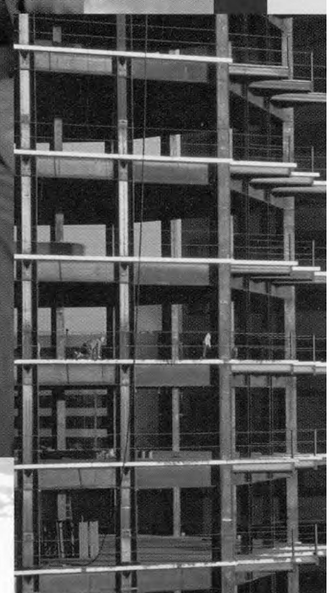
RESEARCH REPORT



Study of High-Rise Envelope Performance in the Coastal Climate of British Columbia

October 2, 2001

Homeowner Protection Office

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STUDY OF HIGH-RISE ENVELOPE PERFORMANCE IN THE COASTAL CLIMATE OF BRITISH COLUMBIA

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EXECUTIVE SUMMARY

The purpose of this study was to identify causal relationships that have resulted in building envelope problems and successes, in non-combustible high-rise residential buildings in the coastal climate area of BC. This was done by correlating building envelope performance with sources of moisture, and features of design and construction of assemblies and details. This study has facilitated the identification of key factors for successful design and construction of the building envelope assemblies and details.

Thirty-five buildings were studied, with 151 wall and window assemblies and 131 assembly interfaces. Sixty performance problems were described. Eight different types of cladding were included in the study although the majority of the walls were clad either with stucco or EIFS. The buildings ranged in height from 5 storeys to 28 storeys.

The results of the study indicate that exterior moisture penetration at interfaces between assemblies and at details within assemblies is the dominant cause of moisture problems in high-rise buildings. It also found that windows were a focal point for moisture problems. Complexity of building form and overhangs were not found to be a significant influence on performance. This reflects the general lack of occurrence of meaningful overhangs on high-rise buildings walls as well as the overwhelming influence of detailing, rather than the ineffectiveness of overhangs. For example, balcony doors were not generally found to be problems due to the large overhangs provided by the balcony slab above. None of the walls that incorporated drainage cavities were found to have experienced problems. The majority of the moisture related damage that is causing repairs to be initiated is corrosion of concealed metal components including the steel studs and fasteners. Severe damage was found to occur to exterior gypsum sheathing whereas walls utilizing glass fibre faced gypsum sheathing showed lower extent and severity of damage. Mechanical ventilation provisions for high-rise buildings are not adequately controlling interior humidity conditions.

The key recommendations for improvement in design and construction practices include the need for better design of interfaces between assemblies as well as details within assemblies. In addition, the need for better guidance regarding environmental design loads was identified, and with knowledge of these loads the appropriate selection and design of wall and window assemblies for the higher exposure conditions that typify high-rise buildings. In particular, rainscreen assemblies were identified as being required for most buildings. The durability expectations for assemblies, details, components and materials should be better articulated in standards and guidelines to facilitate the use of materials that will be durable in the service environments. In particular, corrosion resistance was identified as an area requiring greater guidance as was the use of more moisture resistant sheathing products such as glass fibre faced gypsum sheathing. Mechanical ventilation systems and air flow within buildings was identified as an area requiring additional research as well as more consistent application of known principles.

RÉSUMÉ

L'étude avait pour objectif de déterminer les causes des défectuosités ou des cas de réussites relativement à l'enveloppe des tours d'habitation incombustibles situées dans le climat côtier de la Colombie-Britannique. Pour ce faire, on a établi une corrélation entre la performance de l'enveloppe et les sources d'humidité, ainsi qu'avec les caractéristiques de conception et de construction des assemblages et des détails. L'étude a permis de cerner les facteurs clés pouvant mener à une conception et à une construction valable des assemblages et des détails de l'enveloppe.

Trente-cinq bâtiments ont été examinés, ainsi que 151 assemblages de murs et de fenêtres en plus de 131 interfaces d'assemblage. Soixante défauts de performance ont été découverts. L'étude a porté sur huit différents types de parements même si la majorité des murs étaient revêtus de stucco ou comportaient un SIFE. La hauteur des bâtiments est comprise dans une fourchette de 5 à 28 étages.

Les résultats de l'étude montrent que les problèmes d'humidité dans les tours résultent principalement de l'infiltration de l'humidité extérieure par les interfaces entre les assemblages et les détails des assemblages proprement dits. On a aussi découvert que les problèmes d'humidité étaient concentrés autour des fenêtres. Ni la complexité des formes du bâtiment ni la présence de saillies ou d'encorbellement n'ont eu de répercussions significatives sur la performance, ce qui montre bien la difficulté, pour les concepteurs, à prévoir des saillies efficaces sur les tours ainsi que l'influence massive des détails. Aucun des murs dotés d'orifices d'évacuation de l'humidité n'a affiché de problème. Les réparations résultant de la majorité des dommages causés par l'humidité ont trait à la corrosion de composants métalliques cachés, notamment l'ossature d'acier des murs et les fixations. Les revêtements intermédiaires en plaques de plâtre ont subi des dégâts sérieux, alors que les murs comportant un revêtement intermédiaire de plaques de plâtre revêtus de fibre de verre étaient beaucoup moins endommagés. Les exigences relatives à la ventilation mécanique dans les tours ne parviennent pas à maîtriser les taux d'humidité intérieurs.

