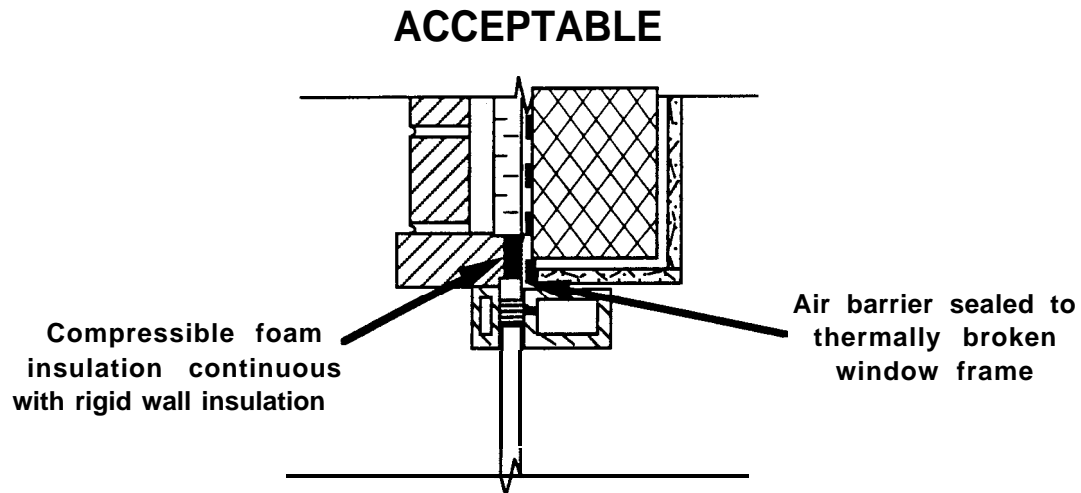


Figure 4.2.20 Wall / Window Jamb (Brand)

Many commercial buildings have fan coil units or convector cabinets installed wall-to-wall beneath the windows. In many designs these metal enclosures act as significant thermal bridges through the wall. While the concrete masonry behind the cabinet need not be finished, continuity of the air barrier and insulation systems must be maintained in these areas. In addition, it is important that the space behind the enclosure does not communicate with the room below through pipe chases and conduits. Such airflow paths increase stack pressures and compromise attempts for smoke control. Figure 4.2.21 shows a window sill with a convector cabinet. In this design thermal bridging occurs through the cabinet and the anchor clips. Air leakage occurs at gaps in the interior finish and continues into the cavity behind the brick veneer. Figure 4.2.22 shows a thermally improved design in which an air barrier is installed on the outer face of the backup wall and is sealed to the window frame by compressible foam. Rigid insulation is installed between the stud wall and the masonry backup. An improved arrangement is used to fix the cabinet in place, ending the direct metal connection from the interior to the outside.

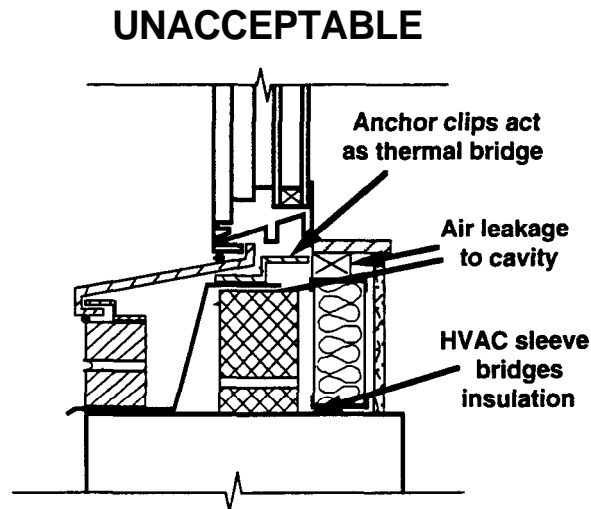


Figure 4.2.21 Wall/Window Sill Connection

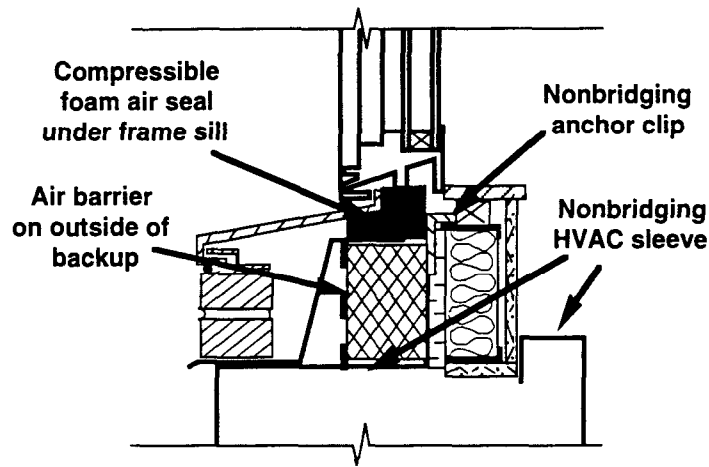
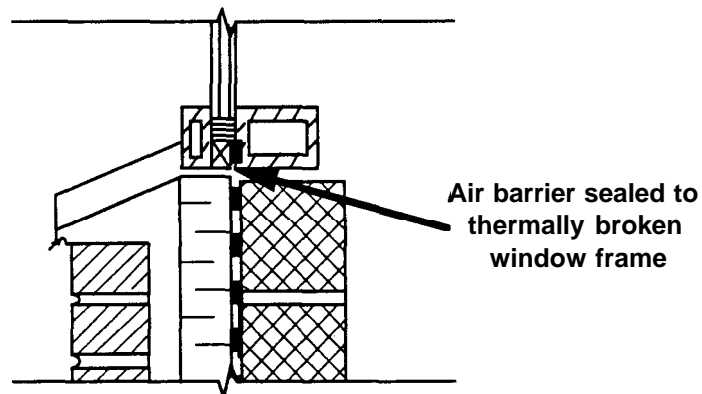
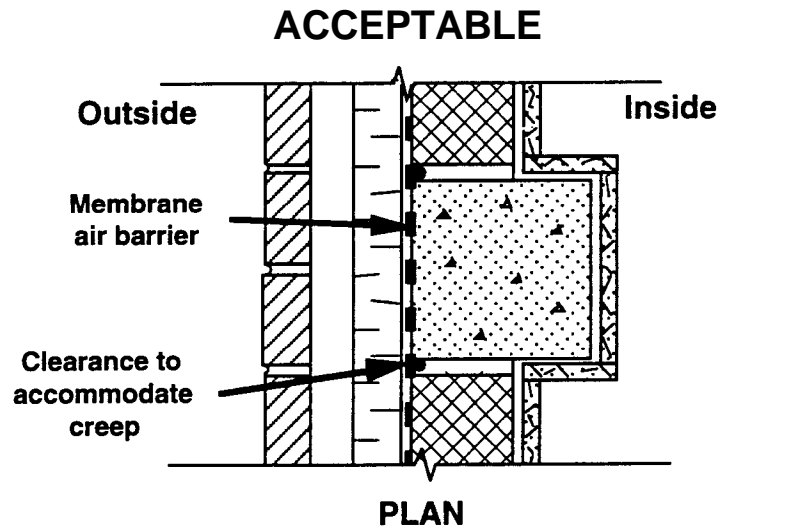
ACCEPTABLE**Figure 4.2.22 Wall/Window Sill Connection**

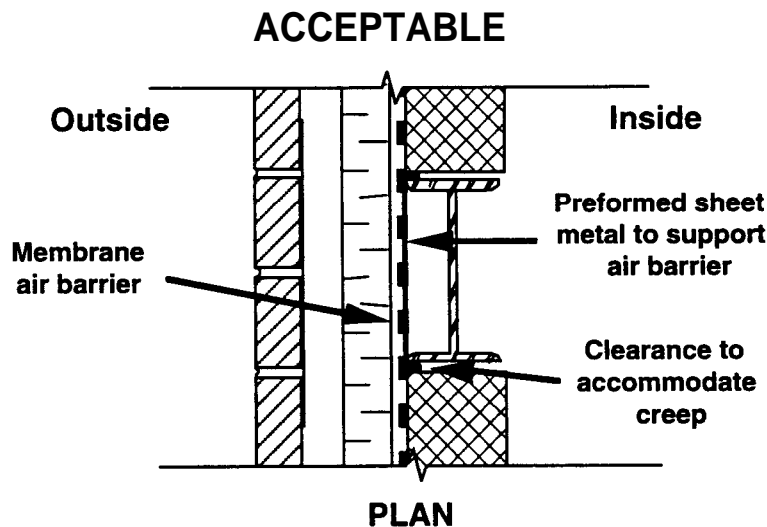
Figure 4.2.23 shows the connection between the window sill and the wall (Brand). It is similar to the window head connection shown in Figure 4.2.17.

ACCEPTABLE**Figure 4.2.23 Wall / Window Sill (Brand)**

Figures 4.2.24 and 4.2.25 show the intersection of a Structural column with the wall construction for concrete and steel frame buildings respectively (Burn 1980). In both cases, the columns are in the plane of the backup wall. The air barrier must be flexible in order to accommodate differential movement between the column and the wall. A flexible membrane air barrier will perform well. In the case of the steel column, a piece of sheet steel bridges the outer flanges of the column, providing a structurally sound support for the air barrier. The columns can be set back from the backup wall, reducing floor space by a small amount. Setting back the column can simplify the design in the steel frame case, where the detail shown in Figure 4.2.25 requires an additional trade to install the sheet metal support for the air barrier.



**Figure 4.2.24 Wall/Column Connection -
Concrete Frame (Burn 1980)**



**Figure 4.2.25 Wall/Column Connection -
Steel Frame (Burn 1980)**

The connection of a masonry wall and a concrete foundation is shown in Figure 4.2.26 (Brand). In this detail, the outer face of the backup wall and the outer face of the foundation wall are in the same plane and support the air barrier. The insulation below the termination of the brick veneer must be protected, for example with a cement coating.

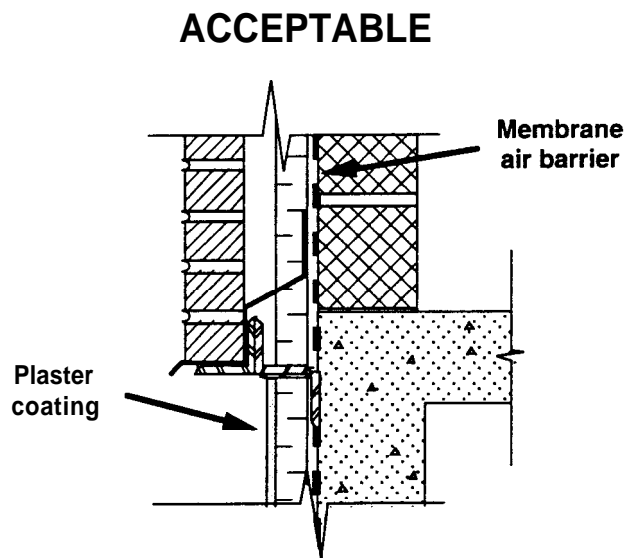


Figure 4.2.26 Wall / Foundation Connection (Brand)

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4.3 METAL STUD WALLS

Metal stud infill walls are used with a variety of exterior claddings including brick veneer, EIFS (see Section on EIFS), stucco, metal siding and other lightweight exterior finishes. Figure 4.3.1 shows the basic elements of a metal stud wall with a brick veneer. There are several advantages to metal stud walls including speed of erection and low weight. Their use with brick veneers is a relatively recent development and has been associated with a certain amount of controversy as discussed below. There is limited guidance on metal stud wall construction, relative to other wall systems. Some design guidance is provided in a 1981 *Design Guide for Insulated Buildings* (Owens/Corning Fiberglas), however the material in this document does not specifically address air leakage control through the use of air barrier systems. The Canada Mortgage and Housing Corporation (CMHC) Seminar on Brick Veneer Wall Systems (1989) provides a thorough treatment of brick veneer/metal stud construction, addressing advantages, disadvantages and making recommendations for the design and construction of such systems.

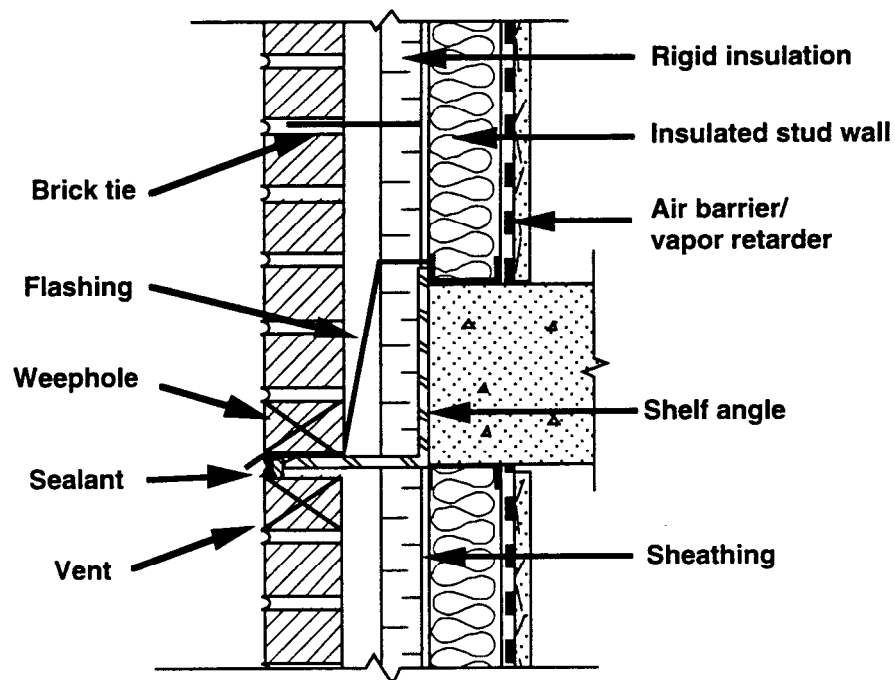


Figure 4.3.1 Metal Stud Wall Components (CMHC)

Thermal Insulation

While metal stud infill walls are relatively straightforward to insulate, the relatively high conductivity of the studs and the horizontal supporting channel results in severe thermal bridging. This thermal bridging at the studs degrades the overall thermal performance of the wall by about one-third and can lead to condensation on the interior surface of the wall during the heating season. Such thermal bridging also occurs at corners. In order to obtain good thermal insulation system performance in these systems, the thermal bridging of the design needs to be reduced. This can be done through the use of a layer of rigid insulation outside of the stud wall and the rearrangement of the metal studs themselves. Also, when the stud spaces are insulated with friction-fit batts of fibrous insulation, the entire space must be filled with insulation to prevent convection within the space. Special attention must be given during installation to fill all spaces with insulation, including corners.

Figure 4.3.2 shows a thermal bridge at a metal stud corner and an alternate nonbridging design (Steven Winter Associates). In this detail, the two studs in the corner constitute a significant thermal bridge, made worse by the fact the the corner space is uninsulated. The alternative design eliminates one of the studs and fills the corner with insulation. A steel clip is attached to one of the corner studs for the attachment of the interior finish.

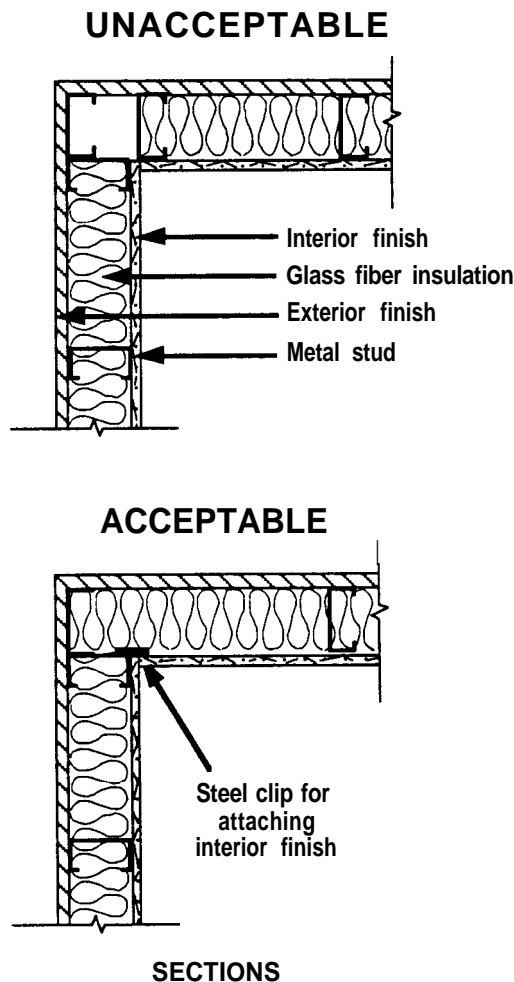


Figure 4.3.2 Metal Stud Corners (Steven Winter Associates)

Another location associated with thermal bridging is the intersection of the floor slab and the wall. Figure 4.3.3 shows such a bridge in a metal stud wall with a lightweight exterior finish and a steel frame (Steven Winter Associates). In the alternative design the slab and beam are moved back so that the insulation is continuous across the floor slab. A fire stop must be provided at the slab edge.

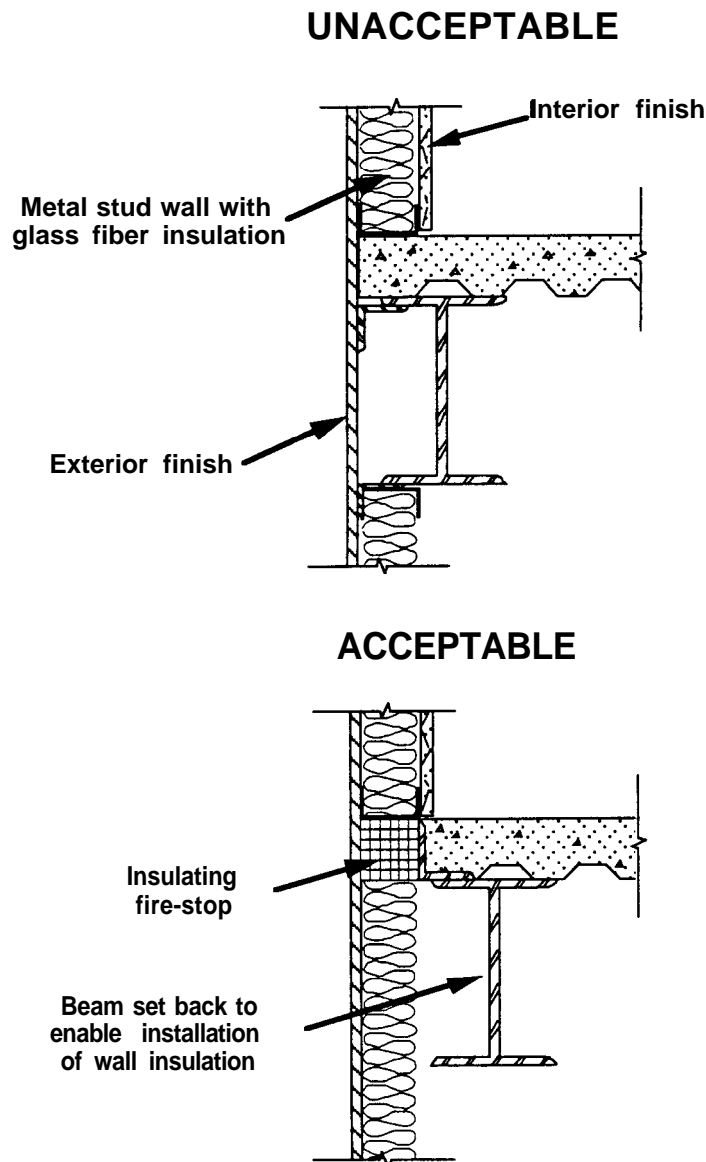


Figure 4.3.3 Slab Edge / Perimeter Beam (Steven Winter Associates)

Air Barriers and Vapor Retarders

An air barrier system is required in metal stud infill walls to control air leakage. The air barrier can be located on either side on the studs. If the air barrier is located on the inside of the studs, e.g., the interior gypsum is the air barrier, the air barrier must be sealed to the floor slab, windows and other penetrations to maintain continuity. This approach has several advantages including that the air barrier is kept at a relatively constant temperature and is therefore less susceptible to opening of cracks and degradation of sealants due to temperature cycling. An interior air barrier is also easier to inspect and repair during construction. However, an interior air barrier is more susceptible to puncture during the installation of services in the wall. An air barrier located outside of the studs will be protected from such construction activities and can be carried continuously over the floor slab. On the down side, long term maintenance and repair of an exterior air barrier is almost impossible. Therefore, high quality materials and construction must be employed. Unless an additional layer of insulation is included outside of the air barrier, the air barrier material will be outside of the insulation and subjected to outdoor temperature cycling. The positioning and water vapor permeability of an outer air barrier must be considered with reference to the whole wall's water vapor transmission characteristics.

The vapor retarder location must be based on consideration of the climate and the total wall design, as it needs to be kept relatively warm to control condensation. In heating climates the vapor retarder needs to be inside of most of the insulation, and an interior air barrier can also serve as the vapor retarder. If an outside air barrier is used, it must be sufficiently permeable to water vapor so as not to constitute a second vapor retarder. In cooling climates, the vapor retarder needs to be located outside of most of the insulation and can be readily combined with the air barrier system. Care needs to be exercised in cooling climates when using low permeability interior finishes, since these surfaces will be cold and will act as vapor retarders. A much lower permeability vapor retarder needs to be used outside of the insulation, and air leakage must be controlled on the warm side of the insulation.

Wall details that depict the installation of a continuous air barrier system for brick veneer systems are shown in the following section. Many of these concepts can be applied to metal stud walls with other exterior finishes.

Brick Veneer Systems

As mentioned above, brick veneer/ metal stud wall systems have been the subject of some controversy concerning their structural performance. The questions have centered around the relatively flexible stud wall backup as compared with systems employing more traditional masonry backup. If the stud wall deflections are too large, the brick veneer can crack. Some have pointed out that making the stud wall backup sufficiently rigid to avoid this problem can make the system less economical. The corrosion of metal fasteners and brick ties is another concern with these systems.

While there was once much discussion regarding the applicability of brick veneer/metal stud systems, the issue is much less controversial today. BIA Technical Note 28B contains a thorough discussion of these systems. The CMHC Seminar on Brick Veneer Wall Systems also discusses brick veneer/metal stud systems and presents the results of a survey conducted in Canada to determine the state-of-the-art regarding their design, construction and performance. In addition to the concerns mentioned above, the survey also revealed concerns with the installation of air barrier systems and vapor retarders in these walls and the adequacy of inspection practices.

It is revealing to compare the respective advantages and disadvantages of metal stud backup to masonry backup in brick veneer walls, as identified in the CMHC report. Masonry backup offers the advantages of a well-established track record of good performance, stiffness to lateral loads, a continuous surface for the application of insulation, air barriers and vapor retarders, and no problems of corrosion. The disadvantages include having a large self-weight that impacts the structural requirements, construction being more dependent on weather conditions, complex installation of services in the wall, and the system stiffness complicating the accommodation of movement of structural frame. The advantages of a metal stud backup include a low self-weight that requires lighter structural framing, rapid erection that is relatively independent of weather, ease in accommodating electrical services in the wall, and ease in installing insulation in the wall. The disadvantages of metal stud backup include the lack of long term performance history, the low stiffness of the stud wall, and the susceptibility to corrosion of the metal components.

A brick veneer/metal stud system places the same requirements on the brick veneer that were discussed in the section on Masonry, including high quality and compatible masonry materials, mortar joints that provide a good barrier to rain penetration, flashing that is securely and continuously attached to the backup, and good drainage behind the veneer through the cavity and open weepholes.

Quirouette developed a series of design details for brick veneer/metal stud walls for cold climates, in which the air barrier is generally applied outside of the studs but on the warm side of an outer layer of rigid insulation. This allows the stud wall to be used as a space for the installation of electrical and other services. Figure 4.3.4 shows a wall/foundation connection where the air barrier is located between the stud wall and a layer of rigid insulation. The air barrier is applied to the outside of the stud wall and a flexible connection is used at the interface of the wall and the foundation. Locating the air barrier outside of the stud wall allows services to be installed in the wall without having to worry about the air barrier.

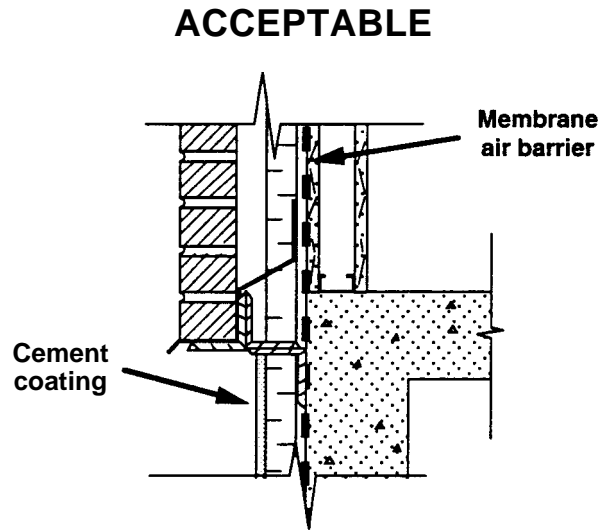


Figure 4.3.4 Metal Stud Wall / Foundation Connection (Quirouette)

The intersection of the stud wall and the floor slab is shown in Figure 4.3.5. The outer gypsum board is carried over the floor slab to provide a continuous surface for the installation of the air barrier. The vertical studs are shortened to accommodate deflection of the floor slab, preventing damage to the interior gypsum.

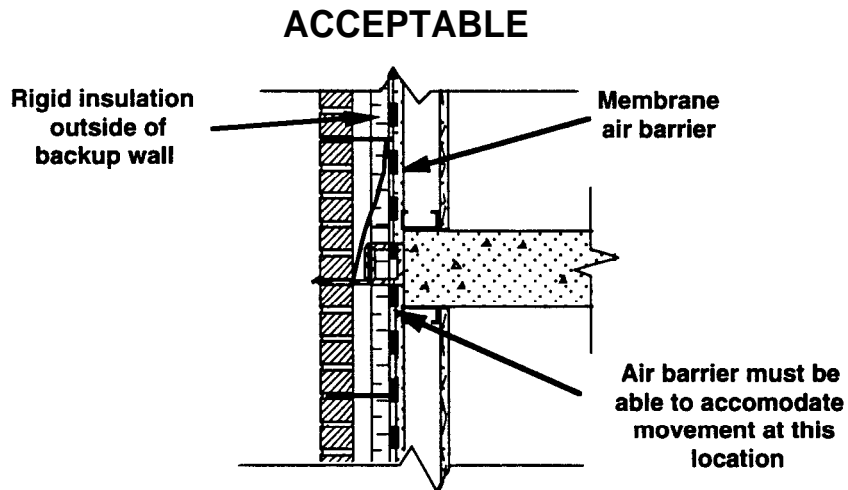


Figure 4.3.5 Metal Stud Wall / Floor Connection (Quirouette)

Figure 4.3.6 also shows a wall/floor intersection. In this case the interior gypsum serves as the air barrier. A flexible mastic is used to seal the connection between the gypsum and the floor slab.

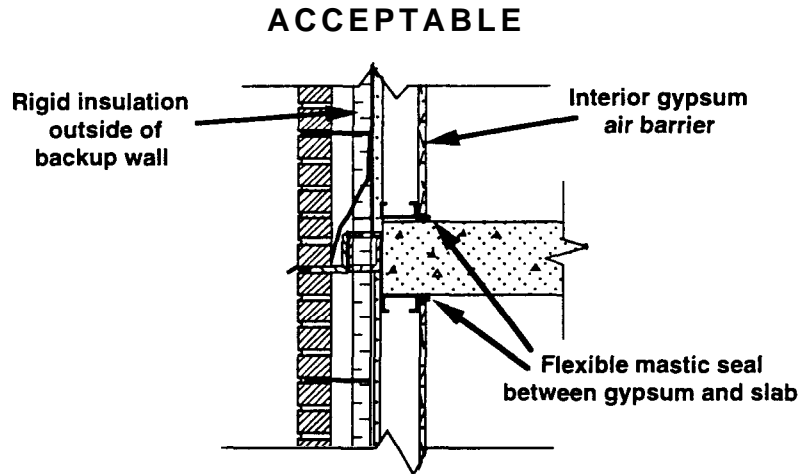


Figure 4.3.6 Metal Stud Wall / Floor Connection (Quirouette)

In steel frame structures, the exterior gypsum can serve as the air barrier in which case it must be extended over the structural members. Studs should be shortened and connections designed to account for deflection of the structural members and floor slabs. Flexible membranes are required to maintain air barrier continuity at locations where movement will occur. Figure 4.3.7 shows a wall/ floor and window head and sill connection in a stud wall with a steel frame. Flashing is required at the sill to keep water out of the cavity and at the window head to keep water clear of the window.

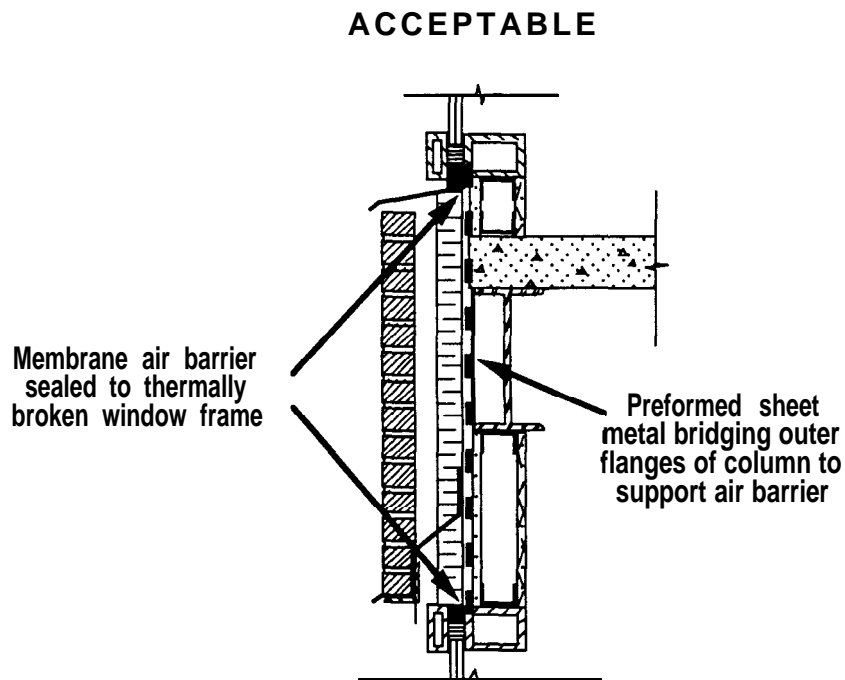


Figure 4.3.7 Metal Stud Wall / Floor Connection and Window Head and Sill (Quirouette)

Figure 4.3.8 shows a section of the intersection between a wall and a steel column. The exterior gypsum serves as the wall air barrier. At the window, a flexible membrane brings the air barrier inside to the window frame.

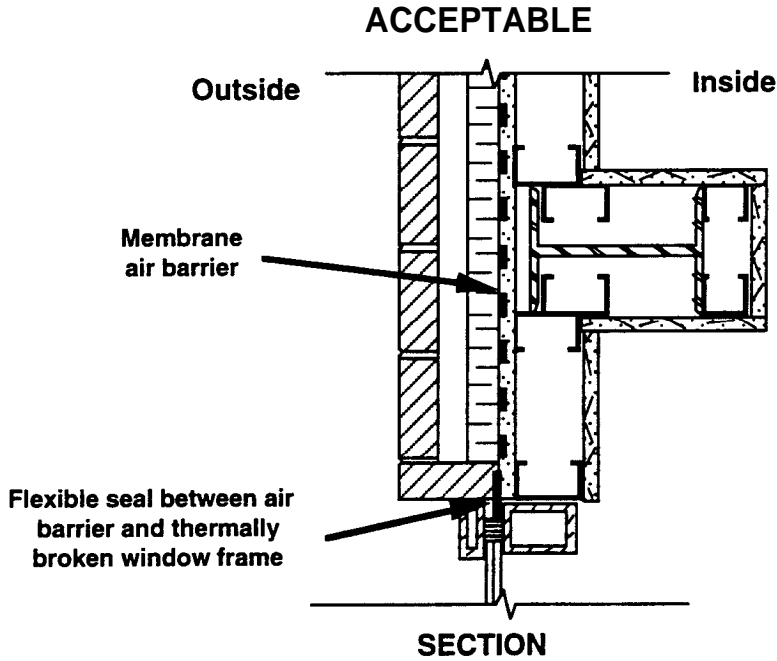


Figure 4.3.8 Metal Stud Wall / Steel Column Connection and Window Jamb (Quirouette)

Figure 4.3.9 shows a wall/roof junction, again in a steel frame building. The exterior gypsum serves as the air barrier, running past the spandrel beam. Flexible membranes are used to seal the air barrier at the top of the stud wall. The wall air barrier is also sealed to the roof membrane to prevent leakage at this point.

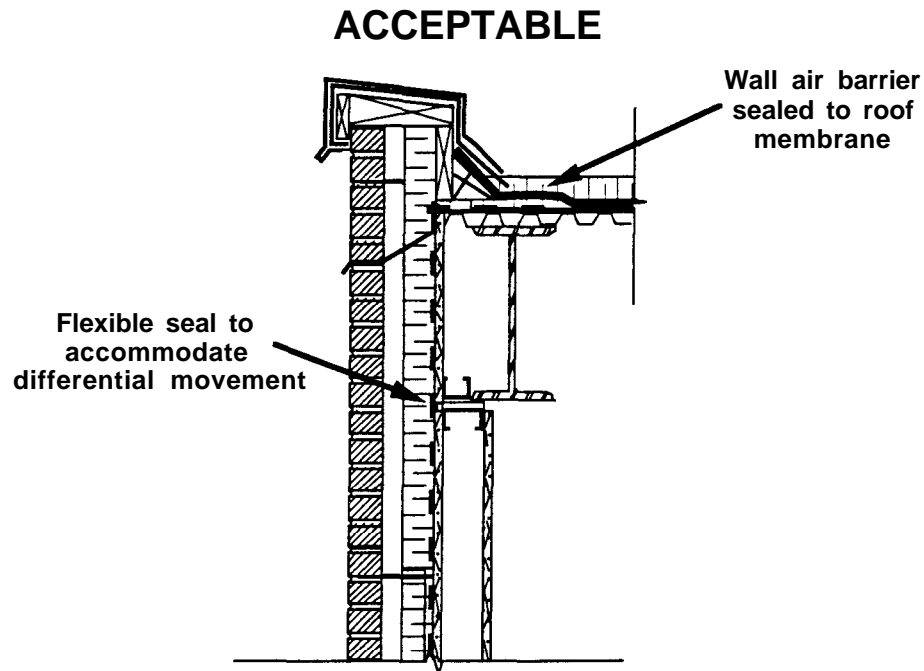


Figure 4.3.9 Metal Stud Wall / Flat Roof Edge (Quirouette)

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4.4 PRECAST CONCRETE PANELS

Precast concrete panel walls are composed of factory-made concrete panels erected on a structural frame of steel or cast-in-place concrete. Additional elements are installed inside of, and perhaps within, the panels to fulfill other building envelope requirements. Figure 4.4.1 shows the basic elements of a precast concrete panel wall. In so-called conventional systems, the panels constitute a single-wythe facade and the inner wall contains thermal insulation, an air barrier, a vapor retarder and other elements. In precast sandwich panel walls, the precast unit contains the insulation, vapor retarder and air barrier. The sandwich panels are then erected on the structural frame, the panel joints are sealed, and the interior finish is applied. Precast concrete panel walls can be either load-bearing or nonload-bearing.

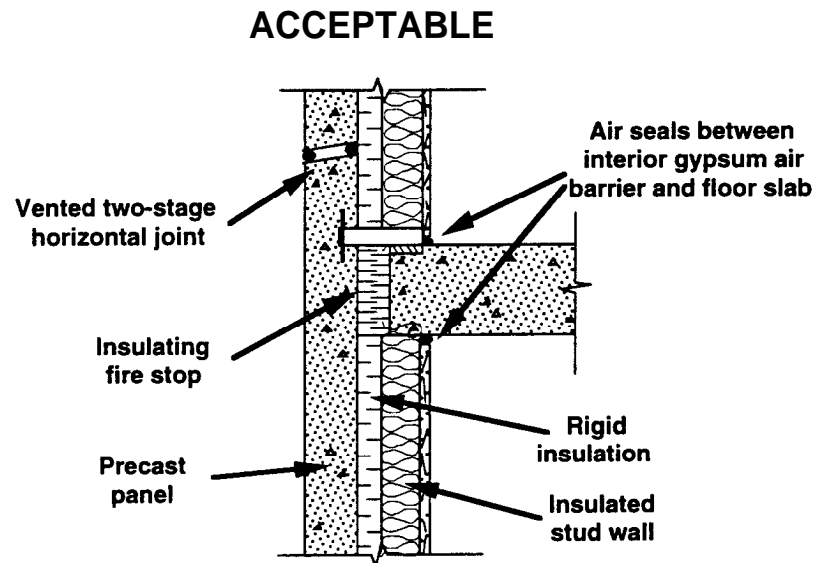


Figure 4.4.1 Precast Panel Wall (PCI)

Precast concrete panel walls offer several advantages including great flexibility of form, color and texture. The functional advantages of precast concrete include good crack control, fire resistance, durability, low maintenance, and airtightness of the panels themselves. The on-site erection of these units is also relatively fast and less influenced by weather conditions than other systems. These advantages, along with the basics of precast panel wall design, are discussed in the PCI Design Handbook, Architectural Precast Concrete also published by PCI, and Freedman.

As with other walls systems, the key to achieving good thermal and airtightness performance in precast concrete panel walls is maintaining the continuity of the thermal insulation and air barrier systems. Other related performance issues in precast systems include the control of water leakage, weathering and condensation. Because the panels themselves are airtight and watertight, many aspects of their thermal performance are determined by the joints between the panels rather than by the panels themselves. Rain penetration can be a problem at the panel joints and at window penetrations. Air leakage through panel joints can lead to condensation within the wall, increasing the potential for corrosion of metal panel supports. Thermal bridges occur both at panel joints and at the panel supports.

Design Fundamentals

Guidance on the design and construction of precast concrete panel walls is provided in the publications of the Precast/Prestressed Concrete Institute (PCI). These publications cover issues of material properties, structural design, surface aesthetics, rain penetration, rainwater runoff control, joint design, and thermal, acoustical and fire considerations. A recent article by Freedman also contains general design and performance information.

Most precast concrete panel wall design considerations are structural, focusing on the design of the panels and their attachment to the structural frame. These structural connections are critical design elements, associated with several nonstructural issues. The metal connectors must be protected from the elements in order to avoid corrosion. They must also be able to accommodate differential movement between the panels and the frame, and must not be allowed to compromise the continuity of the air barrier and thermal insulation systems. Some thermal bridging at panel supports is inevitable, but it should be minimized.

Another structural issue of concern regards the provision of adequate clearance between panels to accommodate differential movement. When clearance is insufficient, loads can be transferred to the panels that are beyond their design capacity. This can lead to joint sealant failure, panel displacement, cracking or more severe failures.

Rain Penetration and Joint Design

Because uncracked precast concrete panels are watertight, panel joints and other penetrations are the prime points for the control of water leakage. The design of panel joints are discussed in Architectural Precast Concrete (PCI) and by Rousseau . The PCI manual contains a thorough presentation of joint design including many details and discussions of practical considerations in design and construction.

As discussed in the section on Principles/Rain Penetration Control, there are four mechanisms for rain penetration: capillary action, gravity flow, kinetic energy and air transport. Capillary action can be controlled by designing a large gap into the joint, and by using drips and grooves. Gravity-driven water leakage is controlled by sloping the joint to the outside. Water leakage due to kinetic energy refers to water droplets being driven into the joint by wind, and it can be controlled by designing a deflector into the joint. Air pressure across the joint will also induce water flow into and across the joint, and this mechanism can be controlled by either sealing the joint or controlling the pressure difference. The basic options to joint design for leakage control include face sealing or one-stage joints, two-stage joints and the pressure-equalized rain screen approach. The first two options attempt to seal the joint to airflow, while the third approach attempts to eliminate the air pressure difference across the joint.

The face seal approach employs a single line of defense against rain penetration and air leakage by employing a field-installed elastomeric joint sealant (see section Design/Sealants). A simple one-stage joint is shown in Figure 4.4.2. This is the lowest initial cost option and can perform well for several years, given good joint design, good sealant materials, and careful installation. However, the sealant is fully exposed to the degrading effects of sunlight, ultraviolet radiation, water and temperature cycling, increasing the material requirements on the sealant. Over time the performance of these sealants will decrease, increasing maintenance costs. Also, any defect in the sealant, even a small gap, will lead to water and air leakage.

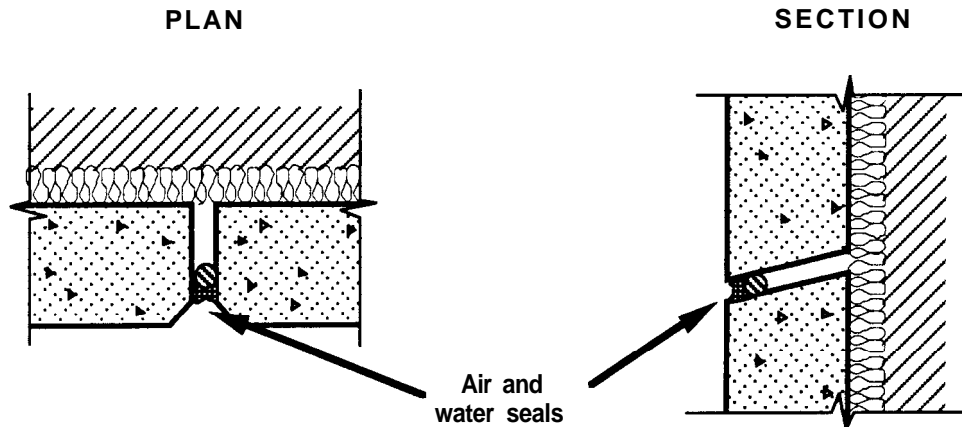


Figure 4.4.2 Precast Concrete Panel - One-Stage Joints (Rousseau)

Two-stage joints employ an outer seal to control water leakage and an inner seal for airtightness, as shown in Figure 4.4.3. Any rainwater that does penetrate the rain barrier drains to the outside well before it is able to reach the air seal. The inner air seal is now in a less severe environment, being protected from water and ultraviolet radiation, placing less severe requirements on the sealant material.

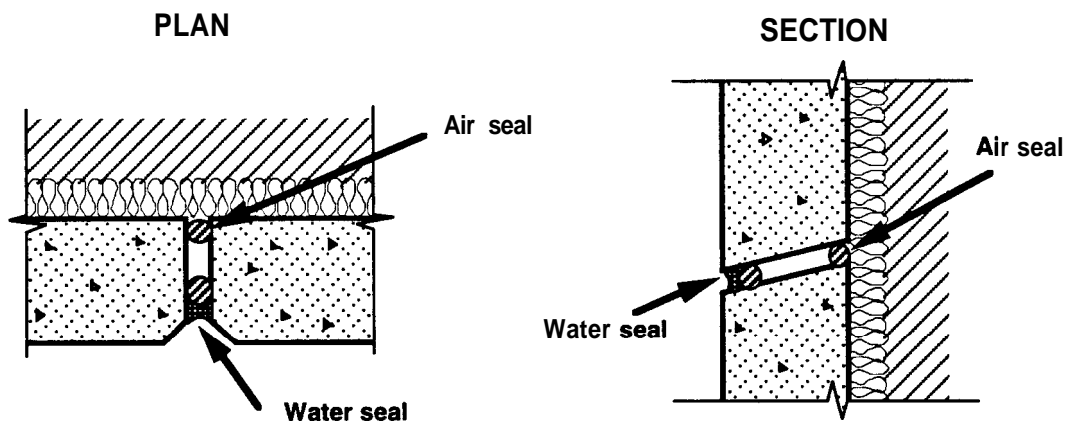
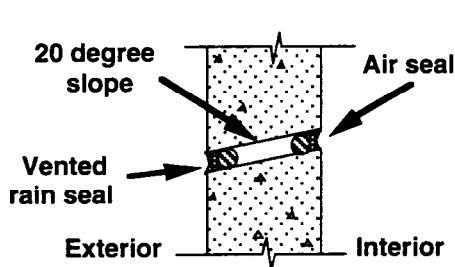
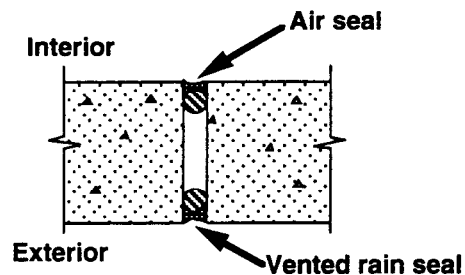


Figure 4.4.3 Precast Concrete Panel - Two-Stage Joints (Rousseau)

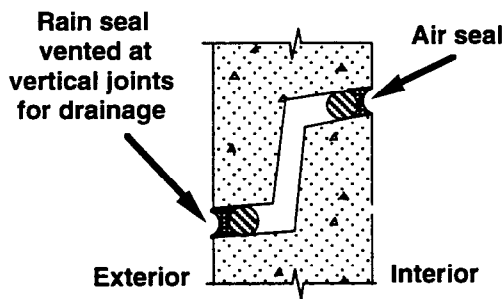
The two-stage joint approach can be used in a pressure-equalized rain screen joint design to further improve performance. In this approach, vents are purposely provided in the rain seal and a pressure equalization chamber is provided between the rain and air seals. The vents and the chamber provide for rapid equalization of the outdoor air pressure and the chamber air pressure, reducing the pressure-driven flow of water past the rain seal. Figure 4.4.4 shows two-stage, pressure-equalized joints from Architectural Precast Concrete (PCI). For this joint system to work it is important that any water that does penetrate the rain seal is drained to the outdoors and that good air-tightness is achieved at the air seal. The higher initial cost of this approach as compared to the face seal approach are balanced by the lower maintenance costs and better performance. Achieving the desired performance requires careful design and construction, including intensive supervision of the work since inspection of the completed installation is difficult. The most common construction errors in this approach are not sealing the air seal completely and making the rain seal airtight.