Selon l'étude, il importe donc d'améliorer la conception des interfaces entre les assemblages ainsi que les détails des assemblages à proprement parler. On a également établi qu'il fallait de meilleures lignes de conduite en matière de surcharges environnementales, et qu'avec une meilleure connaissance de ces surcharges, on arriverait à concevoir et à choisir des assemblages de murs et de fenêtres pouvant répondre aux exigences d'exposition plus élevées associées aux tours. Plus particulièrement, on a déterminé que les écrans pare-pluie étaient nécessaires dans la plupart des bâtiments. Les attentes quant à la durabilité des assemblages, des détails, des composants et des matériaux devraient être mieux articulées dans les normes et les lignes de conduite dans le but de favoriser l'utilisation des matériaux durables dans leur milieu environnant. La résistance à la corrosion a été spécifiquement signalée comme domaine requérant plus de directives de même que l'utilisation de revêtements intermédiaires plus résistants à l'humidité tels que ceux revêtus de fibre de verre. On a déterminé qu'il fallait mettre plus

d'effort de recherche dans le domaine des installations de ventilation mécanique et des mouvements de l'air dans les bâtiments et qu'une mise en œuvre fidèle des principes connus s'imposait.

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TERMINOLOGY

Many of the technical terms used in this report are defined below. Several of the terms have meanings specific to this report and may not represent the generally accepted definitions used within the industry.

Air Barrier refers to materials and components that together control the flow of air through an assembly and thus limit the potential for water penetration, heat loss and condensation due to air movement.

Assembly refers to the collective layers of components and materials that together comprise the complete cross section of the wall or roof.

Balcony refers to a horizontal surface exposed to outdoors, and intended for pedestrian use, but projected from the building so that it is not located over a living space or acting as a roof.

Base Flashing refers to the part of the roofing that is turned up at the intersection of a roof with a wall or another roof penetration. It may be made of the same material as the main roofing membrane or of a compatible material.

Building Envelope, now called an environmental separator in building codes, generally refers to those parts of the building that separate inside conditioned space from unconditioned or outside space, such as windows, doors, walls, roofs, and foundations. The building envelope can also include assemblies that separate environmentally dissimilar interior spaces (swimming pool and residential space). Some building envelope elements can be exposed to exterior environmental loads but not separate dissimilar environments (balcony guard walls).

Cap Flashing sheds water from the tops of walls and must be sloped toward the roof to prevent staining of the exterior cladding. It is difficult to make waterproof at the joints and intersections, and it requires a secondary, continuous and waterproof membrane below it.

Cladding refers to a material or component of the wall assembly that forms the outer surface of the wall and is exposed to the full force of the environment.

Cladding Attachment Failure means the failure of the intended load transfer mechanisms for the cladding or window to the secondary structure. This implies that failure may have occurred but that the cladding may not have fallen from the building. This could be due to the fact that it has not experienced the design load conditions, because an alternate load transfer mechanism is transferring the loads (bearing, sealant), or through a combination of these factors.

Concealed Barrier refers to a strategy for rain penetration control that relies on the combination of the cladding as well as a secondary water resistive layer located further into the assembly to limit water ingress. This strategy differs from a drained cavity wall assembly primarily because it does not provide a capillary break between the cladding and the secondary water resistive layer.

Counter Flashing prevents water from penetrating behind the top edge of base flashing, and consists of a separate piece of flashing placed over the top of the base flashing. It is usually made of sheet metal.

Cross Cavity Flashing intercepts and directs any water flowing down the cavity of a wall assembly to the exterior, and prevents exterior moisture from entering the wall assembly below the flashing.

Curtain Wall is a high performance aluminum framed wall system containing both vision glass and opaque metal or glass spandrel panels. These systems are supported by brackets attached to the floor slabs and typically run entirely outside the structure, past the slab edge.

Damage refers to symptoms of deterioration that have occurred as a result of a particular problem.

Deck refers to a horizontal surface exposed to outdoors, located over a living space, and intended for pedestrian use in addition to performing the function of a roof.

Defect refers to the inability of a material or component to meet it's normally accepted standard for quality. A defect does not necessarily result in a failure or a problem.

Deflection refers to a water management strategy that utilizes features of the building and assembly geometry to limit the exposure of the assemblies to rain.

Detail refers to a location within a building envelope assembly where the typical construction is interrupted because it meets a penetration of the assembly. Examples include balcony guard rail connections, dryer and other vent grilles, control joints within a wall assembly).

Drainage refers to a water management strategy that utilizes surfaces of the assemblies to drain water away from the assembly.

Drained Cavity refers to space behind the water shedding surface (cladding or glass typically) that provides a path for free drainage (provides a capillary break) of bulk water within the assembly.

Drip Flashing directs water flowing down the face of vertical elements, such as walls or windows, away from the surface so that it does not continue run down the surface below the element.

Drying refers to a water management strategy that incorporates features and materials to facilitate diffusion and evaporation of moisture out of an assembly (from materials that get wet within an assembly).

Durability refers to the ability of a material, components, assembly or building to perform its required functions in its service environment over a period of time without unforeseen maintenance, repair or renewal.

EIFS is an acronym for Exterior Insulation and Finish System and refers to the cladding portion of an assembly that utilizes insulation that is adhered or mechanically fastened to a substrate and is then finished with a thin reinforced base coat followed by a finish coating to provide final texture and colour.

Exterior Moisture Barrier refers to the surface farthest into an assembly from the exterior that can accommodate some exterior moisture in the form of bulk water without incurring damage to the assembly.

Face Seal refers to a strategy for rain penetration control that relies on the elimination of holes through the cladding to limit water ingress.

Failure refers to the inability of an assembly, interface or detail to perform it's intended function(s).

Flashing refers to materials used to deflect water at interfaces and details within and between assemblies to the exterior.

Housewrap refers to a sheet plastic material that is used as a breather type sheathing membrane, generally between the wall sheathing material and the exterior cladding. Although at one time used as a proprietary term, housewrap is now used to represent a generic group of materials. One common type of housewrap consists of Spun-Bonded Polyolefin (SBPO); another is made of perforated polyethylene.

Interface refers to a location within the building envelope where two different assemblies meet. This could be two different wall assemblies or a wall and a window assembly.

Maintenance refers to a regular process of inspection, minor repairs and replacement of components of the building envelope to maintain a desired level of performance for the intended service life without unforeseen renewal activities.

Moisture Content refers to the weight of water contained in a material expressed as a percentage of the weight of oven dry material.

Movement Joint refers to a joint on a wall that provides capability for differential movement of portions of the building structure (expansion joint) or prevents or localizes cracking of brittle materials such as stucco (control joint).

Operation of the building or envelope refers to normal occupancy of the building where the envelope is affected by interior space conditioning, changes to light fixtures, signs, vegetation and planters, and accidental damage or vandalism.

Penetration refers to an intentional opening through an assembly for ducts, electrical wires, pipes, scuppers, fasteners, etc.

Pressure Equalized Rainscreen refers to a rainscreen assembly in which additional measures have been taken to reduce pressure differentials across the cladding and therefore further limit water penetration. These measures could include compartmentalization of the exterior drained cavity and optimization of venting arrangement, cavity size and stiffness of the cladding and back-up wall assembly.

Premature Failure refers to the inability of an assembly, interface or detail to perform it's intended function(s) for its expected service life.

Primary Structure: refers to structural system that carries the gravity (self weight and live) loads as well as the lateral loads imposed to the foundation. In a high-rise residential building the primary structure typically consists of a concrete frame or shear walls with cast in place concrete floor slabs.

Problem refers to the unacceptable performance of the building envelope that has resulted in expenses to repair that are in excess of normal and expected renewal costs. For this study this cost has been further defined as a repair that exceeds $400 per suite per year for the building as a whole ($400 x building age x # of suites). This criteria ensures that typically only systemic problems are considered problems.

Rainscreen refers to a strategy for rain penetration control that relies on deflection of the majority of water at the cladding, a cavity that provides a drainage path for water that penetrates past the cladding. Rainscreen walls do not generally utilize pressure moderation techniques beyond the basic provision of an air tight surface to the interior of the drainage cavity to limit pressure differentials across the cladding.

Rehabilitate refers to a program of comprehensive overall improvements to the building envelope assemblies and details so that it can fulfill its originally intended functions.

Renewals refers to activities associated with the expected replacement of worn out components or materials of a building envelope and are typically for items with life cycles in excess of one year.

Repair refers to replacement or reconstruction of envelope assemblies, components or materials at specific localized areas of the building envelope so that it can fulfill its originally intended functions.

Saddle refers to the junction of horizontal surfaces, such as the top surface of a balcony, or roof parapet wall with a vertical surface, such as a wall.

Secondary Structure: refers to the structural support system (framing, clips and fasteners) required to transfer the imposed gravity and lateral loads acting on or through the building envelope to the primary structure. These components typically include the steel studs, exterior sheathing and cladding attachment clips along with associated fasteners.

Service Life refers to the period of time during which building envelope materials, components and assemblies perform without unforeseen maintenance and renewals costs.

Sheathing refers to materials (generally gypsum based sheathing or concrete board products for high-rise buildings) used to provide structural stiffness to the wall framing and to provide structural backing for the cladding and sheathing membranes.

Sheathing Membrane refers to a material within an exterior wall assembly whose purpose is usually to function as part of the exterior moisture barrier. This material limits penetration of water further into the structure once past the cladding. Waterproof type sheathing membranes can also perform the function of the air barrier and the vapour barrier. Materials include both breather type (vapour permeable) sheathing membranes such as sheathing paper and housewraps, and waterproof (non-vapour permeable) sheathing membranes.

Sheathing Paper refers to asphalt impregnated organic sheet material (breather type sheathing membrane) that creates a water shedding surface behind the cladding.

System describes a combination of materials and components that perform a particular function such as an air barrier system, or exterior moisture barrier system.

Through-wall Flashing refers to a waterproof membrane or metal flashing placed under segmented precast concrete, stone masonry or brick units known as copings that close the tops of masonry walls to prevent water from entering the wall at joints in the coping. Through wall flashing is also used to prevent capillary transfer of moisture through porous materials such as concrete or masonry if they extend from high moisture locations such as below grade.

Vapour Barrier refers to material(s) with low vapour permeability that are located within the assembly to control the flow of vapour through the wall assembly and limit the potential for condensation due to diffusion.

Walkway refers to a corridor exposed to outdoors that provides pedestrian access between suites and stairwells or elevators. It may or may not also be a roof.

Water Shedding Surface refers to the surface of assemblies, interfaces and details that deflect and/or drain the majority of exterior moisture impacting on the façade in the form of bulk water.

Window-Wall refers to the use of traditional residential windows adapted for floor to ceiling use. They are typically supported directly on the slab rather than outside the slab edge. They resemble curtain-wall in overall appearance.

1. INTRODUCTION

1.1 Background

Over the past few years reports of moisture related problems in high-rise residential buildings have become more common in the coastal climate area of British Columbia. Knowledge of water ingress problems in high-rise buildings expands the earlier focus and concern regarding building envelope performance in low-rise wood frame buildings. The existing knowledge and guidance documents established through the Building Envelope Research Consortium (BERC), while providing sound fundamentals for wood frame construction, do not address some of the unique characteristics of high-rise buildings. The materials used in high-rise buildings are different, with the primary structure being concrete rather than wood, and steel stud wall framing used instead of wood (typically steel studs do not form part of the primary structure). In addition to these fundamental differences in the materials used, there are differences in the environmental forces that act on high-rise envelope assemblies. As examples, the exposure to wind and rain is generally more severe, and stack effect can create sustained inward and outward acting forces on the envelope. Mechanical systems also play a role in pressurization of parts of the building, and mechanical ventilation can be a key factor in managing interior moisture sources.

These differences in materials and environmental forces result in corresponding differences in the way in which buildings respond, the way in which problems manifest themselves, the time frame in which failures occur, the way in which problems are investigated, the extent and nature of repairs required, and the urgency of the repairs required. For example, the fact that the primary structure is not likely to be appreciably damaged by moisture means that the risk of failure of the primary structure that exists in wood frame buildings does not exist in high-rise buildings.