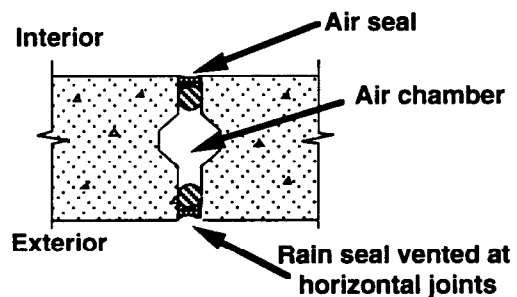
Section of Horizontal Joint



Plan of Vertical Joint



Section of Horizontal Joint



Plan of Vertical Joint

Figure 4.4.4 Precast Concrete Panel - Two-Stage Pressure Equalized Joints (PCI)

The pressure-equalized rain screen approach can also be applied to the whole wall system by incorporating a cavity behind the precast panel. Vents equalize the cavity pressure to the outdoor pressure, decreasing the pressure-driven rain penetration of the cavity. An air barrier within the wall is essential to achieving pressure equalization. Ideally this air barrier is located behind the insulation, protecting the air barrier and associated seals from outdoor temperature swings. The cavity must be well drained to the outside in order to remove any water that does penetrate. This design approach is discussed further in the section Air Leakage and Water Vapor Control.

Along with the control of water leakage into and through the envelope, the flow of water over the precast facade is important. Changes in facade appearance over time caused by dirt and pollutants in surface runoff water, so-called weathering, does not impact thermal and air-tightness performance. However, controlling runoff is important to lessen the demands on water leakage control elements and is another design factor to consider in joint design. Architectural Precast Concrete (PCI) contains a very thorough discussion of weathering and its control through the use of water drips to prevent water from running over the entire height of the building.

Thermal Insulation

There are several approaches to insulating precast panel walls, with the key to good performance being continuity of the insulation system over the entire envelope. Insulation may be part of a backup wall within the panel facade (such as an insulated stud wall), attached directly to the back of the panels, or incorporated into the panel itself, a so-called sandwich panel. Insulation in an inner stud wall results in thermal bridging at the floor slabs, as shown in Figure 4.4.5. Air leakage can also be a problem at this intersection. Figure 4.4.6 shows an alternative design to eliminate this thermal bridge by adding a layer of rigid insulation between the precast panels and the studs.

UNACCEPTABLE

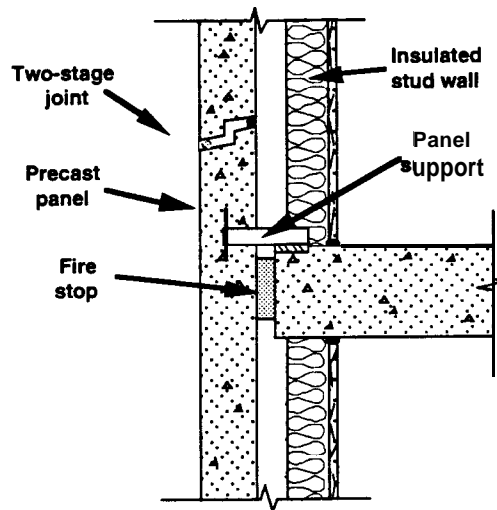


Figure 4.4.5 Conventional Precast Panel Wall

ACCEPTABLE

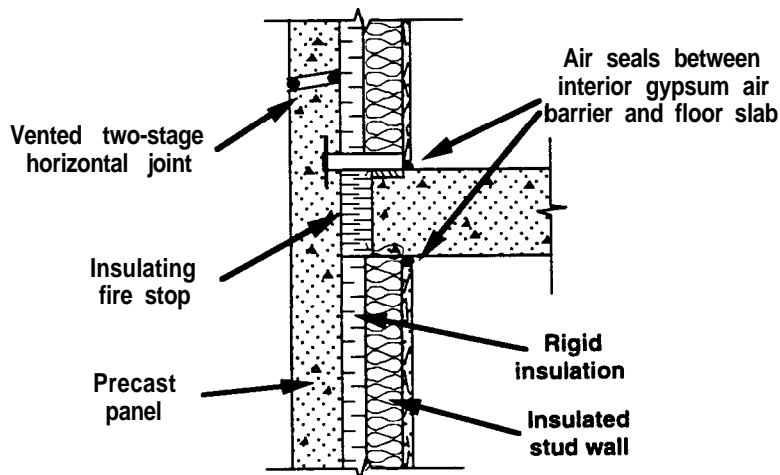


Figure 4.4.6 Precast Wall with Rigid Insulation (PCI)

Rigid insulation can be installed on the back of precast panels using adhesives or a variety of mechanical attachment systems. If an adhesive is used, it must be compatible with the insulation material. The adhesive should not be applied in daubs as shown in Figure 4.4.7, from Architectural Precast Concrete (PCI). Using daubs of adhesive creates air gaps behind the insulation, which in turn lead to airflow behind and around the insulation. Besides decreasing the thermal effectiveness of the insulation, such airflows can also lead to condensation on the back of the panel. A grid of adhesive beads is an improved method of application, while a full bed of adhesive provides the best performance. A full bed will act as a vapor retarder, and its water vapor permeance must be analyzed with reference to the entire wall system. If a vapor retarder is unacceptable at this location, a grid of adhesive may be used instead.

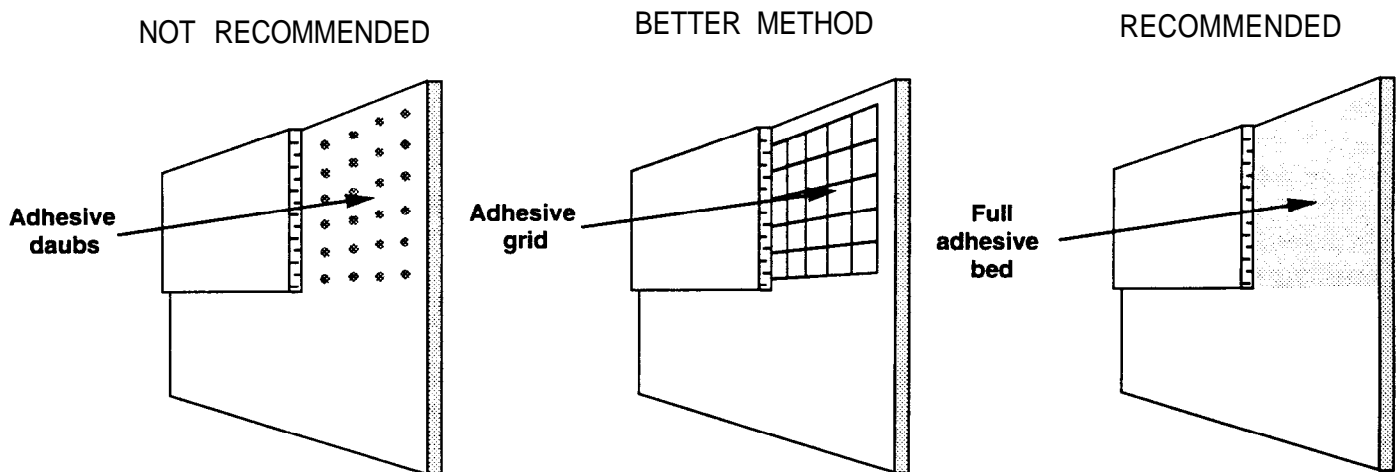


Figure 4.4.7 Application of Rigid Insulation with Adhesives (PCI)

A variety of mechanical means exist for attaching insulation onto panels including stick clips and furring systems. In all cases, it is important that the insulation is attached tightly to the precast concrete with no air spaces between the two elements. Such air spaces will decrease the insulation performance. Rigid fibrous insulation boards have been recommended because they are sufficiently flexible to conform to irregularities in precast panel surfaces.

Precast concrete sandwich panels incorporate the thermal insulation within the concrete panel, between two wythes of concrete. The interior finish system can also be incorporated directly onto the factory-made panel. As discussed in Architectural Precast Concrete (PCI) and in Sauter, this approach can improve the thermal performance of the wall by enabling good insulation system continuity. In order to achieve this continuity in a sandwich panel, the use of concrete webbing and framing within the panel must be reduced. Further improvements can be obtained by using nonconductive ties between the two wythes of concrete, e.g. composite materials. The references contain a great deal of information on sandwich panel walls, including their attachment and the design of ties. The performance of the whole wall system is determined in large part by the design and performance of the panel joints in terms of water and airtightness. These joints must be designed in conjunction with the panels and the air barrier system. Sauter contains a series of precast sandwich panel details that show how insulation system continuity is maintained with this system. However, these details do not explicitly address air leakage control.

Air Leakage and Water Vapor Control

As mentioned earlier, uncracked precast concrete panels are airtight and have a high resistance to water vapor transmission. However, they alone do not constitute an effective air barrier system or an appropriate vapor retarder. A continuous air barrier system must be specifically designed into the wall, with its location based on rational design principles. Similarly, a vapor retarder should be included at an appropriate location within the wall based on the climate and the total wall design. Architectural Precast Concrete (PCI) contains a thorough discussion of condensation control and air barriers. This manual states that both an air barrier and a vapor retarder are needed, pointing out that a single system can sometimes perform both functions.

In heating climates condensation problems arise when interior moisture is allowed to reach cold, outer elements in the building envelope. Such condensation can cause discoloration and damage to the precast panels, corrode metal panel supports and wet and degrade thermal insulation. In cooling climates, moisture from outside will condense on cold elements within the wall, causing similar problems and potentially damaging interior finish materials. A vapor retarder will slow the transport of this water vapor due to diffusion, but a much larger amount of water vapor can move due to air leakage. An air barrier is needed to prevent this means of air and water vapor transport. The performance requirements and design issues regarding vapor retarders and air barriers are discussed in the sections Principles/Air Barriers and Principles /Vapor Retarders. Of particular importance is the relative positioning of these elements and the thermal insulation within the envelope. In general, it is important to keep both elements on the warm side of the insulation.

With regard to precast panel walls, there are several options for controlling air and water vapor transport. The face seal approach was discussed above in the section on water leakage. In this approach the air barrier is in the facade of the building, placing the air seal material in a relatively harsh environment. In heating climates, one needs to control the transport of water vapor from the building interior to this cold air seal in order to reduce condensation problems. A vapor retarder on the interior side of the insulation will help, but it will not prevent water vapor transport due to airflow. Because the precast panels and the air seals constitute an effective vapor retarder, installing a vapor retarder on the inside of the wall results in a wall with two vapor retarders, an undesirable situation.

A two-stage joint design moves the air seal to a location within the wall, protecting it somewhat from the elements, but not from cold temperatures. In a heating situation, the air seal is still on the cold side of the insulation, and moist interior air that reaches the back of the air seal will condense. Again, an interior vapor retarder can reduce the transport of water vapor by diffusion, but not by convection. And an interior vapor retarder will result in a wall with two vapor retarders.

A pressure-equalized rain screen design approach, discussed in the section on Water Leakage and Joint Design, solves many of these problems in heating climates if designed and installed properly. This approach to precast wall construction has been discussed as early as 1967 by Latta. In this approach, the air barrier is installed behind the insulation, where it is protected from fluctuations in outdoor temperatures. Figure 4.4.8 shows a sketch of a precast panel wall employing a pressure-equalized rain screen from Rousseau. In this particular example, a layer of gypsum board on the inside of an insulated steel stud wall serves as the air barrier. Air seals are used where this gypsum meets the floor slab to maintain the continuity of the air barrier system. A vapor retarder is also installed outside of the gypsum board. A second layer of gypsum is located inside of the air barrier to create a cavity for the installation of services to avoid compromising the air barrier. A pressure equalized cavity exists between the insulation and the precast cladding. The pressure equalization is achieved through the open horizontal joints, which are sloped to the outside for drainage. There is no need for any sealant at these joints if they are properly designed to deflect and shed water. The cavity must be properly flashed from the cladding to the inner air barrier.

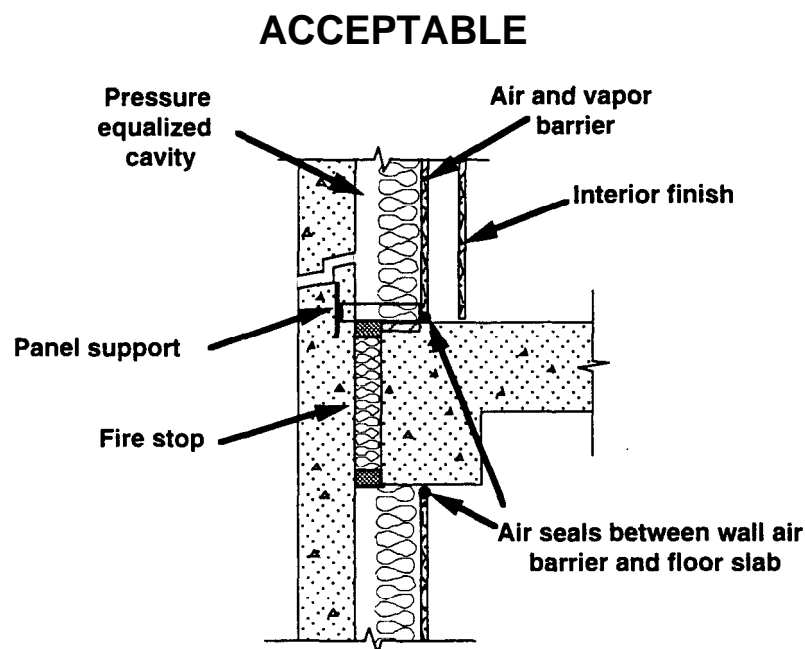


Figure 4.4.8 Pressure Equalized Rain Screen (Rousseau)

Selected Design Details

This section contains a series of precast concrete panel wall details for heating climates, developed with explicit attention given to the inclusion of continuous air barrier and insulation systems. The precast panel system depicted in these details contains a continuous layer of rigid insulation outside of an inner stud wall. Details describing the connection of the wall and roof are contained in the section on Roofing Systems.

Figure 4.4.9 shows a wall/floor connection in a concrete frame building (Brand). In this system a flexible membrane between the rigid insulation and the inner stud wall serves as the air barrier. Brand points out that it is safer and cheaper to fasten the panel from inside the building, and therefore recommends this somewhat unusual connection where the stud wall is terminated to allow access to the panel support. An airtight metal enclosure is fabricated to maintain the air barrier continuity at this location. The insulation system continuity is maintained at this location with batt insulation.

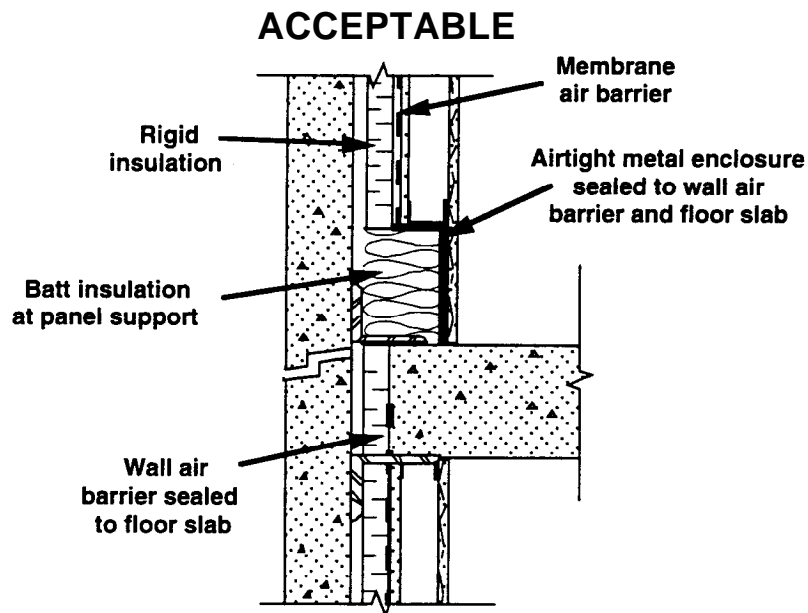


Figure 4.4.9 Wall/Floor Intersection - Concrete Frame (Brand)

The connection between a precast concrete wall and the foundation is shown in Figure 4.4.10. The outer drywall air barrier is sealed to the foundation waterproofing with a flexible membrane. The exposed insulation under the bottom of the precast panel is protected with a cement coating.

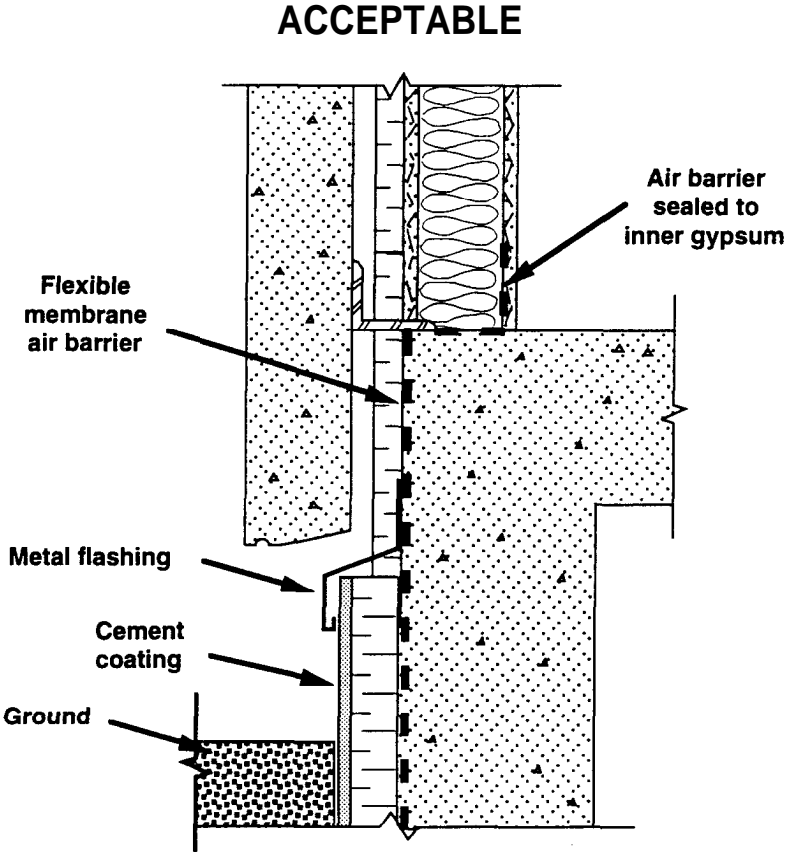


Figure 4.4.10 Wall / Foundation Intersection (Brand)

Figure 4.4.11 shows the connection between the wall and the window head and sill for a wall with an air barrier at the outer drywall surface. The air barrier is connected to the window frame with a flexible membrane. In order to keep the air barrier warm, compressible foam insulation is used at the connection.

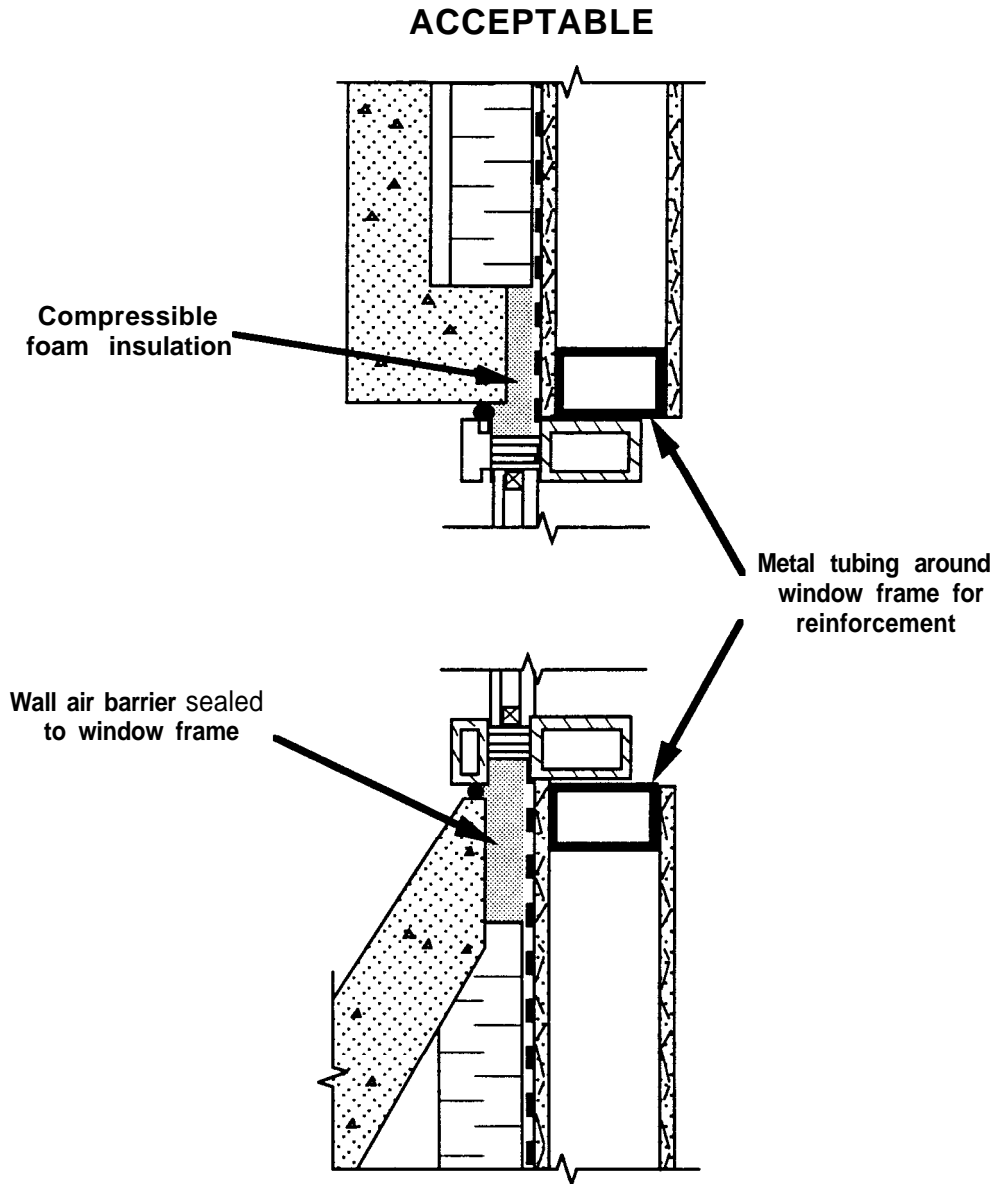


Figure 4.4.11 Wall / Window Intersection (Brand)

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4.5 STONE PANELS

Stone panel facades have offered richness and durability for ages. The development of thin stone curtain walls and other technical advances have renewed interest in stone facades. A variety of stone materials are in use today, mainly limestone, marble and granite, and a variety of systems for the attachment of stone facades exist including their serving as a veneer over concrete masonry backup walls, truss systems on metal framing and mounting on aluminum mullions as in glass and metal curtain walls. The design of stone panel systems employing aluminum mullions is covered in Smith and Peterson. Thin stone veneers can also be mounted on mullions with structural silicone (Carbary). The recent availability of thin stone veneers has increased the options for the use of stone. A recent ASTM publication (Donaldson) contains much useful information on stone wall technology, particular for thin stone systems. This section addresses the thermal integrity of the thin stone panel systems that dominate current stone panel construction, as opposed to the heavy, load-bearing stone construction of the past.