Much of the initial information and focus on solutions resulting from failures of wood frame building envelopes was developed in a study for BERC entitled *Survey of Building Envelope Failures in the Coastal Climate of British Columbia (Low-Rise Survey).* The strategies and methodology used in that study are the foundation for this current study of high-rise envelope performance.

While there is clearly value in establishing the prevalent cause(s) of envelope failures in high-rise buildings based on methodology adapted from the *Low-Rise Survey*, it is also clear that many high-rise building envelopes have performed well. The most notable difference between the current study and the *Low-Rise Survey* is that the reasons why building envelopes have performed successfully are also examined in the current study.

This study is considered to be the first step in a process that will help the construction industry better understand the behaviour of building envelopes and more consistently build envelopes that perform well.

This study is not intended to provide a statistical representation of the overall population of target buildings; both because of the small size of the sample, and because of the non-random method of selecting buildings for inclusion in the sample. The buildings were selected from the files of consultants based largely on the completeness of the information available. Thus statistics generated from the sample data should not be extended to apply to the entire population of high-rise multi-unit buildings in the Lower Mainland. In particular, the split between successful and failed buildings, assemblies, and details is not necessarily representative of the total population of buildings and no inferences should be developed in this regard. However, the findings and conclusions regarding causal relationships (for example, the relationships between certain building design and construction practices and the occurrence of failures and problems) are valid for similar buildings within the general population of high-rise buildings.

1.2 Objectives

The primary objective of this study is to identify causal relationships that have resulted in both building envelope problems and successes, in non-combustible high-rise residential buildings in the coastal climate area of British Columbia. This will facilitate the identification of key factors for successful design and construction of the building envelope assemblies, interfaces, details and associated mechanical systems.

1.3 Project Team

The project team was led by RDH Building Engineering Limited (RDH). Other team members included Paul Kernan Architect, Sheltair Scientific, Keen Engineering Limited, GS Sayers Ltd., and B.R. Thorson Consulting Ltd. These team members contributed data to the study and participated in the analysis of the data and development of recommendations. The majority of the building information for the study was sourced from RDH's files, but contributions were also received from Morrison Hershfield Ltd., Read Jones Christoffersen Ltd., and Vancouver Condominium Services Ltd.

2. METHODOLOGY

2.1 Criteria for Study Buildings

The buildings included in this study were chosen based on the availability and quality of information to facilitate gathering of data regarding the wall assemblies used in the buildings and to correlate this data with the performance problems that have been experienced, if any. The study findings and conclusions **cannot** be extrapolated as an indication of failure rates or trends for the general population of high-rise residential buildings.

The specific attributes of the buildings for inclusion in the study are as follows:

- Residential buildings of five storeys or more located in the Coastal area of B.C. The five storey cut-off can be more appropriately considered to be the change from combustible to non-combustible construction. The coastal area has been further defined as including the B.C. Lower Mainland and Vancouver Island, within 30 km. of the coast of the Strait of Georgia. Both market (strata title or rental) and non-market (social housing) have been included in the study.
- Age of no more than nineteen years. Buildings with a first occupancy date prior to January 1981 were considered ineligible for inclusion in the study. The purpose of this was to restrict the study to the perceived problem population of recent buildings that have experienced rapid deterioration. Age is a substitute criterion for the use of designs, materials, and construction representative of the problem population, and the change in emphasis from construction for the rental market to construction for the condominium market. Also, a building boom in the types of buildings exhibiting problems occurred during that timeframe.

  One exception was made to the above criterion. A building was identified which was constructed in 1974 using a “drained cavity” design in its major wall assembly. This building had experienced good performance from its envelope assemblies over the past 26 years, and represents one of the earliest known implementations of the “drained cavity” design which is now required in most jurisdictions in the study region. With the exception of the drained cavity aspect of the construction other wall features were similar to the typical face seal wall assemblies that were examined in the study (similar insulation levels, polyethylene vapour barrier, exterior gypsum sheathing and 92 mm studs).
- Although each building provided an average of two different wall assemblies and two window/door assemblies, we were unable to include examples of all the envelope system type/assembly variable combinations shown in Chart 3 of the request for proposal (RFP). Of the 48 different combinations shown in that chart, we were able to find examples of 16, all those being in the category of “Poly and Drywall” air barrier design. Some of the “assembly variables” (which are actually types of air, vapour, and weather barrier combinations) do not have any examples; for example the ADA for air/vapour control has been used very little on high-rise residential buildings. In a large number of assemblies, no discernible design intent for the air barrier could be found in the drawings; these were classified as “Not designed” air barrier, a type that does not appear in Chart 3 of the RFP.

- The study was intended to include buildings that appear to be performing well and exhibit no outward signs of moisture problems in their wall assemblies. The criteria for eligibility of these buildings in the study was defined to be as outlined above, with a further requirement that they be completed no later than 1995; this provides a minimum five-year time period during which no problems have become evident. There are 4 problem-free buildings in the database.
- The criterion for “problem” was developed to try to exclude expenditures on building envelope renewals that can be expected over the lifetime of a typical building. The wide range of ages of buildings to be included in the study means that some wall assemblies (on older buildings) will have required renewals expenditures due to components reaching the end of their design service life. Thus a “problem” is defined as a requirement to spend well in excess of the typical renewals expenditures over the expected lifetime of the building envelope. This was simplified to the basic measure that any expense that exceeded $400/suite x the age of the building at the time that the repair was undertaken, constitutes a problem. This amount represents more than double the expected Capital Cost Allowance or reserve fund allocation for the building envelope of a typical suite in a high-rise building.
- In addition to buildings in which no problems have occurred, we have collected information on assemblies that have performed adequately on buildings that have had problems in one but not all of their wall or window assembly types.

2.2 Study Building Candidates

The choice of buildings to be included in the study has a major impact on the reliability of the conclusions drawn from analysis of the buildings and their problems. The criteria for selection of buildings is set to ensure that the sample is representative of the population of buildings we want to address, that is, high-rise residential buildings located in the coastal climate region of B.C. and built in the period since 1980. However, the nature of the selection process is not random, and statistics from the sample group will not necessarily be applicable to the entire population of high-rise buildings. The selection criteria also emphasize the need to obtain samples of a large number of different wall assemblies, some of which are likely to be extremely rare.

One of the major objectives of this project is to provide an indication of whether there are specific differences in materials, detail design, construction, or maintenance between assemblies and details that have problems, and those that do not. The sample of buildings, assemblies and details must therefore be divided into two types; ‘successful’ and ‘unsuccessful’. It is worth noting that successful performance can only be determined in the context of the environment in which it exists. For example, rain penetration performance will always be a function of exposure to wind and rain. A given component or assembly may perform well in some exposure conditions and not well in others.

The number of buildings that can be included in a study of this type is dependent primarily on the depth of investigation required to generate the information required, within the total budget available. Where the existing project file included description of the visual inspection and detailed destructive testing done to reach the report conclusions, the information was generally acceptable for the purposes of this study. Thus, visual inspection and field investigation was done only as required by lack of information already existing in the files.

The intent was to identify a large pool of potential buildings to not only obtain a full cross section of representative assemblies, but also to choose buildings where an acceptable amount of information was already available regarding performance problems that may have occurred. Although the proposal identified a pool of approximately 155 buildings meeting the criteria for which at least some information was available, the actual number of buildings for which the high level of detailed information required for this study was available was much smaller. A number of building ownership groups and property managers were unwilling to cooperate in the study. Thus the 35 buildings included in the study is a smaller number than the 50 originally foreseen in the proposal.

The buildings in the study are identified only by their assigned "Building Identifier"; no names or addresses of individual buildings are included in the database.

2.3 Data Collection Protocol

The primary objective of the study was to gather data describing high-rise residential building envelopes in the coastal climate of BC, and the performance issues that have been experienced with them. This data must be adequately detailed to allow identification of the cause-effect scenarios that have resulted in both satisfactory and unacceptable performance of building envelopes.

The data collection protocol from the *Low-Rise Survey* was used as a starting point for this study. That protocol was intended to gather data concerning envelope characteristics and performance problems in low-rise residential buildings. A number of changes and additions were made to focus on some of the typical problems that were identified in the low-rise study, and to orient the data towards the specific characteristics of high-rise buildings, as follows:

- The data to be collected for each building was organized into 4 groups, each represented by a form. A guide was developed to describe each of the data fields on the forms, and assist evaluators in completing the forms. Sample forms and the guide are found in Appendix A.
- The first form is titled "Basic Building information". It is intended to capture data applying to the entire building, such as age, height, number of suites, and type of ownership.
- Weather exposure data was collected in order to identify any relationships between increased exposure to prevailing winds or driving rain, and damage to envelope assemblies.
- The ventilation systems and characteristics were collected to determine the relationship between them, and high interior humidity and excess condensation on envelope surfaces.

- During the eligible age period of this study (1980 – 2000), there were a number of different Building Codes which sample buildings may have been built to conform to. The City of Vancouver Building Bylaw was somewhat different for many years from the BC Building Code applying in other municipalities in the Coastal region. New versions of the BC Building Code were adopted on average every 5 years during this period. The Building Code information allows analysis of the effect of Code requirements and changes on envelope performance.
- There has been debate over the role played by building form and degree of articulation – the division of wall and roof areas into large numbers of smaller surfaces and planes to provide visual interest in the building shape. It is suggested that the large number of joints and unusual details that result from greater form complexity carry a greater risk of envelope performance problems. We collected three indicators of building form complexity: the number of corners on a typical floor plan, the number of different roof levels, and the degree of integration of the balconies into the building façade.
- The second form is titled “Wall and Window Assemblies” and is designed to capture characteristics of each different assembly used to create the building envelope. In this study, windows and doors are treated as separate assemblies; this allows collection of much more complete information than in the *Low-Rise Survey*, where they were treated as details.
- For each assembly, information is collected describing its location on the building; its design characteristics and the nature of components intended to provide the various functions of the building envelope – structural support, visual appearance, water control, and air leakage control.
- Information is collected describing the details that occur on each wall assembly. These include joints with other wall and roof elements, penetrations for ducts and services, and interfaces with balconies, patios, and decks.
- The third form is titled “Assembly Interface Details”. The *Low-Rise Survey* concluded that one of the major problem areas in envelope performance is failure at the interfaces between wall and window assemblies. This form is designed to collect information detailing the design approaches, geometries and materials used to construct each type of interface between wall and window assemblies. An assessment of the performance of each interface is included.
- The final form is titled “Problem Details” and collects information on the nature and extent of damage to components of the wall or window assembly, the cause-effect scenario relating to the physical aspects of the problem, and the “design-construction-maintenance process scenario” describing the industry procedures and environment within which the problem was able to develop.

At a meeting of the Steering Committee for this project held on April 3, 2000, the proposed data collection forms and guide were presented, reviewed and revised. The final version of these forms and guide were circulated to Steering Committee members during the first week of July, 2000.

2.4 Training of Assessment Personnel

The four members of the study assessment team participated in a group training session held on June 29, 2000. The objectives of this session were:

- To present, test, and fine-tune the data collection methodology, forms, and guide.
- To establish consistent standards and procedures for the evaluation of the buildings, assemblies, interfaces, and problems.

The session included the complete data collection procedure for one building. A number of valuable comments and questions were raised and resolved during the session. The data input forms and guide were modified during the session to incorporate several improvements and corrections.