Design Information

Information on the design of stone walls is available from the Indiana Limestone Institute of America, Inc. and the Marble Institute of America. Their publications cover a wide of range of information including material properties, load calculations, recommended practices for erection and various details for parapets, anchors and joints. The provision of thermal integrity with continuous thermal insulation and air barrier systems is not explicitly addressed in these documents.

Bortz discusses some of the problems associated with stone curtain wall systems in the field, particularly thin veneers, but these issues are relevant to most stone wall systems. Material problems of weathering, staining, moisture permeability and structural integrity are important issues, particularly with thin veneers. The design issues raised by Bortz include the need to adequately accommodate differential movement between panels and between panels and their supports. Otherwise, cracking and other serious structural problems can result. Proper design for wind loads is an issue of obvious importance. Panel joints, along with systems for drainage and weeping, must be properly designed following the recommendations contained in industry design manuals. Bortz discusses problems of panel anchorage, pointing out that stone is brittle and sensitive to stress concentration. The final area of field problems discussed by Bortz is that of construction technique including the failure to remove temporary shims and spacers, and careless caulking and mortar droppings that lead to the clogging of drains and weepholes.

Because stone itself is air and watertight, the panel joints become the critical elements in the system when using the face seal approach in a stone facade. Smith points out that good air and water-tightness performance can be achieved when proper detailing is employed and realized during construction. In addition, the inevitable penetration of the facade by water must be acknowledged and dealt with through water deflection, collection and drainage systems. If instead a rain screen approach is employed, an air barrier system is required elsewhere within the envelope.

Thermal Insulation

The issues relevant to the insulation of stone panel walls are similar to those for other panel systems, with insulation system continuity being the key. Benovengo points out some important issues for the insulation of stone trusses, specifically that these panels can be preinsulated before being installed in the field. Installing insulation on the interior of the panel has the advantages of running continuously outboard of the structure and of the better quality achievable with off-site work. However, this approach is problematic in terms of performance because the wall will likely experience some water penetration, which can affect the performance of the insulation material. During construction, window openings are generally vacant for some time before glazing. This allows rain to soak the insulation, ruining the thermal barrier. Insulation at columns and spandrels may not be accessible for replacement when this occurs. Therefore, temporary protection of the insulation is essential during construction.

Benovengo and Gulyas advise against locating the insulation directly on the backside of the stone since it will result in draining water being held in contact with the stone for long periods of time, and this can weaken the stone.

Selected Design Details

The following details were developed with explicit inclusion of an air barrier system and the maintenance of insulation system continuity. They all employ stone cladding on concrete masonry backup on either concrete or steel structural frames. All of the details are designed for heating climates.

A wall/floor intersection in a concrete frame building is shown in Figure 4.5.1 (Brand). An open joint between the stone panels is used for drainage and clearance for construction inaccuracies. Brand points out that it is difficult to install the cavity flashing properly. Often the flexible membrane flashing is threaded through horizontal joints in the insulation boards, with the membrane being just as likely to slope inward as outward. Brand recommends that the membrane should lap over the shelf angle as shown. Space at the top of the masonry backup wall is provided for creep and deflection of the concrete floor slab.

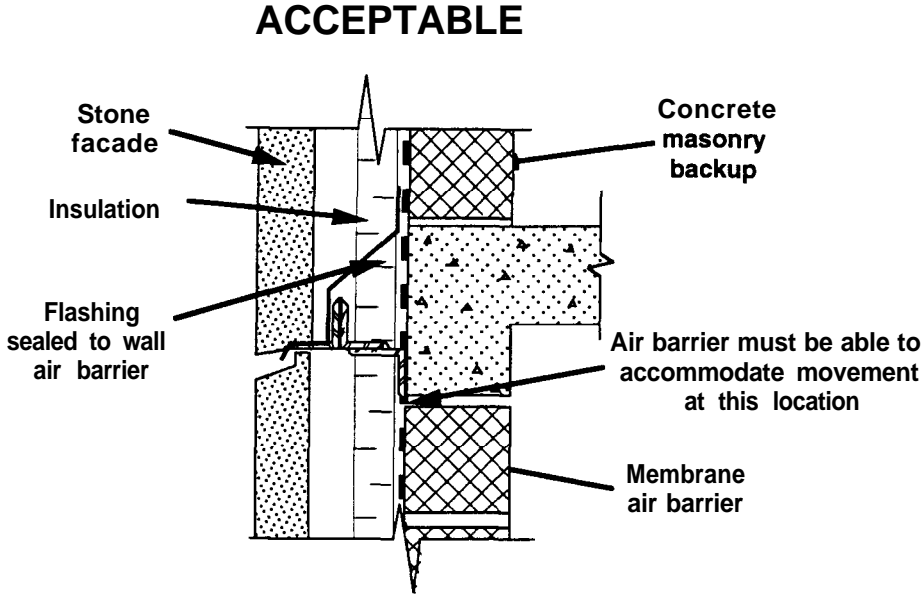


Figure 4.5.1 Wall/Floor Intersection - Concrete Frame (Brand)

A wall/floor intersection in a steel frame building is shown in Figure 4.5.2 (Brand). In order for the face of the steel frame to be flush with the masonry, a metal or drywall cover is installed over the steel structural elements. This cover is required for air barrier support. Again, space is provided at the top of the backup wall for deflection of the beam.

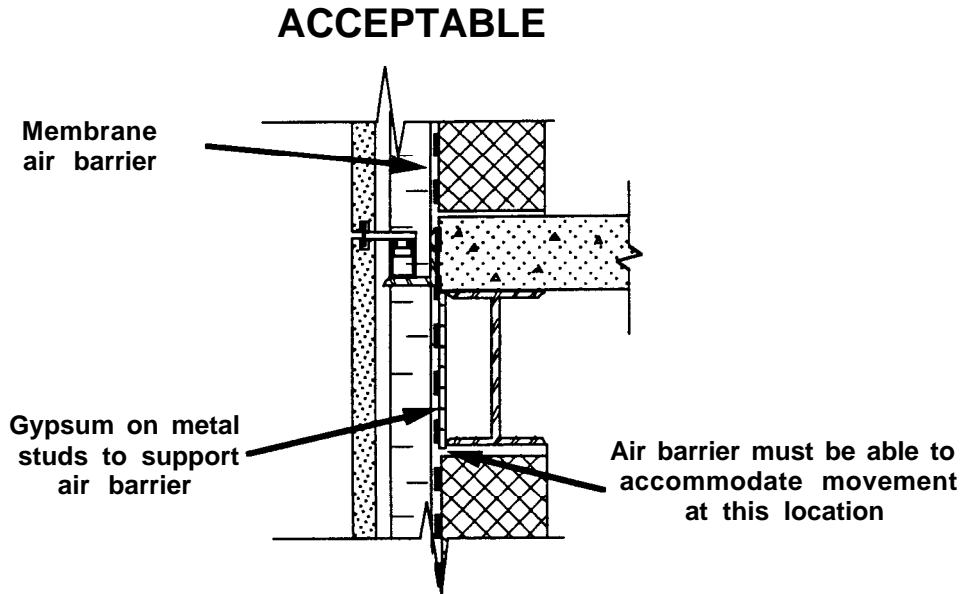


Figure 4.5.2 Wall/Floor Intersection - Steel Frame (Brand)

The connection between a wall and the foundation is shown in Figure 4.5.3 (Brand). Whether the building has a concrete or a steel frame, Brand recommends that the floor slab and the foundation be concrete. This makes it much easier to keep the junction air and watertight.

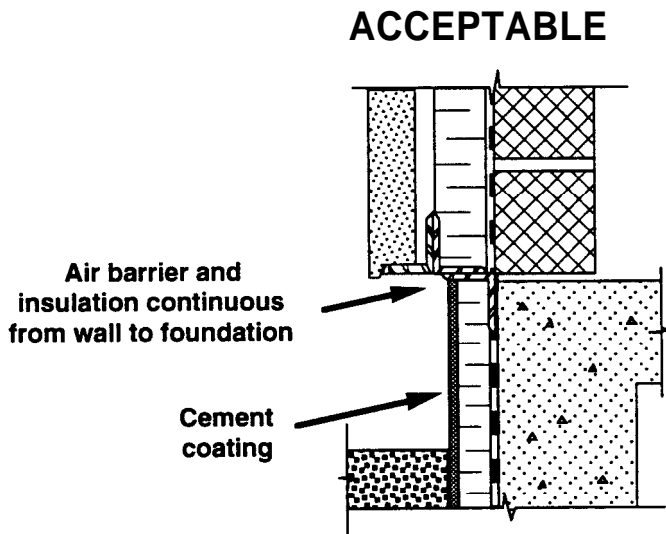


Figure 4.5.3 Wall/Foundation Intersection (Brand)

Figure 4.5.4 (Brand) shows the connection between the wall and the window head and sill. The membrane air barrier from the wall is clamped to the window frame, and flexible foam insulation is installed outside of this membrane.

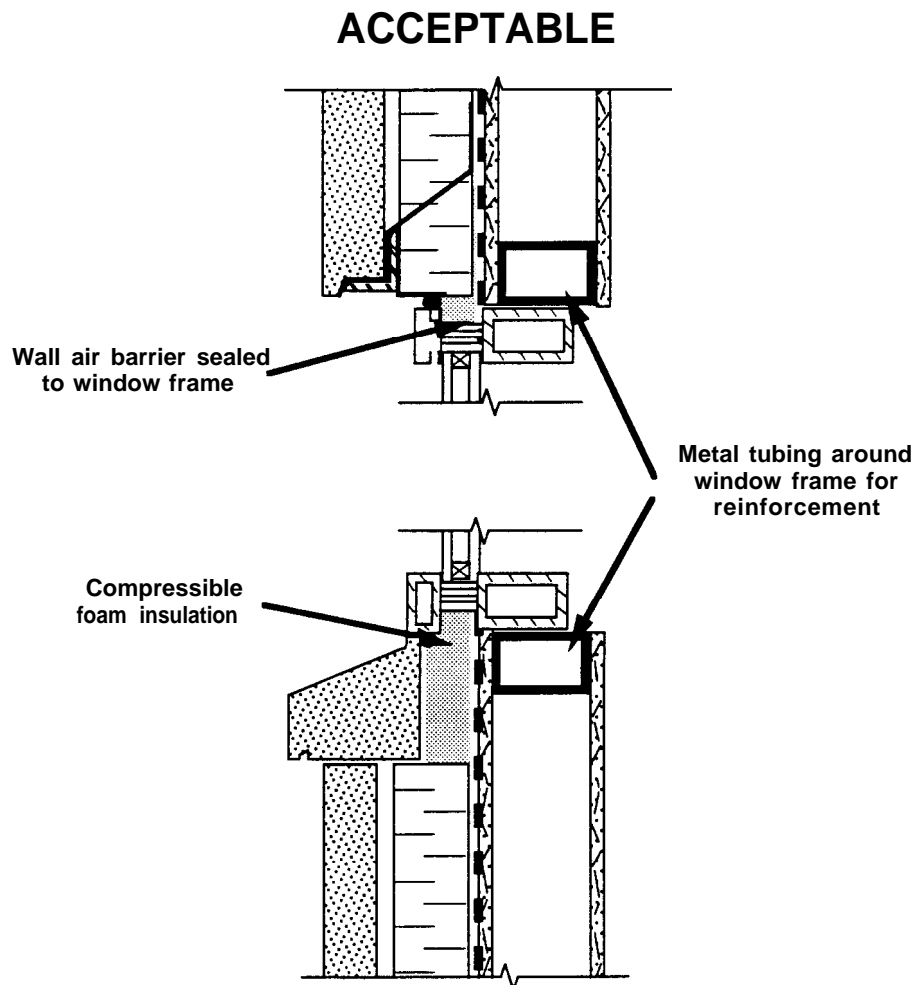


Figure 4.5.4 Wall/Window Intersection (Brand)

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4.6 METAL BUILDING SYSTEMS

Metal building systems are popular in light commercial construction due to their low first costs and their fast, simple and efficient assembly. The panels can be engineered in a variety of forms and finishes and prefabricated in the factory for efficient construction that is relatively unaffected by weather. The basic wall construction consists of a metal siding mounted on a steel girt system with an interior finish consisting of a metal liner or gypsum on studs or furring. Metal roofs are similarly constructed using purlins as the structural elements. The Metal Building Manufacturers Association (MBMA) has a Low Rise Building Systems Manual that contains design information on metal building systems, primarily concerning structural issues.

In metal buildings, thermal insulation system integrity is generally associated with the interaction of the insulation and the structural systems. Since the metal liners and facings are airtight, the air-tightness of the panel joints control the airtightness of these systems.

Thermal Insulation

Metal building systems are often insulated between the inner and outer skins with fibrous or sprayed foam insulation. Fibrous insulation can suffer from poor thermal performance due to compression of the insulation by the girts and purlins. These structural elements and other metal connectors act as thermal bridges with any type of insulation. Two examples of such design defects and improved alternatives are shown below. These cases are presented for roof purlins, but also apply to wall girts. Figure 4.6.1 shows a detail in which the insulation is interrupted by the roof purlins (Steven Winter Associates). In the alternative detail, a spacer of rigid insulation is placed over the insulation to maintain continuity of the insulation system. In this alternate design, the insulation should be in close contact with the spacer so there are no air spaces in the overall insulation system.

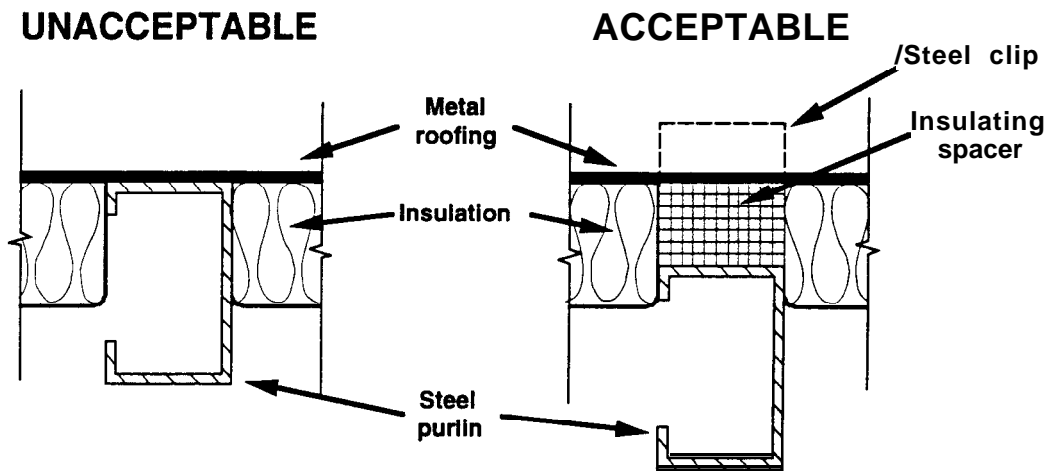


Figure 4.6.1 Insulation Between Roof Purlins (Steven Winter Associates)

Figure 4.6.2 shows a case in which there is a continuous layer of fibrous insulation, but the roof purlins compress the insulation, degrading its effectiveness. The alternate detail employs rigid insulation at the purlin to improve the performance.

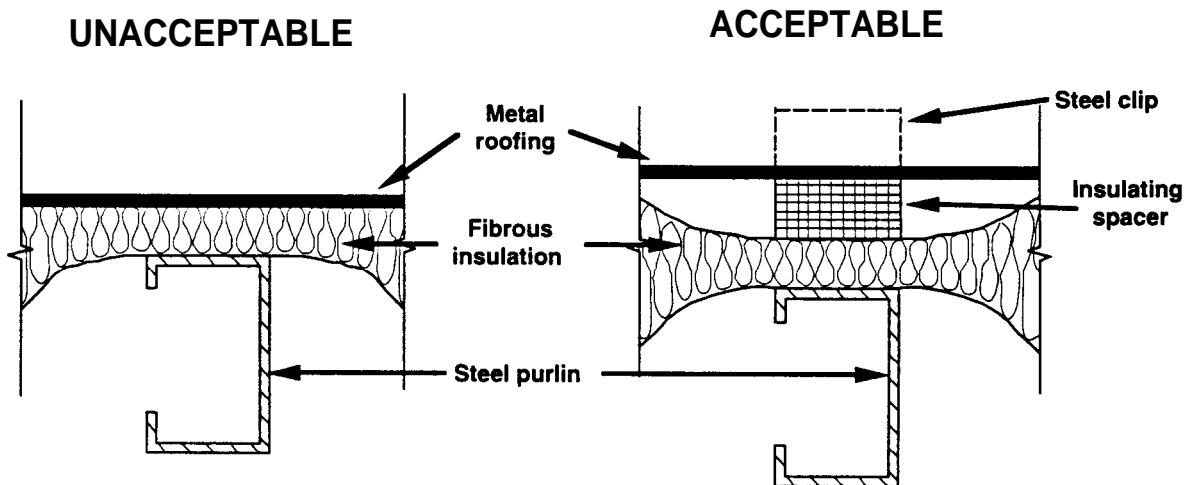


Figure 4.6.2 Insulation over Roof Purlins (Steven Winter Associates)

Insulated panels are sometimes fabricated in the factory for field construction, providing good quality control over the panels. In these systems, the joints between the panels become critical to thermal performance. Figure 4.6.3 shows a joint detail with poor performance due to the fact that it interrupts the continuity of the insulation system (Steven Winter Associates). The alternate design contains an improved joint design with improved continuity of the insulation system.

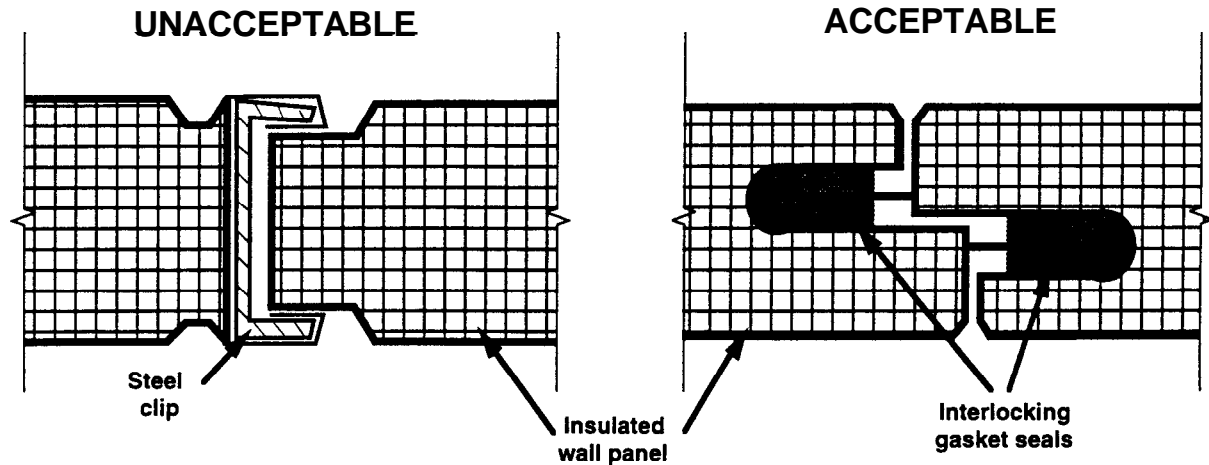


Figure 4.6.3 Sandwich Panel Joints (Steven Winter Associates)

Selected Design Details

The intersections between envelope components are the most critical locations for maintaining the continuity of the air barrier and insulation systems in metal building systems. Figure 4.6.4 shows a generic wall/roof connection in which the structural steel girder acts as a severe thermal bridge (Steven Winter Associates). In the alternative design, both the wall and roof employ insulated panels outside of the steel structure. The intersection between the wall and roof panels still requires special attention to maintain the continuity of the air barrier system and to avoid thermal bridging as covered in the section on Roofing Systems.

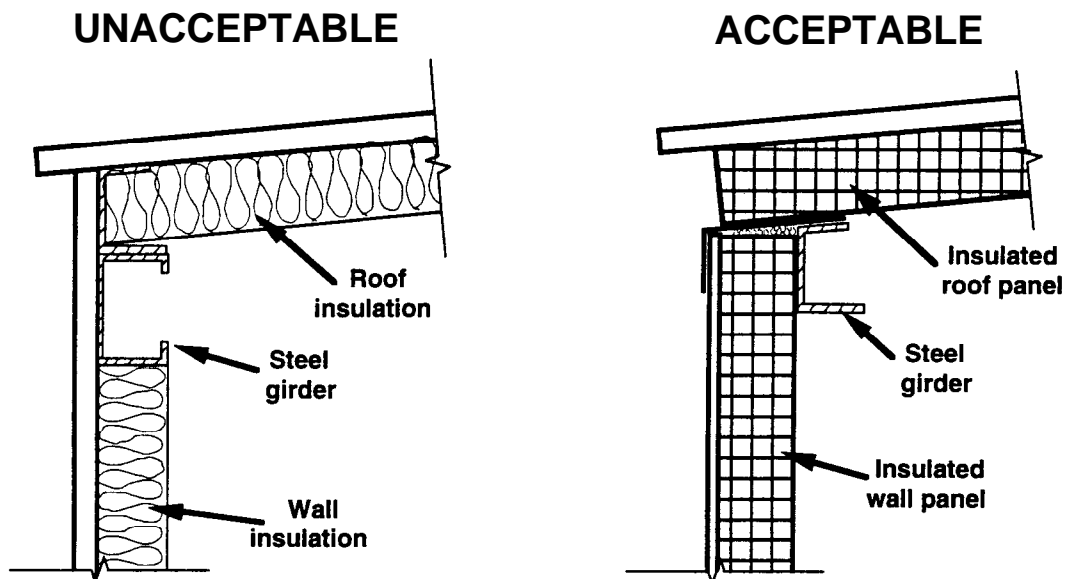


Figure 4.6.4 Wall / Roof Connections (Steven Winter Associates)

The following details show acceptable approaches to envelope intersections for metal building systems applicable to heating climates. Figure 4.6.5 shows a wall/floor connection in a concrete frame building (Brand). The critical item here is the design and installation of the joint to maintain the continuity of the insulation and air barrier systems. A membrane air barrier is installed at the inside of the panel and fibrous insulation is installed to keep the air barrier warm and to maintain insulation system continuity. The insulation is covered with a plate that acts as a rainscreen.