The initial set of buildings was assigned to assessment staff at the end of this session. At this time, the assessment staff was instructed to collect all information available from the building files, report, photographs, and drawings, and to use “DK” (short for Don’t Know) for any fields that could not be answered based on the above information. The intent was to review the first few completed buildings to determine the extent of further work that would be required to collect the missing information in each case.

Each set of data collection forms was reviewed by the Project Technical Manager after submittal. This process revealed that quality and extent of information in the Condition Assessment reports varied considerably. In order to have completed all of the data fields, further openings in wall assemblies, and visits to a sample of suite interiors would have been required for a majority of buildings, since desired data was not included in the drawings or reports. Therefore some fields on the form were left as “DK” (don’t know).

2.5 High-Rise Database

The High-Rise Database was implemented using Microsoft Access 97. The database organization follows the format of the input forms, but provides drop-down boxes showing all the accepted choices for each data input item. Records for the 35 buildings were input to the database.

The database records are stored by major key of “Building ID”, which was assigned to each building by the Project Technical Manager. Associated tables store the data describing wall and window assemblies, assembly interfaces, and problems. Each set of records can be filtered by selecting the combination of values desired in each of the fields of interest. The database returns only records matching the selected values.

2.6 Data Analysis

Initial data analysis used the Access 97 filter command to determine numbers of records matching each possible value of each field. Subsequent correlation analyses were completed by copying the database tables to Microsoft Excel.

3. SUMMARY AND ANALYSIS OF DATA

3.1 General

The following findings are based on the analysis of the 35 buildings whose data have been input to the "High-Rise Envelope Performance" database. Table 3.1 presents general statistics on the database records:

TABLE 3.1
CHARACTERISTICS OF STUDY GROUP OF BUILDINGS

Statistic	Number	Comment
Buildings in Database	35	
Groups of Multiple Buildings in Database (more than 1 high-rise building on one site)	4	Containing 9 buildings
Buildings with at least one problem in Database	31	89%
Wall Assembly Records	65	1.86/bldg
Window/Door Assembly Records	86	2.46/bldg
Assembly Interface Records	131	3.74/bldg
Problem Description Records	60	1.71/bldg, 2/problem bldg

3.2 Characterization of Buildings

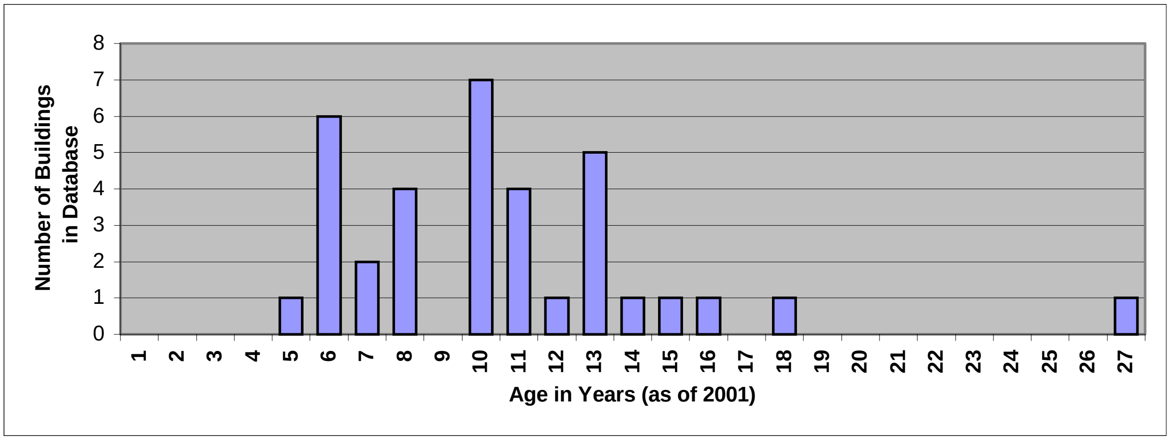
Age of Buildings

Figure 3.1 shows the age distribution of the buildings included in the study. There is one building included in the study group whose age falls outside the specified eligibility range; however this building was included because it is constructed with a "drained cavity" wall assembly (relatively unique for its time), and has performed adequately for more than 20 years in the Lower Mainland climate.

The average age of buildings in the database is just under 10 years. The four buildings for which no envelope problems were detected have an average age of nearly 11 years, but if the unique "drained cavity" building discussed above is excluded, the successful buildings' average age is less than 6 years. The lower age of the other three successful buildings may be attributed to several possible causes:

- Not enough time has elapsed for problems to develop or be identified
- Failures that have occurred are smaller than the problem criteria definition
- Changes in technology (better assemblies, details, materials) have resulted in successful buildings

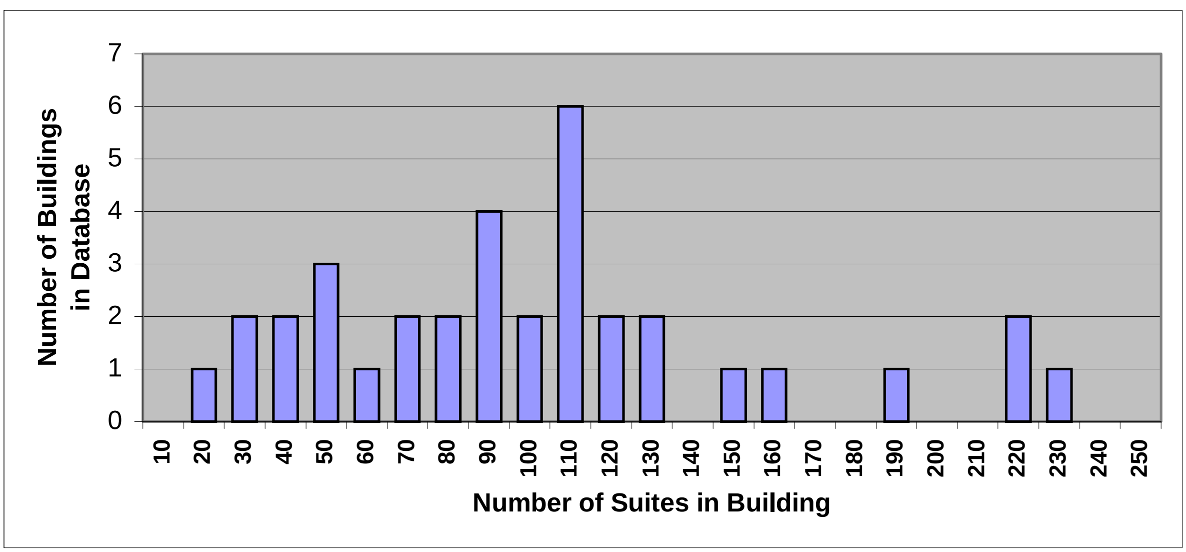
FIGURE 3.1
AGE PROFILE OF BUILDINGS



Size and Number of Suites

Figure 3.2 presents the distribution of study group buildings with respect to the number of suites, a good indicator of the size of the building. The average "problem" building in the study group has 91 suites, while the 4 no-problem buildings have an average of 135 suites. There is a weak correlation between the age of study group buildings and the number of suites in them, indicating a trend for newer buildings in the study group to contain more suites.

FIGURE 3.2
BUILDING SUITES PROFILE



Building Suite Size Occupancy Load

Table 3.2 presents information regarding the suite size distribution.

TABLE 3.2
SUITE SIZE

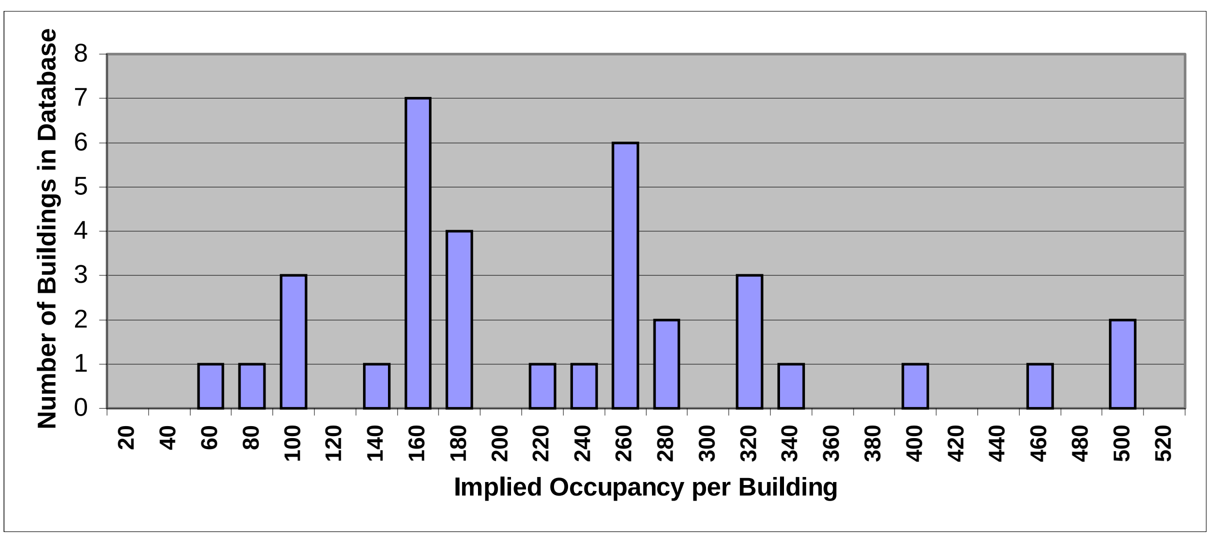
SUITE TYPE	Totals	Comments
Studio	318	3 buildings, 106/building
One- Bedroom	1787	29 buildings, 62/building
Two-Bedroom	1226	27 buildings, 45/building
Larger than 2 Bedroom	45	7 buildings, 6/building
Total Residential Suites	3376	96/building

Figure 3.3 shows the distribution of "implied occupancy" in the study group buildings. The implied occupancy has been calculated using the following assumptions:

- One occupant in each studio suite
- Two occupants in each 1-bedroom suite
- Three occupants in each 2-bedroom suite
- Four occupants in each "larger than 2-bedroom" suite

The average occupancy load of the "problem" buildings is 207, for an average suite occupancy of 2.28 persons. The average occupancy load for the "no-problem" buildings is 329, for an average suite occupancy of 2.44 persons. Three of the five largest-occupancy buildings are in the "no-problem" category.

FIGURE 3.3
BUILDING IMPLIED OCCUPANCY PROFILE



Building Ownership and Occupancy Type

Table 3.3 presents information regarding the building and suite occupancy types.

TABLE 3.3
BUILDING AND SUITE OCCUPANCY TYPE

OCCUPANCY TYPES: (note that some buildings contain more than one occupancy type)		
Strata Residential	27	77 %
Rental Residential	2	6 %
Social Housing	6	17 %
Strata Commercial	1	3 %
Rental Commercial	3	10 %
Assembly/Public	1	3 %
Conversion	0	
Total Residential Suites	3376	96/building
Total Commercial Suites	29	5 buildings