ACCEPTABLE

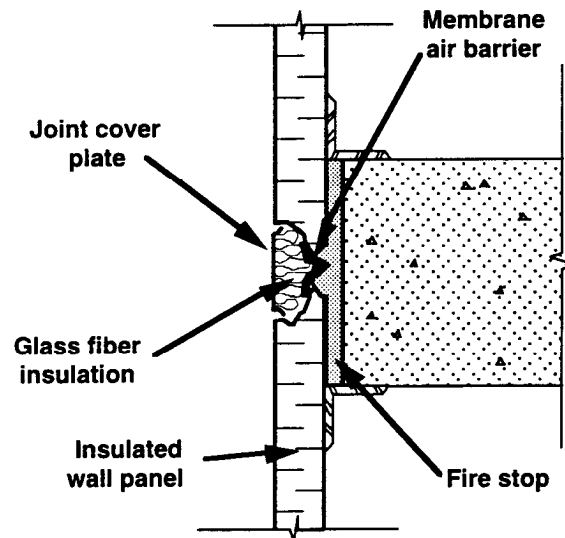


Figure 4.6.5 Wall / Floor Connection - Concrete Frame (Brand)

Figure 4.6.6 shows a wall/floor connection in a steel frame building with a panel joint system that is different from the above example (Brand). The panel edges are designed to form a draining joint; an outer weather seal and an inner air seal are installed in the field.

ACCEPTABLE

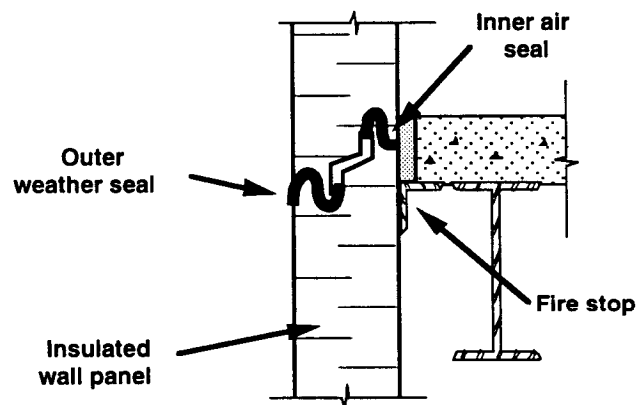


Figure 4.6.6 Wall / Floor Connection - Steel Frame (Brand)

Figure 4.6.7 shows a wall/foundation connection (Brand). A flexible membrane air barrier is used to carry the line of airtightness from the wall to the foundation waterproofing. Brand suggests sealing this air barrier to the inner liner of the wall with an asphalt impregnated foam.

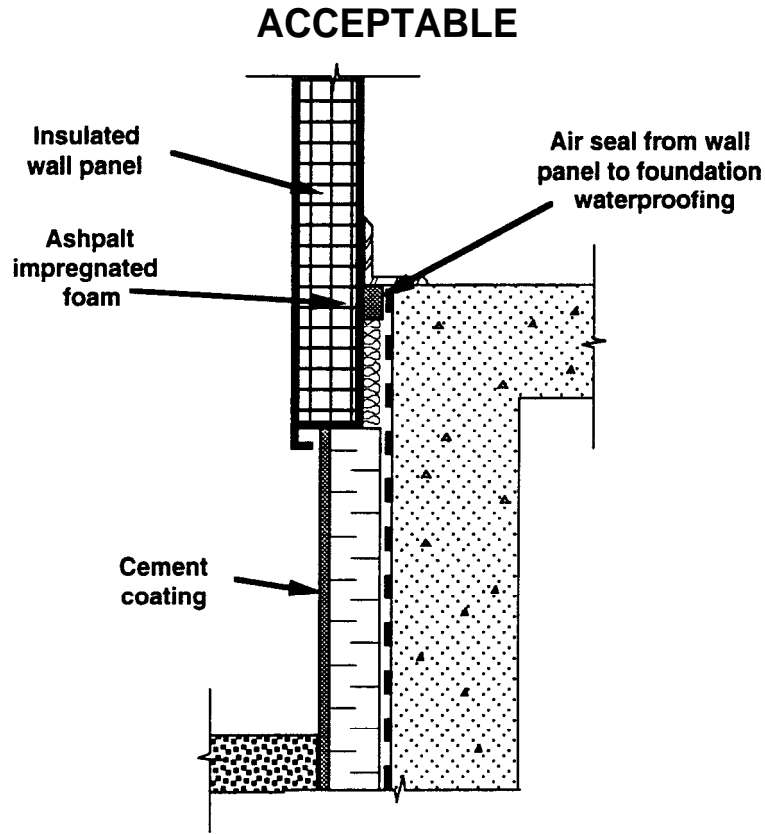


Figure 4.6.7 Wall / Foundation Connection (Brand)

Figure 4.6.8 shows the connection between a metal panel wall and a window (Brand). In order to make an airtight connection between the inner liner and the window frame a flexible membrane is sealed to the liner and to the frame. The outside of the air barrier is insulation with foam to keep it warm.

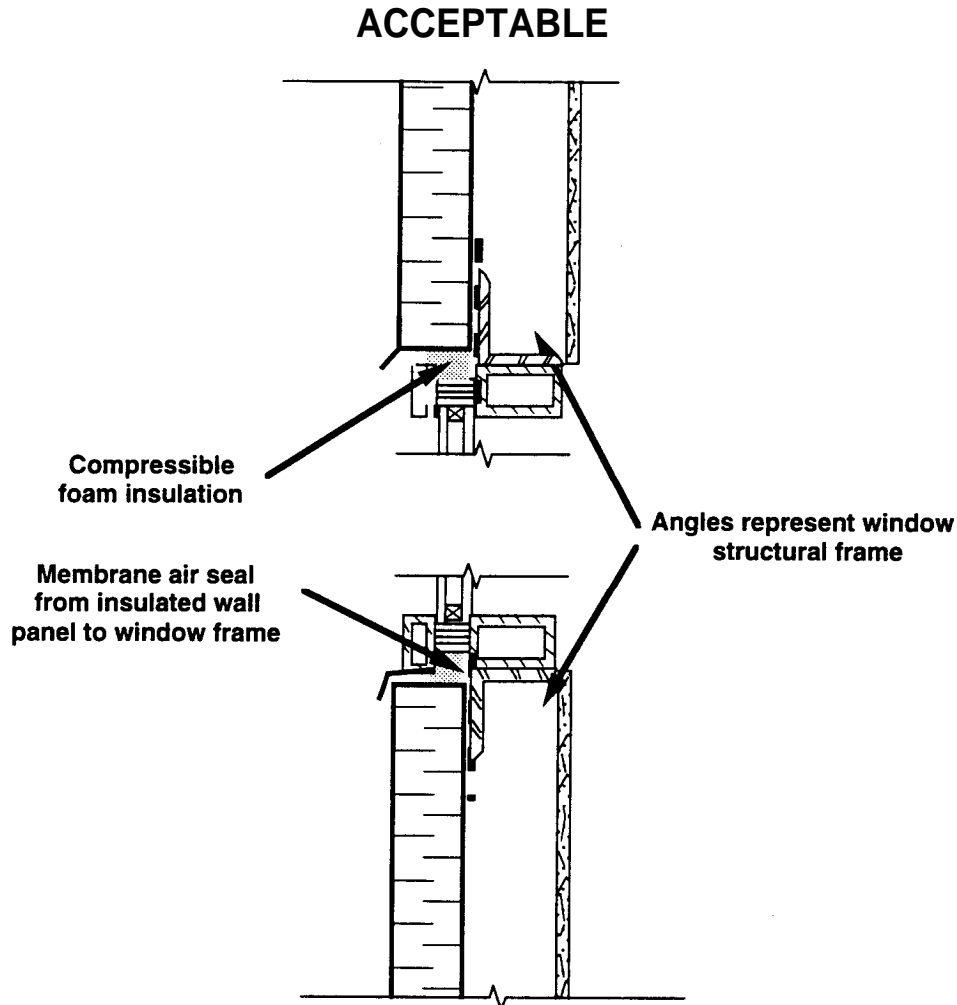


Figure 4.6.8 Wall / Window Connection (Brand)

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4.7 EXTERIOR INSULATION FINISH SYSTEMS (EIFS)

EIFS envelope systems offer the advantages of cost effective construction and exterior insulation of building structural elements, eliminating the associated thermal bridges. Figure 4.7.1 shows the basic components of an EIFS wall, in this case employing a metal stud wall substrate. The unique aspect of this system is the cementitious or stucco finish that is continuously applied to insulation boards that are attached to a substrate. An article by Labs discusses the basic components of EIFS and some recent developments. The Exterior Insulation Manufacturers Association (EIMA) has produced a series of guideline specifications for EIFS, which are primarily directives to follow the instructions of product manufacturers. EIFS are classified by EIMA as polymer based (Class PB) or polymer modified (Class PM). PB systems are also referred to as thin coat, soft coat or flexible systems, while PM systems are sometimes referred to as thick or hard coat.

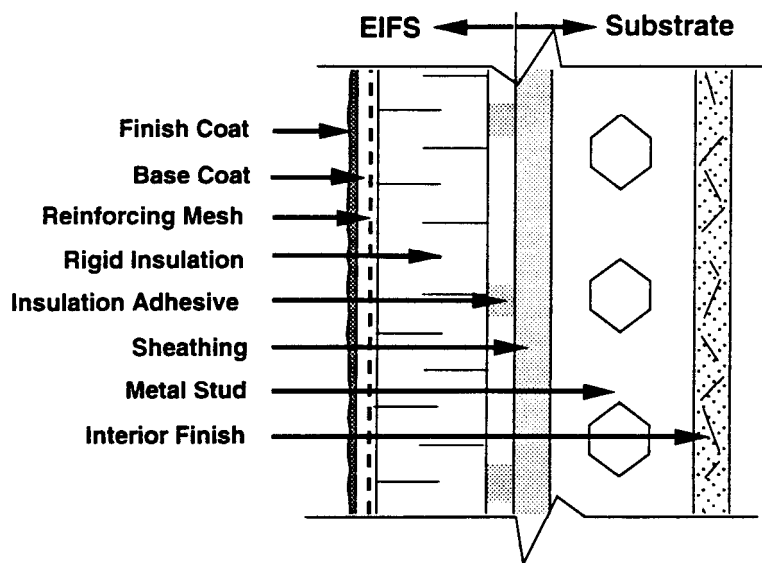


Figure 4.7.1 Components of EIFS Construction

EIFS employ the face-seal approach to leakage control in which the exterior face of the envelope is sealed to prevent both air leakage and rain penetration. As with all envelope systems, moisture tightness is very important for EIFS to prevent the degradation of system components and to protect the wall's integrity. Water may enter the system at leaks in panel joints, at locations where delamination has occurred, and at voids in the finish coat when exposed to moisture for extended periods of time. The latter problem can occur at joints that do not drain well or at other facade articulations. It is important to design roof edges, window sills and other articulations to shed water away from the building, rather than continuously testing the water-tightness of the building skin. The control of water vapor diffusion requires a vapor retarder, specifically designed for the climate and the wall insulation level. In cold climates, this vapor retarder must be placed inside of the insulation and must have a water vapor permeance sufficiently below that of the exterior finish. In hot climates the exterior finish could serve as the vapor retarder, providing it has a sufficiently low permeance. However, it is crucial that the face sealing is continuous and durable to prevent hot, humid air from migrating into the envelope and condensing on cold elements. It is also important in hot climates that extreme care be exercised if a highly vapor impermeable interior finish (e.g. vinyl wallcovering) is used, as it may be less permeable than the outer face, resulting in condensation behind the interior finish. If such an interior finish is employed or anticipated, another vapor retarder may be needed within the envelope. This additional vapor retarder should be installed outside of an additional layer of insulation.

Substrates

EIFS, as originally developed in Europe, employ substrates of solid masonry or concrete. Most application of EIFS in this country is on gypsum-sheathed, metal-stud walls. The concrete or masonry substrate has the advantages of providing a more stable backup for the finish system than a stud wall. In addition, gypsum is vulnerable to water damage from leakage or condensation. Cases of moisture damaged sheathing and corrosion of metal studs have occurred due to water penetration or accumulation in the wall systems. If the finish were absolutely watertight, then moisture damage to the substrate would not be an issue. However, it is unrealistic to assume perfect water-tightness over time in the field. One proposed solution to this problem is not to use gypsum sheathing at all, and the use of only concrete and masonry substrates is advocated by some groups. Several other options are described in the article by Piper. If gypsum sheathing is used, a weather barrier such as 15# felt can be placed between the sheathing and the finish, but this will require the use of mechanical fastening of the insulation. Alternatively, a weather barrier can be placed behind the sheathing, but this will protect only the studs and the building interior. One can also use a more durable sheathing material, such as cement board or cement fiber board.

Crack Control

in order to reduce air and water leakage, it is important to control the cracking of the finish through proper design and construction. Piper has described the occurrence of several classes of cracks in EIFS. Diagonal cracks at windows and other large openings can occur if diagonal mesh reinforcement is not installed at these locations. Such reinforcement is necessary because of the stresses that are concentrated at these locations. Cracks can also occur at gaps between insulation boards. This gap becomes partially filled with the base coat, and this T-shaped cross section in the base coat leads to concentrated stresses that can result in cracks. These gaps can result from the use of inadequately aged insulation boards, application methods that result in adhesive being forced between the boards, and excessively out-of-square installations of boards.

Panel joints

The integrity of panel joints is a critical area in EIFS construction. Leaky joints degrade air and water tightness performance, and can lead to more serious problems with the wall components.

Sealant Failure Due to Delamination

It is common practice to install sealants in panel joints for air and water tightness, with the sealant applied to the finish coat. However, when the finish coat is exposed to water for an extended length of time, it will soften. The potential then exists for delamination, in which the finish coat pulls away from the system. As shown in Figure 4.7.2, from Williams and Williams, such delamination breaks the air and water seal at the joint. Rather than sealing to the finish coat, Williams and Williams suggest stopping the finish coat at the panel edge, wrapping the base coat and reinforcing mesh around the insulation board, and applying the sealant to the base coat. It is also recommended that low modulus sealants be employed since they will apply less stress to the base coat bond.

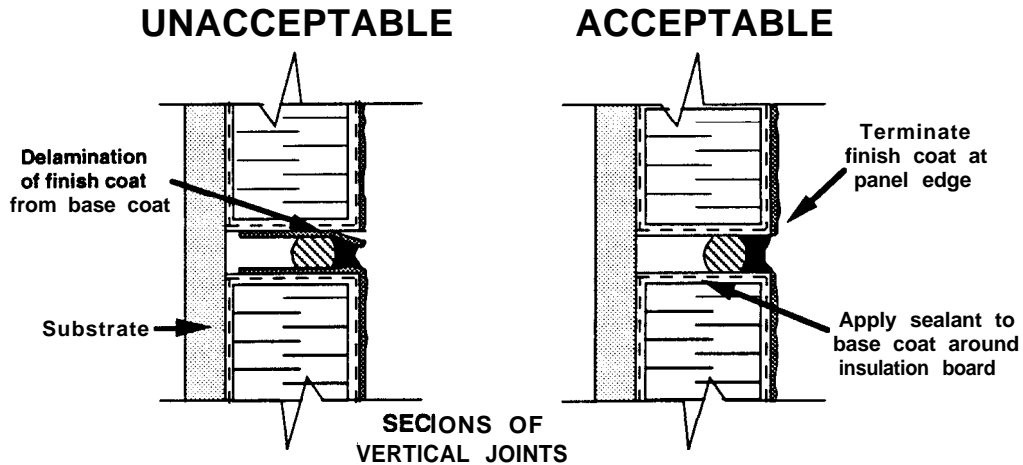


Figure 4.7.2 Sealant Joint Delamination (Williams and Williams)

Thermal Bridge at Joint

Because the wall insulation is outside of the structural frame, EIFS have the potential of reducing thermal bridging of the building envelope. However, the insulation system continuity can break down at uninsulated panel joints. This can easily be remedied with the addition of insulation behind the panel seal, as shown in Figure 4.7.3.

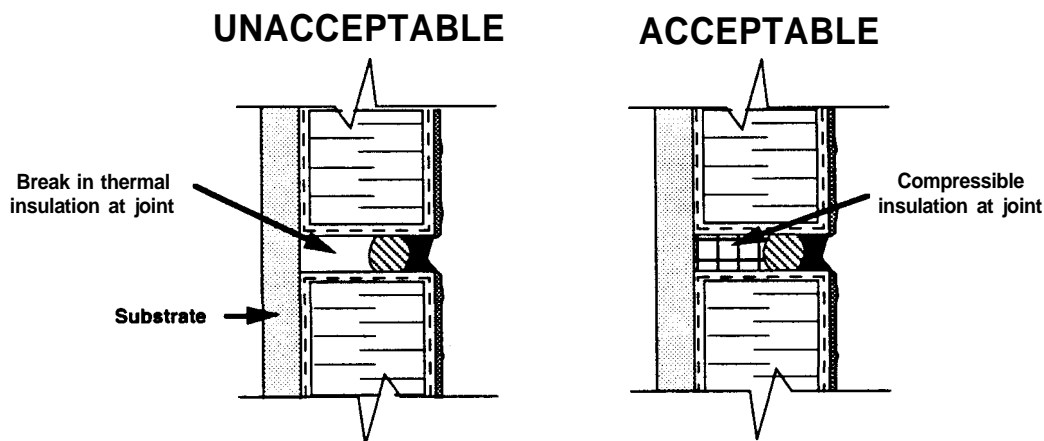


Figure 4.7.3 Thermal Bridging at Panel Joint

Other Considerations in Panel Joints

Additional guidance on the design of joints for good air and water tightness performance through the consideration of the following factors is provided in Williams and Williams.:

Thermal Movement

Based on the investigation of joint sealant failures, Williams and Williams believe that joint movement is often greater than anticipated. One factor is that coefficients of thermal linear expansion are seldom available for EIFS claddings. Also, the color of the cladding is not always properly taken into account. They therefore recommend that joints be designed to be 4 times the anticipated degree of movement.

Joint Sealants

As is the general case with sealant joints (see section Design/Sealants), a width to depth ratio of 2 to 1 and closed-cell backup rods are recommended. In applying the sealant, care must be taken to avoid puncturing the backup rod to prevent "outgassing" and the associated problems of gas bubbles in the sealant. As mentioned earlier, low modulus sealants are recommended since they will apply less stress to the base coat bond.

Backwrapping

At all exposed edges of the insulation board, the base coat and reinforcing mesh should be returned from the system face, over the edge and around the back of the insulation board. Neither the mesh nor the insulation should ever be exposed to the elements. Such backwrapping reduces moisture intrusion into the EIFS layers.

Construction Technique

Prior to the application of sealants, all surfaces should be clean, dry and free of particles. Sealant mixing and priming instructions should be followed closely in the field, with no substitutions.

Selected Design Details

As with all wall systems, the intersections between different envelope components are critical areas for the maintenance of air barrier and insulation system continuity. This section presents unacceptable and acceptable design details for several such component intersections.

A common roof parapet detail with a metal stud backup wall, is shown in Figure 4.7.4, along with an improved alternative. In the unacceptable case, insulation is installed between the studs up to the roof insulation, but the thermal bridging caused by the studs increases heat transfer and cools the studs below the roof deck. In addition to the energy loss, in heating climates this situation can damage the drywall due to the condensation that forms on the cold studs. Also, the discontinuity in the air barrier at the roof line will allow airflow from the building interior up the stud space and out the top of the parapet, further aggravating the energy loss and the potential for condensation. In the alternate detail, rigid insulation is added to the roof side and top of the parapet. The base flashing is used as an air barrier and must be capable of windstanding the high wind pressures at the top of the parapet. This air barrier is sealed to the EIFS on the outer facade, run under the metal cap flashing, and sealed to the roof membrane.

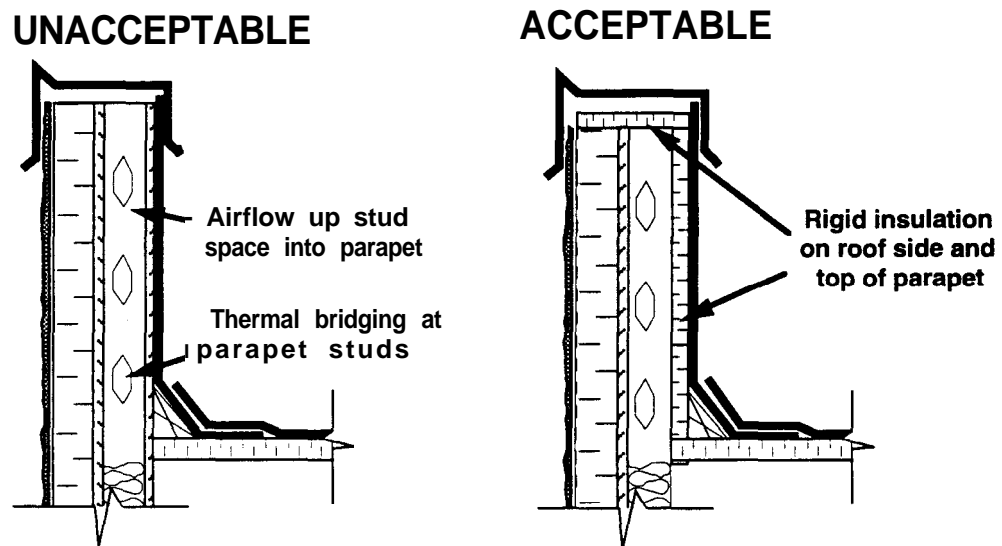


Figure 4.7.4 Thermal Defect at Parapet

Another parapet design is shown in the Figure 4.7.5. In the unacceptable case, the EIFS cladding is carried partway down the inner wall of the parapet. This is an improvement over the previous case, but the thermal bridge caused by the studs remains at the top of the parapet and below the inner wall's EIFS. In the modified detail, rigid insulation is added at the top of the parapet and to the inner parapet wall below the EIFS cladding. As in the previous case, the base flashing serves as an air barrier.

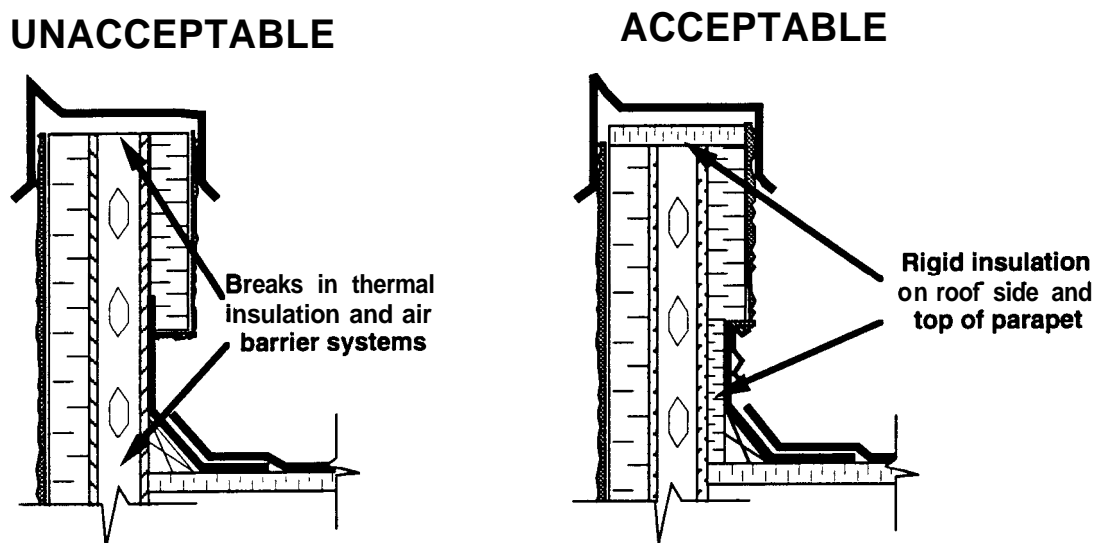


Figure 4.7.5 Thermal Defect at Parapet

Foundations

The detail shown in Figure 4.7.6, or a variation of it, is commonly used to protect the ground-level insulation of the EIFS cladding from punctures and other damage. Although damage to the cladding is reduced, this system results in a significant thermal bridge below the insulation. Alternatively, the modified detail shows a continuous layer of insulation all the way down the wall, with the lamina carried below grade to protect the insulation. It is recommended that this alternate approach be used and some other means be used to keep the public and building staff from getting too close to the building facade. Pavers will protect the insulation from damage due to landscaping activities.

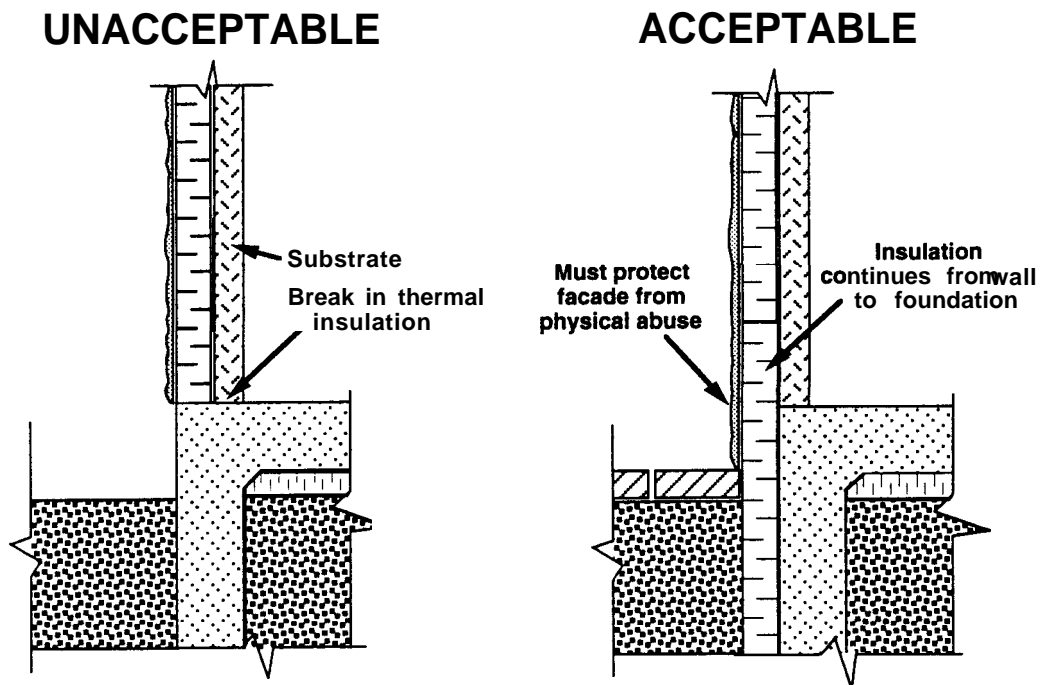


Figure 4.7.6 Thermal Defects at Foundation

Design and Construction Issues

There are several design and construction issues relevant to the performance of EIFS. As with other construction systems, it is important to follow the installation requirements of the EIFS manufacturer. These systems are sensitive to poor application and require careful construction technique, especially at joints and penetrations. One issue of construction technique is the application of a sufficient thickness of base coat. The base coat thickness, coupled with proper embedding of the mesh, is critical for the system's durability in terms of impact and water resistance. A minimum thickness of about 1.6 mm (1/16 inch) is recommended by many manufacturers, while others recommend a minimum thickness of 2.4 mm (3/32 inch).

Bordenaro points out that some performance problems in EIFS cladding systems are due to the fact that since they are among the last components of a building to be applied they are often shorted in the number of detailed drawings that are developed relevant to their application. Drawings are sometimes not provided to show how the EIFS cladding will relate to other products and finishes such as doors, windows and other penetrations. Many manufacturers have standard details for large penetrations such as windows and doors, and these need to be followed. However, details for other small and common penetrations, such as at conduits, are generally not available. Continuity of the insulation and air barrier systems must be purposefully addressed at each component connection over the entire building envelope. Details must be developed for each such connection, otherwise this continuity will break down and the overall system performance will suffer.

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4.8 ROOFING SYSTEMS

The design and construction of roofing systems is discussed in the NRCA (National Roofing Contractors Association) Roofing and Waterproofing Manual. The NRCA manual contains a thorough treatment of roofing issues such as basic design options, membranes, insulation, sealants, flashing, drainage, and expansion joints. This section concentrates on those issues that are crucial to the heat, air and moisture transfer performance of roofing systems through the maintenance of the continuity of the envelope insulation and air barrier systems.

Roofing System Design

Roofing system design issues related to thermal performance include the provision of thermal insulation, keeping rainwater out of the building, the prevention of condensation of water vapor within the roofing system and the maintenance of insulation and air barrier continuity at the roof edge and at roof penetrations. There are a wide variety of roofing systems and materials in use, and the NRCA Roofing and Waterproofing Manual is a good reference to roofing systems and their design. The manual discusses low-slope roofing systems with sections on decks, vapor retarders, insulation, membranes and specifications. There is also a section devoted to design details of flashings, joints, penetrations and drains for built-up and single-ply systems.

The basic roofing systems in commercial construction include so-called conventional systems in which the deck is covered with a vapor retarder, thermal insulation and a roofing membrane (either built-up or single-ply). This system has two disadvantages (Baker 1972). First, the membrane is fully exposed to the degrading effects of weather such as sunlight, temperature extremes and water. In addition, the insulation is contained between two membranes, the vapor retarder and the roofing membrane, which can act as a so-called "vapor trap" for interior moisture that penetrates the vapor retarder. Protected membrane systems, also referred to as inverted or upside-down roofs, offer some advantages by combining the vapor retarder and roofing membrane into a single layer with the insulation positioned outside of this membrane. Interior moisture that penetrates the membrane from inside can more easily evaporate, and the membrane material is protected from the elements. Of course the insulation must be durable given its exposure to weather. Also, the roof slope and drainage is more critical than in a conventional roof, and insulation attachment requires special consideration. Metal building systems, as well as other structures, employ standing seam metal roofs. These systems are discussed in the referenced article.

Single-ply roofing membranes, both in sheet form and liquid applied, have advantages in durability and installation (Brand, Laaly, and NRCA). A variety of single-ply materials and systems are available, but they do not have the history of performance of built-up membranes. Special attention is required in their attachment and in the sealing of lap joints, flashings and penetrations. Gish addresses sealant issues in single-ply roofing systems including lap joints, water stops, pitch pockets and night sealants.

Moisture Control

There are two prime moisture considerations in roofing system design, rain penetration and the condensation of water vapor within the roofing system (Handegord). Rain penetration is controlled by trying to keep water off the roofing membrane with adequate sloping and drainage in conjunction with carefully designed and installed flashing at roof edges and penetrations (Baker 1969, NRCA). Water vapor condensation within the roofing system is controlled by preventing water vapor from the building, or the outdoors in cooling situations, from entering the roof and reaching cold elements within the system. The control of water vapor transport must address both diffusion and air leakage. Diffusion can be controlled with a vapor retarder, but a vapor retarder is insufficient to control the greater amounts of water vapor that can be transported by air movement. As in the case with walls, the vapor retarder must be positioned in relation to the thermal insulation such that it is maintained at a temperature above the dewpoint of the moist air.

The decision on the necessity for a vapor retarder is the source of much discussion. The basic issue of concern is whether a sufficient quantity of water vapor will condense within the roofing system beyond the absorptive capacity of the materials and whether these materials will have an opportunity to dry out before any damage is done. An analysis of climate, conditions within the building and the thermal resistance and moisture absorptive properties of the roofing system elements is necessary to determine the need and appropriate position for a vapor retarder. Such an analysis of the need for a vapor retarder and its position within the roofing system should be conducted in all cases, following the examples contained in the NRCA manual. NRCA recommends that a vapor retarder be considered when the average January temperature is less than 5 °C (40 °F) and the interior relative humidity is at least 45% in the winter. While these general guidelines are useful, Tobiasson points out that these guidelines will result in the use of vapor retarders when they are not needed and their lack of specification when they should be used. He instead recommends the consideration of condensation potential during the entire winter and the drying potential during warm weather, and has developed a map of the U.S. that gives the relative humidity above which a vapor retarder should be specified. This map allows for corrections based on interior temperatures.

In order to control the great quantities of moisture transport due to air movement, a roofing system vapor retarder needs to be as airtight as the roofing membrane is watertight (Condren). As in the installation of an air barrier, extreme care must be taken to insure that the vapor retarder is fully continuous throughout the roofing system, including all seams, penetrations and roof edges. Condren stresses the need to maintain air-tightness at all seals and terminations through the attention to detail during design and rigorous inspection during construction.

Regardless of how much care is taken in the design and construction of roofing systems, it is inevitable that some moisture will migrate into the roofing system from precipitation and condensation of water vapor. Some recommend the use of breather vents and air channels within the roofing system to remove such moisture (Condren). Others state that it is extremely difficult to ventilate a compact roof and that breather vents are apt to do more harm than good. Tobiasson holds the latter viewpoint and has done experimental work that shows it can take decades to dry out a compact roof with breather vents. He states further that he sees no evidence that unvented roofs perform any worse than vented roofs.

Roof/Wall Intersections

The intersection of the roof and the wall is a common site for discontinuities in the thermal insulation and air barrier systems. The key issue for controlling air leakage is sealing the wall air barrier to the roofing membrane, and doing so in a manner that will accommodate the differential movement that generally occurs at this junction. To control condensation at this junction, the vapor retarder needs to be kept warm by a continuous layer of thermal insulation. Continuity of the thermal insulation system also serves to control heat loss at this location. This section presents details of roof/wall intersections for various wall systems.

The first two examples, based on material in Riedel, are roof/wall intersections in masonry wall systems, although they relate to issues in other wall systems as well. These details concentrate on air sealing issues and do not include thermal insulation. The first example in Figure 4.8.1 shows a wall-roof connection consisting of metal edging extending from outside of the masonry wall over wood plates and attached to the roof membrane. Air leaks under the metal edging and between the wood plates, and can then flow under the roof membrane and into the roof insulation and the building interior. Riedel proposes a fix employing a vinyl membrane on the inside of the metal edging that is sealed to the roof membrane and the outside of the masonry wall. The sealant between the metal cap and the masonry wall must be able to accommodate differential movement at this location.

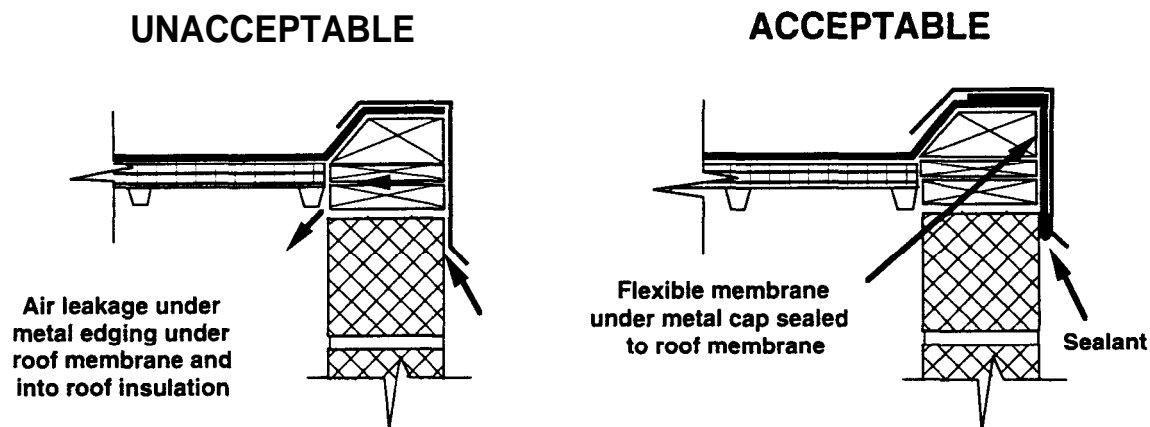


Figure 4.8.1 Air Leakage at Roof Edge (Riedel)

Air leakage at a steel roof deck with an overhang is shown in Figure 4.8.2. Air leaks into the overhang through the bottom and outer edges. This air then passes over the top of the outside wall and into the roof insulation. Air is also able to move past the building wall above the deck since the deck flutes may at best be only loosely stuffed with glass fiber insulation, not an adequate air seal. The suggested fix is to provide seals where the roof deck passes over the top of the outside wall, in this case foam insulation. This foam insulation seal should be in the same plane as the wall insulation. The top of the deck ribs should also be filled or sheathed to provide a flush surface for cementing the roof insulation.

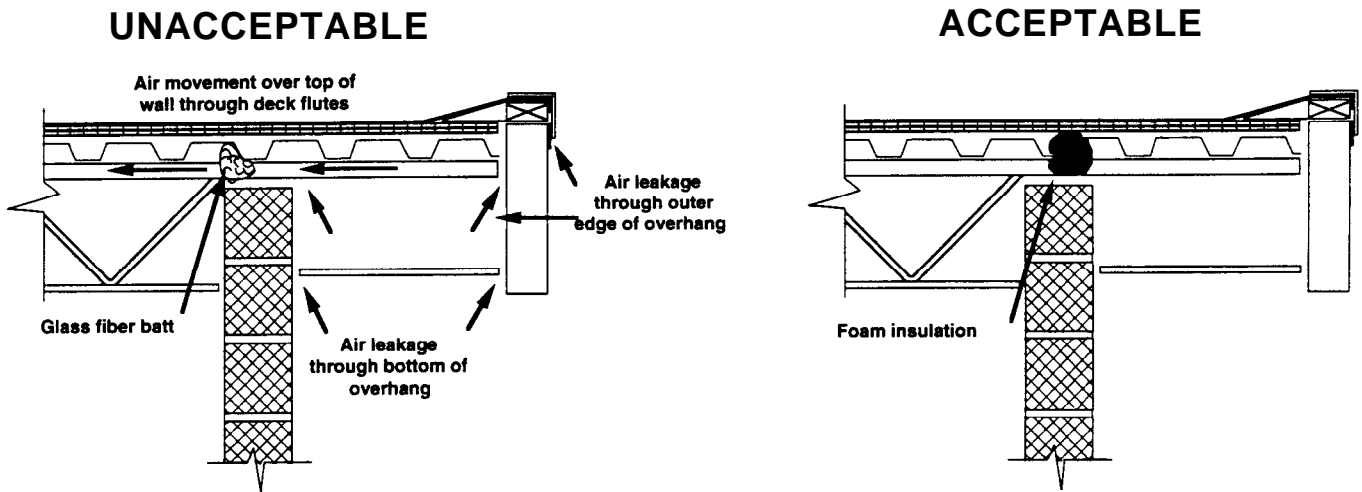


Figure 4.8.2 Air Leakage at Roof Overhang (Riedel)

The intersection between flat roofs and setback walls, for example at rooftop penthouses, is another location requiring careful detailing to maintain continuity. Figure 4.8.3 shows this intersection for a concrete frame building (Brand). In this detail, the setback wall air barrier is sealed to the roof membrane. There is no differential movement between the setback wall and the roof deck, simplifying the attachment of the air barrier and roof membrane. In a heating climate, it is very important that the air barrier insulation is completely continuous. The wall insulation below the termination of the brick must be covered to protect it from ultraviolet degradation.

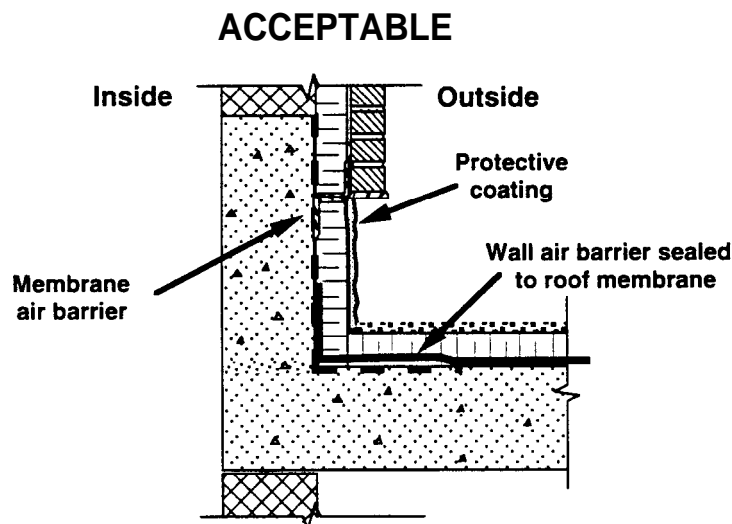


Figure 4.8.3 Masonry Setback Wall/Roof Connection - Concrete Frame (Brand)

A masonry setback wall/roof intersection in a steel frame building is shown in Figure 4.8.4 (Turenne). The roof membrane, located under the roof insulation, is sealed to the wall air barrier. A loop in the membrane is provided at the roof wall gap to accommodate differential movement between the roof and the wall.

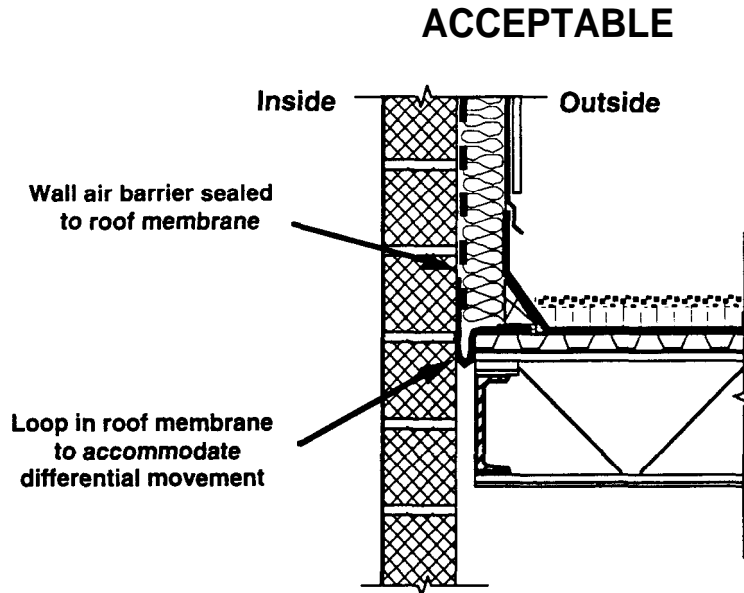


Figure 4.8.4 Masonry Setback Wall/Roof Connection - Steel Frame (Turenne)

Figures 4.8.5 (Burn) and 4.8.6 (Turenne) show intersections between masonry walls and fiat roof edges in steel frame buildings. In the first case, Figure 4.8.5, the steel beam is in the plane of the masonry backup. A gap is provided between the top of the backup and the spandrel beam so that the beam can deflect freely without transferring any loads to the wall. The steel beam is faced with drywall, and a continuous strip of a flexible membrane is installed along the edge of the deck, sealing the drywall to the roof vapor retarder. Another strip of membrane is installed over the drywall and seals the gap at the top of the backup wall.

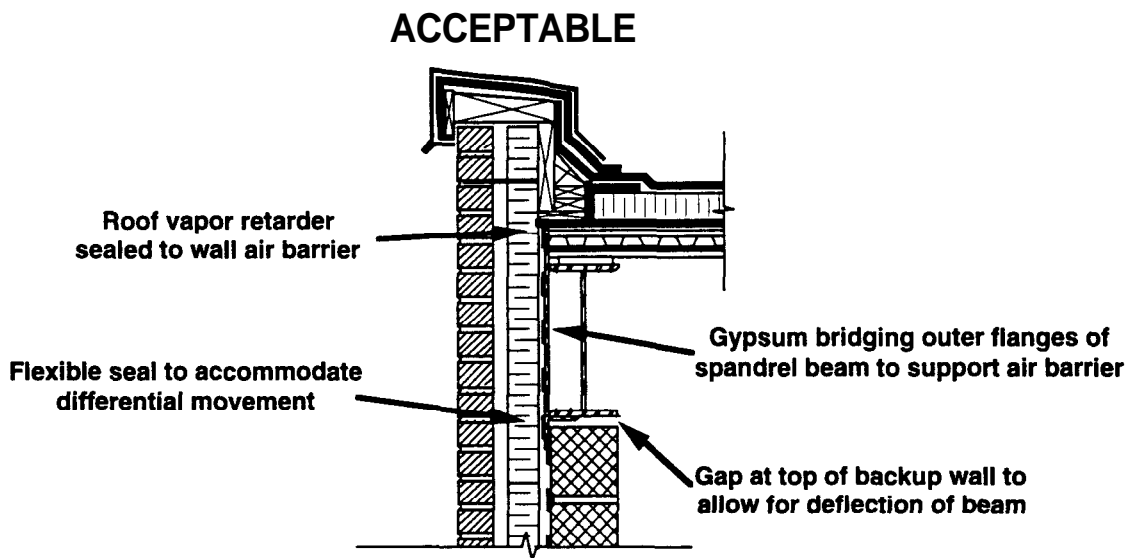


Figure 4.8.5 Masonry Wall/Roof Edge - Steel Frame (Burn)

in Figure 4.8.6 the steel frame is located inside of the masonry wall, again enabling the beam to deflect freely. The roof vapor retarder is sealed to the wall air barrier by a flexible membrane that is supported by a sheet metal closure supplied and installed by the steel deck contractor.

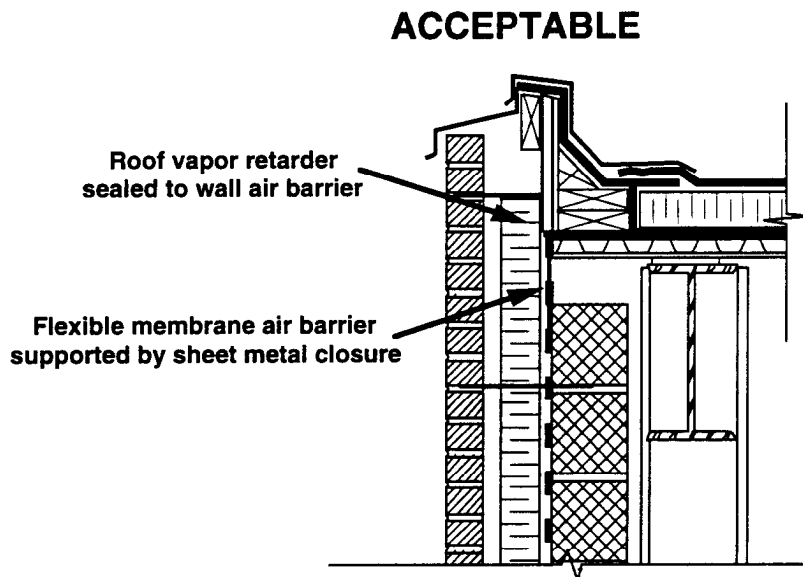


Figure 4.8.6 Masonry Wall/Roof Edge - Steel Frame (Turenne)

Figure 4.8.7 shows the intersection between a masonry wall and a roof edge for a concrete frame building. As in the steel frame case, a gap is provided at the top of the backup wall and a flexible membrane is used to seal this gap.

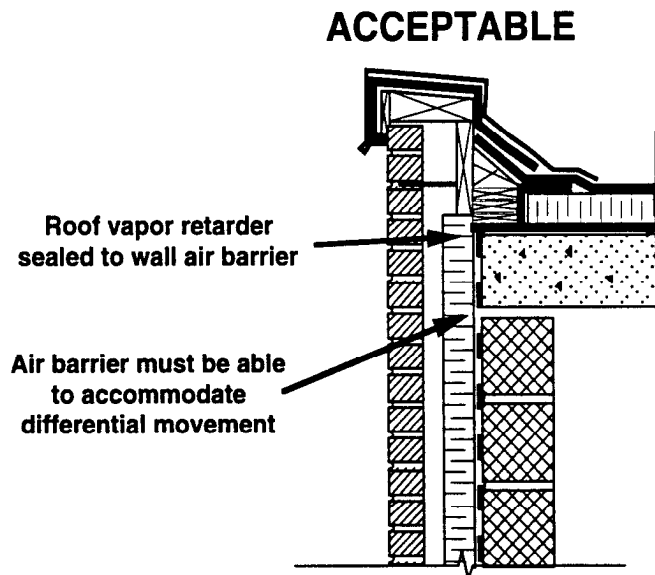


Figure 4.8.7 Masonry Wall/Roof Edge - Concrete Frame (Burn)

The details in Figures 4.8.5 through 4.8.7 still contain discontinuities in the thermal insulation system between the roof and wall insulation. Brand proposes the use of an insulated curb assembly at this location to solve this problem, as shown in Figure 4.8.8 for a steel frame building. The use of such a curb assembly is somewhat unusual, but it does have advantages. The insulation keeps the air barrier beneath it warm. Also, the assembly allows the roofing and flashing to be completed before the walls are erected.

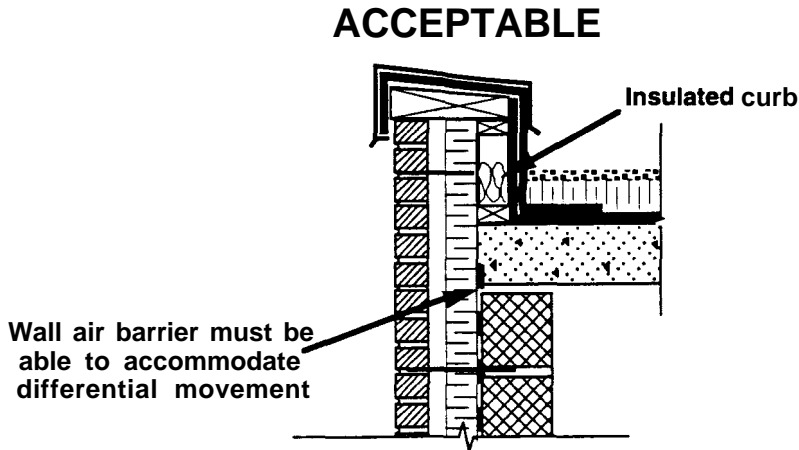


Figure 4.8.8 Masonry Wall/Roof Edge - Concrete Frame (Brand)

Figure 4.8.9 shows a wall/roof intersection for a metal stud wall (Quirouette). The exterior gypsum serves as the air barrier, running past the spandrel beam. Flexible membranes are used to seal the air barrier at the top of the stud wall. The wall air barrier is sealed to the roof membrane to prevent air leakage. Shortened studs are used to allow deflection of the spandrel beam.

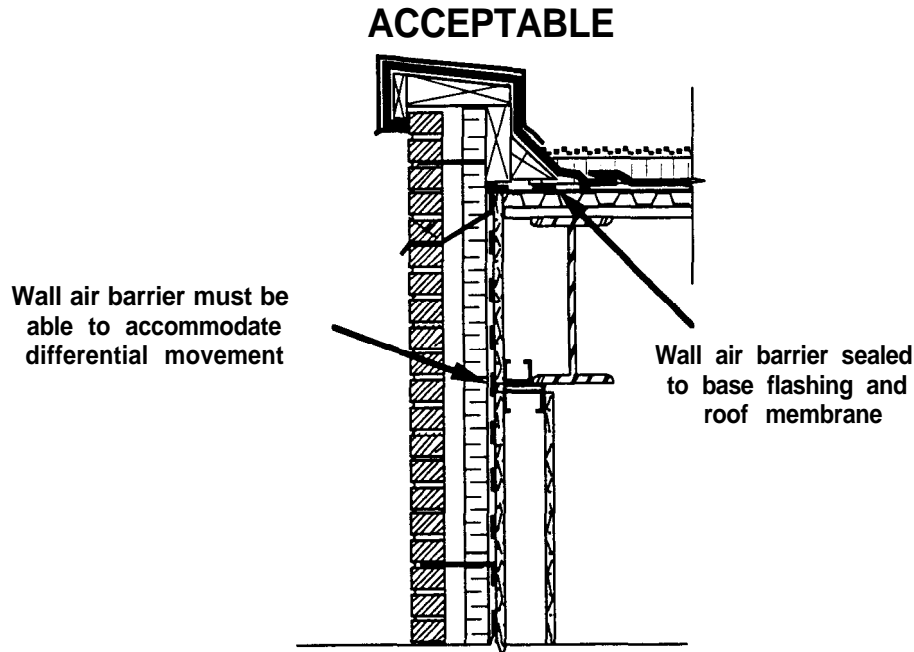


Figure 4.8.9 Metal Stud Wall/Roof Connection (Quirouette)

Similar details to those shown above can be developed for other wall systems. Examples of many such details are given in Brand.

Roof Penetrations

The continuity of the roof vapor retarder, thermal insulation and roofing membrane are inevitably violated by various penetration including equipment supports and drains. These penetrations can be the sites of both air and water leakage leading to a variety of problems, including thermal bridging, air leakage, condensation, and wetted insulation. Penetrations must be carefully designed and constructed with proper flashing, seals and thermal insulation. Flashing and sealant details for a variety of penetrations are contained in the NRCA manual. The examples below address primarily the continuity of the thermal insulation system.

The ORNL catalog of thermal bridges identified three common penetration designs that lead to thermal bridging and contains improved alternate design details (Steven Winter Associates). The first thermal bridge is at the penetration of the roof by a steel railing, which interrupts the thermal insulation, leading to increased heat loss and the potential for condensation. The alternate design substitutes glass fiber for steel in the railing and its connections to the deck.

Figure 4.8.10 shows a thermally bridging equipment support consisting of a column that extends through the insulated roof deck. In the alternative design, insulation is attached to the outside of the columns to reduce the heat transfer and decrease the condensation potential.

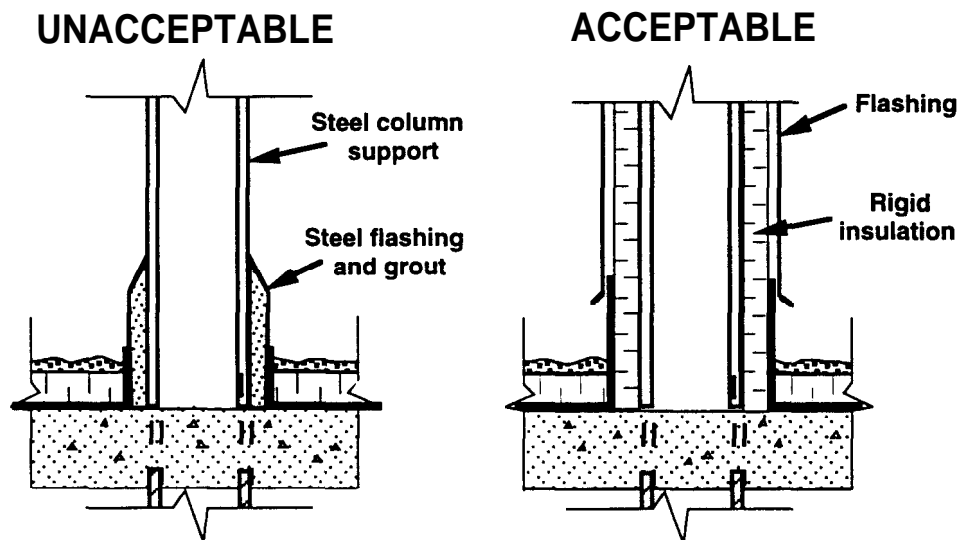


Figure 4.8.10 Heavy Structural Support (Steven Winter Associates)

A thermally bridging support for light equipment is shown in Figure 4.8.11. In the base case a steel support plate is mounted on a steel pipe, acting as a thermal bridge and increasing the condensation potential. In the alternative design, the outside of the pipe is insulated to reduce the heat transfer.

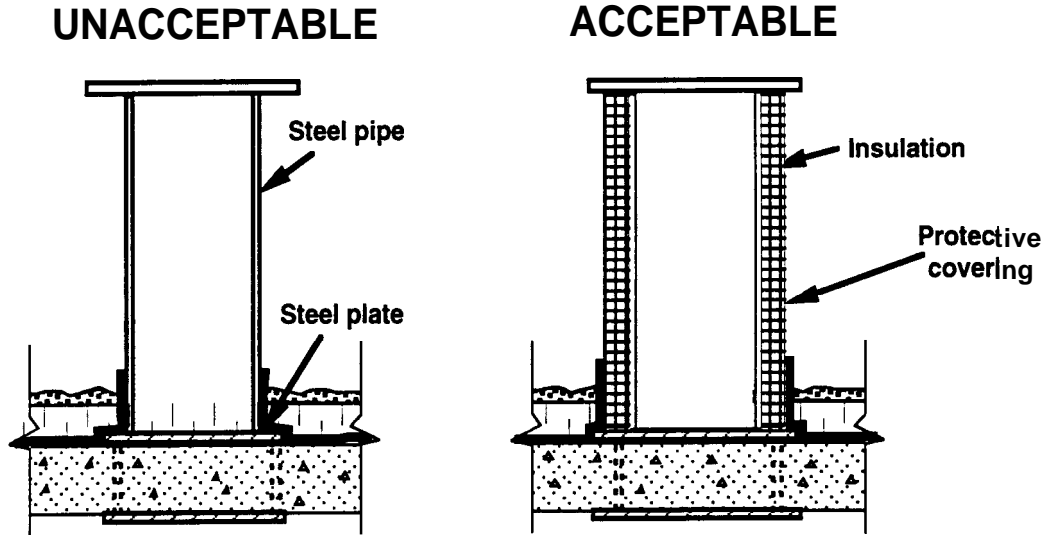


Figure 4.8.11 Light Structural Support (Steven Winter Associates)

Figure 4.8.12 shows a roof drain with a severe insulation discontinuity, along with a thermally improved alternative. In the base detail, the insulation stops far short of the drain and the space around the hub of the drain is open. The alternate detail includes a thermal break between the clamp and the slab, and the air space around the hub is filled with insulation.

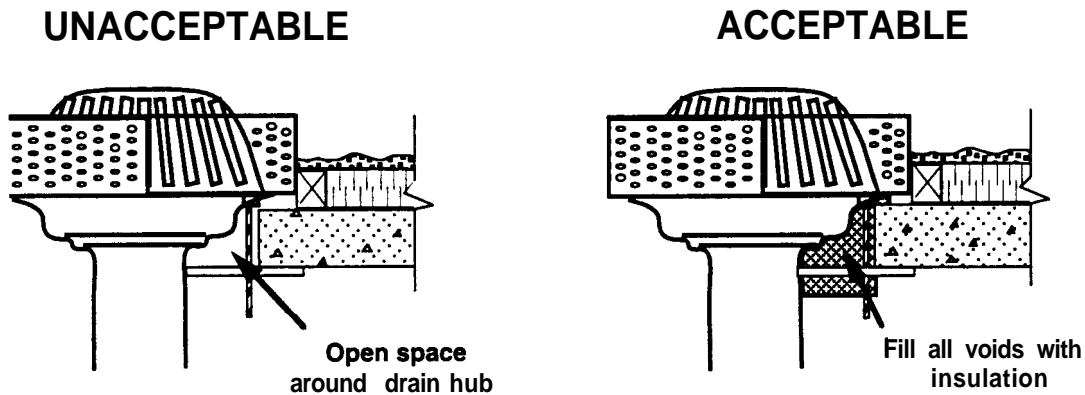


Figure 4.8.12 Roof Drain

The last penetration thermal bridge, shown in Figure 4.8.13, is at a roof expansion joint. In the base case the concrete block curbs on either side of the joint are uninsulated, resulting in thermal bridging. This is also a common situation in parapets, mechanical equipment curbs and various other roof penetrations. In the alternate detail, insulation is installed completely around the curbs, eliminating the thermal bridging except at the required fasteners.

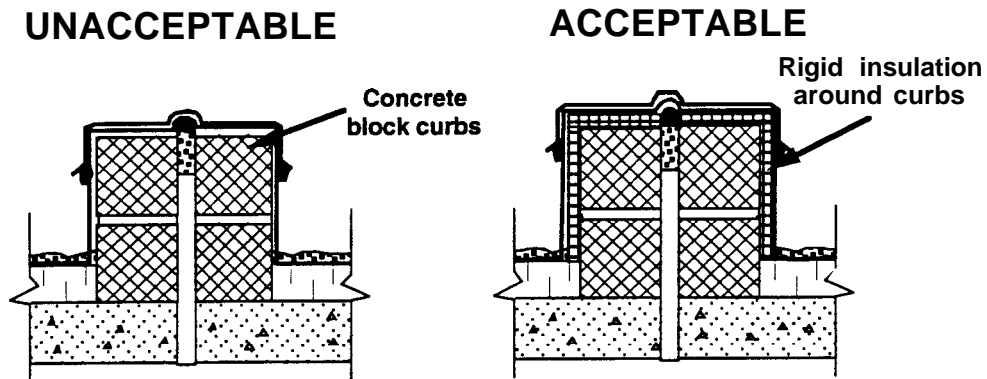


Figure 4.8.13 Roof Expansion Joint

Design and Construction Issues

The design and construction of a roofing system with good thermal performance and good air and water tightness requires the careful development of details and specifications at all penetrations. As the construction proceeds, all work needs to be carefully inspected. Special care must be exercised to protect work at the end of the day to prevent moisture intrusion into roofing materials. To that end, these same materials must be protected and kept dry prior to installation to keep water out of the roofing system at the construction stage. As good as the design and construction might be, a good roofing inspection and maintenance program should be established to identify and repair any problems that develop over the life of the roofing system.

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APPENDICES

- A Bibliography**
- B Glossary**
- C Organizations**
- D Diagnostics**
- E NIBS Project Committee**

A BIBLIOGRAPHY

This section contains a bibliography of publications considered in the preparation of the design guidelines. These documents are organized according to the following categories:

Construction Manuals and Architectural Guides

Wall Systems

Diagnostics

Measured Performance of Envelope Systems

Airtightness and Ventilation

Thermal Bridges

Roofing Systems

Fenestration

Sealants and Water Leakage

General

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B GLOSSARY

The following glossary contains terms relevant to discussions of the thermal performance of building envelopes. Many of the definitions are based on the glossaries of the documents referenced at the end of this section.

Adhesion - the clinging or sticking together of two surfaces. The state in which two surfaces are held together by forces at the interface.

Adhesive - a substance capable of holding materials together by surface attachment.

Adhesive Failure - type of failure characterized by pulling the adhesive or sealant loose from the substrate surface.

Aging - the progressive change in the chemical and physical properties of a sealant or adhesive.

Air Barrier (sometimes referred to as Air Retarder) - an assembly or building element that provides resistance to through-flow of air from inside to outside or vice-versa.

Air Infiltration - air leakage into a building. Conversely, air exfiltration is air leakage out of a building.

Air Leakage - the passage of uncontrolled air through cracks or openings in the building envelope or its components because of air pressure differences.

Alligatoring - cracking of a surface into segments so that it resembles the hide of an alligator.

Ambient Temperature - temperature of the air surrounding the object under construction.

As-built - pertaining to the as-constructed state of a finished product relating to size, shape, materials, and finish regardless of drawings or specifications.

Asphalt - naturally occurring mineral pitch or bitumen.

Back-up - a compressible material used at the base of a joint opening to provide the proper shape factor in a sealant. This material can also act as a bond-breaker.

Bead - a sealant or compound after application in a joint irrespective of the method of application, such as caulking bead, glazing bead, and so on.

Bedding Compounds - any material into which another material such as a plate of glass or a panel, may be embedded for close fit.

Bond-Breaker - thin layer of material such as tape used to prevent the sealant from bonding to the bottom of the joint.

Bond Durability. a test cycle in ASTM C-920 for measuring the bond strength after repeated weather and extension cycling.

Building Envelope - the outer elements of a building, both above and below ground, that divide the external from the internal environments.

Built-Up Roofing - a roof covering made up of alternating layers of tar and asphaltic materials.

Butt Joint - a joint having the edge or end of one member matching the edge, end, or face of another member without overlap.

Butyl Rubber - a copolymer of essentially isobutene with small amounts of isoprene. As a sealant it has low recovery and slow cure.

Capillary Migration - movement of water induced by the force of molecular attraction (surface tension) between the water and the material it contacts.

Caulk (noun) - a material with a relatively low movement capability, usually less than + 10%. Generally refers to oil-based caulks, and sometimes to butyl and acrylic latex caulks.

Caulk (verb) - to install or apply a sealant across or into a joint, crack, or crevice in order to prevent the passage of air or water.

Closed-cell Foam - A foam that will not absorb water because all the cells have complete walls.

Closed Cell - a cell totally enclosed by its walls and hence not interconnecting with other cells.

Cohesion - the molecular attraction that holds the body of a sealant or adhesive together. The internal strength of an adhesive or sealant.

Cohesive Failure - failure characterized by rupture within the sealant, adhesive, or coating.

Compatibility - the capability of two or more materials to be placed in contact or close proximity with one another and each material maintaining its usual physical or chemical properties, or both.

Compression gasket - a gasket designed to be used under compression.

Compression Seal - a preformed seal that is installed by being compressed and inserted into the joint.

Compression Set - the amount of permanent set that remains in a specimen after removal of a compression load.

Condensation - the change of state of a vapor into a liquid by extracting heat from the vapor.

Construction Joint - in the construction of members intended to be continuous, a predetermined, intentionally created discontinuity between or within constructions and having the ends of the discontinuous members fastened to each other to provide structural continuity.

Control Joint - a formed, sawed, tooled or assembled joint acting to regulate the location and degree of cracking and separation resulting from the dimensional change of different elements of a structure.

Crack - a flaw consisting of complete or incomplete separation within a single element or between contiguous elements of constructions.

Crazing - a series of fine cracks that may extend through the body of a layer of sealant or adhesive.

Creep - the deformation of a body with time under constant load.

Cure - to set up or harden by means of a chemical reaction.

Dew-Point Temperature - the temperature at which condensation of water vapor begins for a given humidity and pressure as the vapor temperature is reduced. The temperature corresponding to saturation (100 percent relative humidity) for a given absolute humidity at constant pressure.

EIFS (exterior insulation and finish system) - non-load-bearing outdoor wall finish system consisting of a thermal insulation board, an attachment system, a reinforced base coat, exterior joint sealant, and a compatible finish.

Elasticity - the ability of a material to return to its original shape after removal of a load.

Elastomer - a macromolecular material that returns rapidly to approximately the initial dimensions and shape after substantial deformation by a weak stress and release of the stress.

Elastomeric - having the characteristics of an elastomer.

Epoxy - a resin formed by combining epichlorohydrin and bisphenols. Requires a curing agent for conversion to a plastic-like solid. Has outstanding adhesion and excellent chemical resistance.

Expansion Joint - a discontinuity between two constructed elements or components, allowing for differential movement (such as expansion) between them without damage.

Extrusion Failure - failure that occurs when a sealant is forced too far out of the joint. The sealant may be abraded by dirt or folded over by traffic.

Flashing - strips, usually of sheet metal or rubber, used to waterproof the junctions of building surfaces, such as roof peaks and valleys, and the junction of a roof and chimney.

Gasket - any preformed, deformable device designed to be placed between two adjoining parts to provide a seal.

Glazing - the installation of glass or other materials in prepared openings.

Gunability - the ability of a sealant to extrude out of a cartridge in a caulking gun.

Heat Transfer - flow of heat energy induced by a temperature difference.

Conduction - heat transfer whereby heat moves through a material; the flow of heat due to temperature variations within a material.

Convection - heat transfer by movement of a fluid or gas.

Radiation - heat transfer through space by electromagnetic waves emitted due to temperature.

Humidity, Absolute - the weight of water vapor per unit volume.

Humidity, Relative - the ratio of water vapor present in air to the water vapor present in saturated air at the same temperature and pressure.

Hypalon - a chlorosulfonated polyethylene synthetic that has been used as a base for making solvent-based sealants.

Insulation - a material used in building construction to retard the flow of heat through the enclosure. It is made from a variety of organic and inorganic fibers and foams, e.g., expanded/extruded polystyrene, glass fiber, cellular glass, phenolic foam, perlite, polyurethane foam, polyisocyanurate foam. It can be loose-filled, or used in batt, board, or block form..

Isolation Joint - a formed or assembled joint specifically intended to separate and prevent the bonding of one element of a structure to another and having little or no transference of movement or vibration across the joint.

Jamb - the side of a window, door opening, or frame.

Joint - the space or opening between two or more adjoining surfaces.

Lap Joint - a joint in which the component parts overlap so that the sealant or adhesive is placed into shear action.

Latex - a colloidal dispersion of a rubber resin (synthetic or natural) in water, which coagulates on exposure to air.

Latex Caulks - a caulking material made using latex as the raw material. The most common latex caulks are polyvinyl acetate or vinyl acrylic.

Latex Sealant - a compound that cures primarily through water evaporation.

Lock-strip Gasket - a gasket in which sealing pressure is attained by inserting a keyed locking strip into a mating keyed groove in one face of the gasket.

Masonry - construction, usually set in mortar, of natural building stone or manufactured units such as brick, concrete block, adobe, glass block, tile, manufactured stone, or gypsum block.

Mastic - a thick, pasty coating.

Mechanical Connection - a joining of two or more elements by means of mechanical fasteners, such as screws, bolts, or rivets but not by welding or adhesive bonding.

Metal Building System - a complete integrated set of mutually dependent components and assemblies that form a building including primary and secondary framing, covering and accessories, and are manufactured to permit inspection on site prior to assembly or erection.

Mullion - external structural member in a curtain-wall building. Usually vertical. May be placed between two opaque panels, between two window frames, or between a panel and a window frame.

Open Cell - a cell not totally enclosed by its walls and hence interconnecting with other cells.

Open-Cell Foam - a foam that will absorb water and air because the walls are not complete and run together.

Panel - (1) a portion of a surface flush with, recessed from, or sunk below the surrounding area: (2) a usually flat and rectangular piece of construction material made to form part of a surface (as of a wall, ceiling, or floor).

Parapet - that portion of the vertical wall of a building which extends above the roof line.

Preformed Sealant - a sealant that is preshaped by the manufacturer before being shipped to the job site.

Preshimmed Sealant - a sealant in tape or bulk form having encapsulated solids or discrete particles that limit its deformation within a joint under compression.

Pressure-Sensitive Adhesive - adhesive that retains tack after release of the solvent so that it can be bonded by simple hand pressure.

Primer - a compatible coating designed to enhance adhesion.

Purlin - a horizontal structural member which supports roof covering.

R-Value - a measure of the insulating value of a substance, or measure of a material's resistance to the flow of heat. It's reciprocal is referred to as an U-value.

Sandwich Panel - a panel assembly used as covering; consists of an insulating core material with inner and outer panels or skins.

Seal (noun) - a material applied in a joint or on a surface to prevent the passage of liquids, solids, or gases.

Sealant - a material that has the adhesive and cohesive properties to form a seal. Sometimes defined as an elastomeric material with a movement capability greater than + 10%.

Sealant Backing - a compressible material placed in a joint before applying a sealant.

Sealer - a surface coating generally applied to fill cracks, pores, or voids in the surface.

Sealing Tape - a preformed, uncured or partially cured material which when placed in a joint, has the necessary adhesive and cohesive properties to form a seal.

Shelf Life - the length of time a sealant or adhesive can be stored under specific conditions and still maintain its properties.

Shop Drawing - a drawing prepared by the fabricator based on a working drawing and used in a shop or on a site for assembly.

Shrinkage - percentage weight loss or volume loss under specified accelerated conditions.

Silicone Rubber - a synthetic rubber based on silicon, carbon, oxygen, and hydrogen. Silicone rubbers are widely used as sealants and coatings.

Silicone Sealant - a liquid-applied curing compound based on polymer(s) of polysiloxans structures.

Solvent - liquid in which another substance can be dissolved.

Solvent-release Sealant - a compound that cures primarily through solvent evaporation.

Spacer - a piece of resilient material placed to maintain space between a pane of glass or a panel and its supporting frame.

Spalling - a surface failure of concrete, usually occurring at the joint. It may be caused by incompressibles in the joint, by overworking the concrete, or by sawing joints too soon.

Stopless Glazing - the use of a sealant as a glass adhesive to keep glass in permanent position without the use of exterior stops.

Stress Relaxation - reduction in stress in a material that is held at a constant deformation for an extended time.

Structural Glazing Gaskets - a synthetic rubber section designed to engage the edge of glass or other sheet material in a surrounding frame by forcing an interlocking filler strip into a grooved recess in the face of the gasket.

Structural Sealant - a sealant capable of transferring dynamic or static ("live" or "dead", or both,) loads, or both, across joint members exposed to service environments typical for the structure involved, as in stopless glazing.

Substrate - (1) a material upon which films, treatments, adhesives, sealants, membranes, and coatings are applied; (2) materials that are bonded or sealed together by adhesives or sealants.

Tape Sealant - a sealant having a preformed shape, and intended to be used in a joint initially under compression.

Thermal Bridge - a heat-conductive element in a building assembly that extends from the warm to the cold side and provides less heat-flow resistance than the adjacent construction.

Thermal Conductance - the time rate of heat flow expressed in per unit area and unit temperature gradient. The term is applied to specific materials as used, either homogenous or heterogeneous for the thickness of construction stated, not per meter of thickness.

Thermal Conductivity - the time rate of heat flow, by conduction only, through a unit thickness of a homogenous material under steady-state conditions, per unit area, per unit temperature gradient.

Tolerance - the allowable deviation from a value or standard; especially the total range of variation permitted in maintaining a specified dimension in machining, fabricating, or constructing a member or assembly.

Tooling - the act of compacting and contouring a sealant in a joint.

Tooling Time - The time interval after application of a one-component sealant or after mixing and application of multi-component sealant during which tooling is possible.

U-Value - the capability of a substance to transfer heat. Used to describe the conductance of a material, or a composite of materials, in construction. Its reciprocal is referred to as an R-value.

Vapor Retarder - a material or construction that retards water vapor migration, generally not exceeding one perm for ordinary houses in non-extreme climates.

Wall - a part of a building that divides spaces vertically.

Bearing wall - a wall supporting a vertical load in addition to its own weight.

Curtain wall - a nonbearing exterior wall, secured to and supported by the structural members of the building.

Nonbearing wall - a wall that does not support a vertical load other than its own weight.

Water-Repellent - a material or treatment for surfaces to provide resistance to penetration by water.

Waterproofing - treatment of a surface or structure to prevent the passage of liquid water under hydrostatic, dynamic, or static pressure.

Weephole - a small hole allowing drainage of fluid.

Windows and doors -

Frame - an assembly of structural members that surrounds and supports the sash, ventilators, doors, panels, or glazing that is installed into an opening in a building envelope or wall.

Glazing - a material installed in a sash, ventilator, or panel such as glass, plastic, etc.

Head - an upper horizontal member of a window or door frame.

Jamb - a vertical member of a window or door frame.

Mullion - a member used between windows or doors as a means of connection, which may or may not be structural.

Muntin - a member used between lites of glazing within a sash, ventilator, or panel.

Operable - describing a sash, ventilator, or panel designed to be opened and closed.

Sill - a lower horizontal member of a window or sliding door frame.

Working Drawing - A detail drawing, usually produced by a draftsman under direction of an architect, engineer, or other designer showing form, quantity, and relationship of construction elements and materials; indicating their location, identification, grades, dimensions, and connections.

Working Life - the time interval after opening a container of a single component sealant, or after mixing the components of a multi-component sealant, during which application and tooling is possible.

References

ASTM E241, Standard Practices for Increasing Durability of Building Constructions Against Water-Induced Damage.

ASTM E717, Standard Terminology of Building Seals and Sealants.

ASTM E631, Standard Terminology of Building Constructions.

Lstiburek, J., J. Carmody, Moisture Control Handbook. New. Low-Rise. Residential Construction, Report ORNL/Sub/89-SD350/1, Oak Ridge National Laboratory, 1991.

MBMA, Low Rise Building Systems Manual, Metal Building Manufacturers Association, Cleveland, Ohio, 1986.

Panek, J.R., J.P. Cook, Construction Sealants and Adhesives, 2nd Edition, John Wiley & Sons, New York, 1984.

PCI, Architectural Precast Concrete, Precast/Prestressed Concrete Institute, Chicago, 1989.

C ORGANIZATIONS

This section contains the names and addresses of various organizations involved in the design and construction of building envelopes.

American Architectural Manufacturers Association
1540 East Dundee Road, Suite 310
Palatine, IL 60067
(708) 202-1350

American Concrete Institute
P.O. Box 19150
Redford Station
Detroit, MI 48219
(313) 532-2600

American Institute of Architects
1735 New York Avenue NW
Washington, DC 20006
(202) 626-7300

American Iron and Steel Institute
1101 17th Street NW
Washington, DC 20036
(202) 452-7100

ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
1791 Tullie Circle NE
Atlanta, GA 30329
(404) 636-8400

ASTM, American Society for Testing and Materials
1916 Race Street
Philadelphia, PA 19103
(215) 299-5400

Brick Institute of America
11490 Commerce Park Drive
Reston, VA 22091
(703) 620-0010

Canada Mortgage and, Housing Corporation
700 Montreal Road
Ottawa, Ontario
K1A0P7
(613) 748-2000

The Construction Specifications Institute
601 Madison Street
Alexandria, VA 22314
(703) 684-0300

Exterior Insulation Manufacturers Association
2759 State Road, Suite 12
Clearwater, FL 34621
(813) 726-6477

The Foundation of the Wall and Ceiling Industry
1600 Cameron Street
Alexandria, VA 22314
(703) 548-0374

Indiana Limestone Institute of America, Inc.
Stone City Bank Building, Suite 400
Bedford, IN 47421
(812) 275-4426

Insulation Contractors Association of America
15819 Crabbs Branch Way
Rockville, MD 20855
(301) 590-0030

Masonry Advisory Council
1480 Renaissance Drive
Park Ridge, IL 60068
(708) 297-6704

Metal Buildings Manufacturers Association
1300 Sumner Avenue
Cleveland, OH 44115
(216) 241-7333

National Concrete Masonry Association
2302 Horse Pen Road
Herndon, VA 22071
(703) 713-1900

National Insulation and Abatement Contractors Association
99 Canal Center Plaza, Suite 222
Alexandria, VA 22314
(703) 683-6422

National Roofing Contractors Association
O'Hare International Center
10255 West Higgins Road, Suite 600
Rosemont, IL 60018
(708) 299-9070

North American Insulation Manufacturers Association
44 Canal Center Plaza
Alexandria, VA 22314
(703) 684-0084

Portland Cement Association
5420 Old Orchard Road
Skokie, IL 60077
(708) 966-6200

Precast/Prestressed Concrete Institute
175 West Jackson Boulevard
Chicago, IL 60604
(312) 786-0300

Sealant, Waterproofing and Restoration Institute
3101 Broadway, Suite 585
Kansas City, MO 64111
(816) 561-8230

The Society of the Plastics Industry, Inc.
Expanded Polystyrene Division
Polyurethane Foam Contractors Division
1275 K Street NW, Suite 400
Washington, DC 20005
(202) 523-6154

D THERMAL ENVELOPE DIAGNOSTIC TECHNIQUES

Diagnostic techniques have been developed to investigate the thermal performance of building envelopes as installed. These techniques have served to identify many of the performance problems referred to in these guidelines and also provide practical tools for investigating their existence in any given building through a program of envelope testing during the construction phase of a project. This section discusses the diagnostic techniques along with measurement standards and performance ratings relevant to each. Detailed descriptions of these diagnostic techniques are provided in the listed standards and references. More general descriptions, along with example test results are contained in Persily [1986 and 1988] and Grot [1985].

As discussed below, some of these techniques can be applied to a mock-up of the thermal envelope prior to construction in order to assess the thermal performance of the design when the opportunity still exists to modify the design. Other techniques are applicable to the completed building envelope to assess the as-built performance. These diagnostic techniques are not generally employed in all building projects, though they are more common in larger projects. The American Architectural Manufacturers Association (AAMA) suggests the use of diagnostic testing on curtain walls and has developed useful documents describing the test methods and guide specifications for their use.

The diagnostic techniques presented in this section are organized into the following areas:

Heat Conduction

Airtightness

Water Leakage

Test Standards

Heat Conduction

Infrared Thermography

Infrared thermography can be used to evaluate qualitatively, and quantitatively to a limited degree, the effectiveness of a building envelope's thermal insulation system. The technique is covered by ISO Standard 6781-1983, and in the case of wood frame buildings ASTM C 1060. Infrared thermography employs a thermal imaging system to evaluate the continuity of the thermal insulation system over the building envelope and to locate and characterize any thermal defects. The imaging system is used to provide an image of the envelope surface in which the variations in intensity over the surface correspond to variations of the apparent radiant temperature along the surface. Under appropriate test conditions, these variations are due to differences in the heat flow through the surface caused by variations in the thermal resistance. A thermographic inspection involves assessing the heat loss characteristics of the building envelope through such a thermal image. An inspection can be conducted from both inside and outside a building as long as the building interior is heated or cooled to a temperature significantly different from the outside. The technique can also be applied to an envelope mock-up if one side is heated or cooled. Requirements regarding test equipment and environmental conditions during the test are contained in the measurement standards.

While the inspection results, thermograms of the envelope surfaces, do not lend themselves to quantitative determinations of envelope thermal resistance, a qualitative characterization can be made of the insulation system's performance. Various thermal defects can be identified including insulation voids, air leakage sites, and thermal bridges. Drawings of envelope design details can be helpful in interpreting the results of the survey.

Guarded and Calibrated Hot Box Measurements

Guarded and calibrated hot boxes are both devices used to determine the heat transmission rate through a mock-up of a building envelope. They are the subject of ASTM Standards C 236 and C 976, respectively. In both of these techniques, the envelope mock-up is placed between two environmentally-controlled chambers, and a temperature difference is maintained across the specimen. The rate of heat transmission through the specimen is then measured. The R-value of the specimen is equal to the area of the test specimen multiplied by the temperature difference across it, divided by the heat transmission rate measured through the specimen. The two techniques differ in how they determine the value of this heat transmission rate. Both techniques measure this heat transmission rate under steady-state conditions, and the requirements for determining the existence of steady-state as well as other test conditions are given in the ASTM standards. Several commercial and research laboratories across the country possess such hot boxes and conduct these measurements routinely.

Portable Calorimeters

Portable calorimeter boxes have been developed to measure in-situ envelope R-values, though the measurement procedure has not yet been standardized. The technique can be used in new or existing buildings, as long as there is a sufficient indoor-outdoor temperature difference. The calorimeter is a five-sided, insulated box containing an electric heater. The open side of the box is sealed against the outside wall that is being tested. Once installed, the heater is controlled to maintain a zero degree temperature difference between the box and the building interior; thus all the heat supplied to the box passes through the wall to the outdoors. The dimensions of the box can vary but should be large enough to include several stud spaces so that their effect on the R-value is included in the measurement. The test requires a fairly constant indoor temperature and an average indoor-outdoor temperature difference of around 10 °C (20 °F). The outdoor temperature need not be constant, but it must always be below the indoor temperature. The test must last several days in order to avoid inaccuracies associated with envelope thermal mass effects, and the test wall should not be subject to any thermal loading due to solar insolation. A more detailed description of the technique and additional references is contained in Persily (1986 and 1988).

Heat Flux Transducers

The heat transmission of small areas of the thermal envelope can be measured with heat flux transducers. The use of these devices to measure heat flux rates is described in ASTM C 1046, but this standard does not describe their application for measuring wall R-values. Additional information for this particular application is given in Persily (1986 and 1988). Heat flux transducers are thin devices composed of a thermopile for sensing the temperature difference between the two sides of the device. The thermal resistance across the transducer is known, and therefore the measured temperature differences across it can be related to the heat flux through it. In a heat transmission measurement of a wall section, several heat flux transducers are affixed at key locations on the wall, and the heat flux at each location is monitored over time. The heat flux measured at these locations is then related to the average temperature difference across the wall during the test to determine its R-value. These measurements can be made on an envelope mock-up, given some means of maintaining a temperature difference across it during the test. More commonly, these measurements are made in the field.

Airtightness

Component Pressurization Testing

The airtightness of building envelope components, e.g. windows, doors or larger wall sections, can be measured with pressurization testing. ASTM E 283 describes the test procedure as applied to an envelope mock-up. ASTM E783 describes the use of the test procedure in the field. In both cases a chamber is sealed around the test specimen and an air-moving device is used to establish and maintain an air pressure difference across the specimen. Both the pressure difference and airflow rate are then measured at a series of pressure differences to determine the airtightness of the component being tested. Specific requirements of the test equipment are described in detail in the standards including requirements for the chamber, the air-moving system, and equipment for measuring the pressure difference, airflow rate and other parameters. The results of these tests are generally reported as the airflow rate per unit length of specimen perimeter or per unit area of specimen at some specific pressure difference, usually 75 Pa (0.3 in. water, 1.57 psf).

Whole Building Pressurization Testing

The overall airtightness of an entire building envelope can be measured using whole building pressurization testing. This technique is described in detail in ASTM E 779. In this procedure a large fan induces a large and uniform pressure difference across the building envelope, and the airflow rate required to induce and maintain this pressure difference is measured. The airflow rate required to induce a specific reference pressure difference then serves as a measure of the envelope airtightness. Although the test conditions differ considerably from those that normally induce envelope air leakage or infiltration, pressurization testing provides a repeatable and relatively quick measurement of building air-tightness. The technique has been applied to a number of commercial buildings using either a large fan brought to the site, or more often, the existing air handling equipment. When using the building air handlers to conduct a pressurization test, one modulates the airflow through them to obtain a series of inside-outside pressure differences and measures the airflow rate through the air handlers at each pressure difference. If the building is being subjected to a positive pressure difference, one uses the supply fans with 100% outdoor air while sealing all recirculation and exhaust dampers. If the building is being depressurized, one uses the exhaust fans and seals all intake dampers. A detailed description of the technique as applied to large commercial buildings is contained in Persily (1986).

Tracer Gas Measurements of Air Exchange

Building air change rates can be measured with the tracer gas decay technique as described in ASTM E 741. These measurements determine the air change rate caused by weather-induced pressure differences, which serves as a measure of the envelope airtightness. The technique can also be used to determine the air change rate when mechanical ventilation equipment is in operation, though envelope airtightness is not the primary determinant of the air change rate under these conditions. In the tracer gas decay technique, a volume of tracer gas is released in a building and allowed to mix with the interior air until a uniform tracer gas concentration is achieved within the building. The tracer gas concentration decay is then monitored and the rate of decay is related to the air exchange rate of the building during the test. The measurement technique is based on the assumption that the tracer gas concentration is uniform throughout the entire building, and if this assumption is valid then the measurement determines the air exchange rate for the entire building. These measurements can be conducted as soon as the exterior envelope is complete, though it is preferable if they are conducted when the building is being space conditioned so there is a temperature difference to induce infiltration.

Water Leakage

Along with the heat transmission and airtightness measurements discussed above, there are other performance factors relevant to the thermal envelope. Of particular interest, several test methods exist to assess water leakage including ASTM E 331 and E 1105 and AAMA 501.1, 501.2 and 501.3. Both ASTM E 331 and E 1105 are tests for water penetration of envelope mock-ups using a chamber and subjecting the test specimen to an air pressure difference. The results of the test consists of those location where water leakage occurs, along with the pressure differences to which the specimen was subjected. ASTM E 1105 AAMA 501.1 is a water penetration test of a mock-up in which the specimen is subjected to dynamic pressures. AAMA 501.2 is a field test for water leakage which is recommended for checking the wall early in construction. It enables the detection of fabrication and installation problems when there is still an opportunity to correct them. AAMA 501.3 is a field measurement of water penetration of installed windows, curtain wall and doors subjected to a uniform air pressure difference, using both static and dynamic pressures. AAMA has also developed a specification (AAMA 502) for field testing of windows and sliding glass doors that establishes the requirements of air and water leakage testing using ASTM E 331 and E 1105.

Test Standards

This section contains a list of the test standards cited above.

AAMA 501.1, Standard Test Method for Metal Curtain Walls for Water Penetration Using Dynamic Pressure.

AAMA 501.2, Field Check of Metal Curtain Walls for Water Leakage.

AAMA 501.3, Field Check of Water Penetration through Installed Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference.

AAMA 502, Voluntary Specification for Field Testing of Windows and Sliding Glass Doors.

ASTM C 236, Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box.

ASTM C 976, Standard Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box.

ASTM C 1046, Standard Practice for In-Situ Measurement of Heat Flux and Temperatures on Building Envelope Components.

ASTM C 106, Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Wood Frame Buildings.

ASTM E 283, Standard Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors.

ASTM E 331, Standard Test Method for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference.

ASTM E 741, Standard Test Method for Determining Air Leakage Rate by Tracer Dilution.

ASTM E 779, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.

ASTM E 783, Standard Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors.

ASTM E 1105, Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls and Doors by Uniform or Cyclic Static Air Pressure Difference.

ISO 6781-1983, Thermal Insulation - Qualitative Detection of Thermal Irregularities in Building Envelopes - Infrared Method.

References

AAMA, "Metal Curtain Wall Manual," Aluminum Curtain Wall Series 8, American Architectural Manufacturers Association, Des Plaines, Illinois, 1989.

AAMA, "Methods of Test for Metal Curtain Walls," American Architectural Manufacturers Association, Des Plaines, Illinois, 1983.

Grot, R.A., Persily, A.K., Chang, Y.M., Fang, J.B., Weber, S., Galowin, L.S., "Evaluation of the Thermal Integrity of the Building Envelopes of Eight Federal Office Buildings," NBSIR 85-3147, National Bureau of Standards, Gaithersburg, 1985.

Persily, A.K., "Specifications for Thermal and Environmental Evaluations of Advanced-Technology Office Buildings," NBSIR 86-3462, National Bureau of Standards, Gaithersburg, 1986.

Persily, A.K., Grot, R.A., "Pressurization Testing of Federal Buildings," in Trechsel, H.R. and Lagus, P.L. eds. Measured Air Leakage of Buildings, ASTM STP 904, American Society for Testing and Materials, 1986.

Persily, A.K., Grot, R.A., Fang, J.B., Chang, Y.M., "Diagnostic Techniques for Evaluating Office Building Envelopes," ASHRAE Transactions, 94(2) 1988.

E NIBS PROJECT COMMITTEE

In order to obtain input from the building community, NIST issued a contract to the National Institute of Building Sciences (NIBS) to perform specific tasks related to the development of the guidelines. NIBS established a project committee to solicit voluntary contributions for consideration in the preparation of the guidelines, to assess these materials and to review the guidelines as they were developed. The project committee was formed based on responses to a solicitation sent out by NIBS in May 1990. The committee was chaired by Billy R. Manning, PE. NIBS also contracted with five technical experts to conduct detailed reviews of the guidelines. These reviewers were Harry T. Gordon AIA of Burt Hill Kosar Rittelmann Associates, Steve Kimsey AIA of Heery Energy Engineering, Inc., William Morgan FAIA of William Morgan Architects, and Dart Sageser AIA of Mitchell/Giurgola Architects. The members of the NIBS Project Committee and their affiliations are listed below:

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