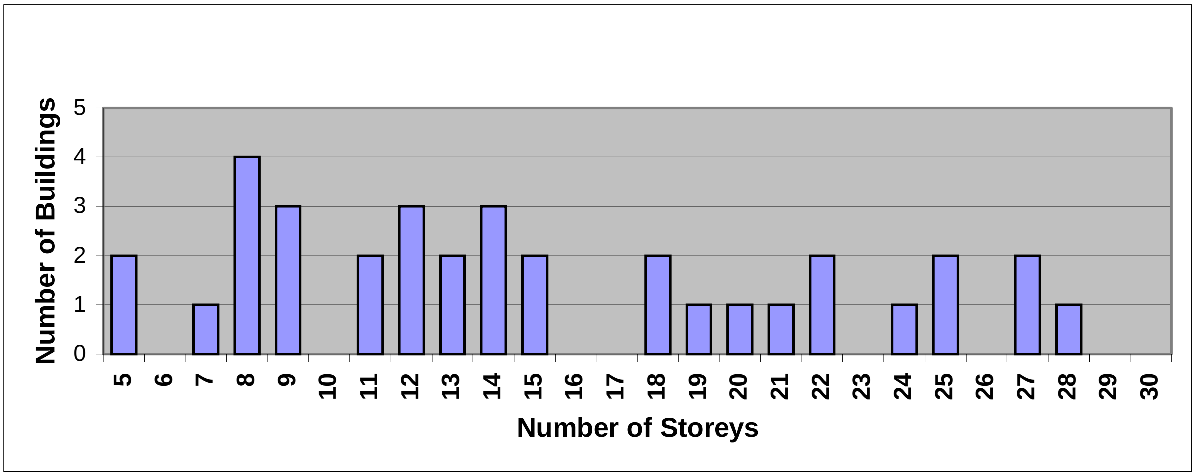
The mix of ownership type in the study group is not necessarily reflective of the overall ratio of strata-title to public-housing buildings constructed during the period. However, the two rental buildings included in the study group are unusual, since very few new rental buildings were constructed during the study time period. All of the “no-problem” buildings are strata-title, but there is insufficient data to conclude that the ownership type was related to the incidence of problems.

Five buildings in the study group contained commercial space at the ground floor, with one containing commercial space at its second floor level also.

Building Height

Figure 3.4 presents the distribution of building height in the study group buildings. The average building is 15 storeys in height; the 4 “no-problem” buildings average 22 storeys high.

FIGURE 3.4
BUILDING HEIGHT DISTRIBUTION



3.3 Building Form

It has been suggested that the incidence of problems in high-rise building envelopes is related to elements of the basic form of a building. More specifically the complexity of the exterior façades and exposure conditions have been identified as two key issues.

Building Form Complexity

The database uses input data to calculate a composite factor termed the Building Form Complexity Factor (BFCF). The theory is that a façade that has few changes of plane and minimal interruptions in surfaces will provide fewer locations for potential failure of details and assembly interfaces. BFCF is calculated using the following formula:

BFCF = ((A1-4)/10) x ((A2)/3) x A3

where	BFCF	= Building Form Complexity Factor
	A1	= number of exterior corners in typical floor plan
	A2	= number of different roof areas in section of building
	A3	= 1 if “Most balconies fully recessed”
		= 1.5 if “Most balconies partially recessed”
		= 2 if “Most balconies project fully”
		= 3 if “Decks and/or exposed balconies on several floors”

The building form rating is weighted so that a building having only 4 exterior corners, one roof, and fully enclosed balconies will have a rating of 0.

Figure 3.5 shows the distribution of “Building Form Complexity Rating” among the study group buildings.

FIGURE 3.5
BUILDING FORM COMPLEXITY RATING DISTRIBUTION

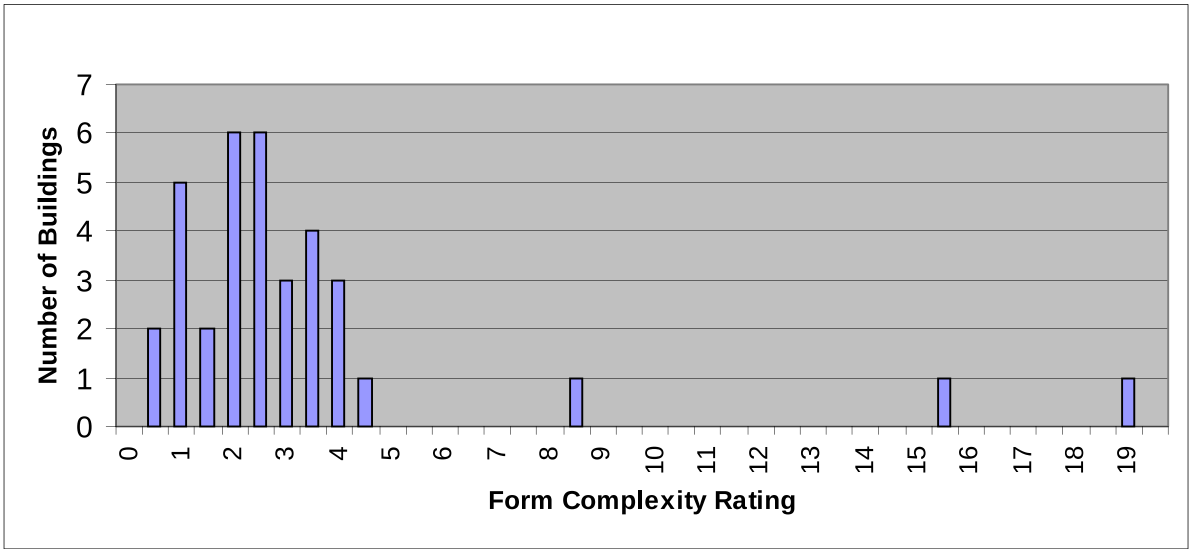


Table 3.4 provides further breakdown of the elements of building complexity.

The average building in the study group has nearly 20 “exterior corners” on its façade, and more than 3 roof levels. The average “building form complexity rating” calculated from the 3 characteristics is 3.07, indicating that the building form in general tends to be much more complex than a simple box. There was no correlation found between the form complexity rating and the building age, nor between form complexity and the cost of repairing problems. This lack of correlation may be explained by the overwhelming influence of problematic details and assembly interfaces (see sections 3.6 and 3.7). The impact and significance of varying building form complexity as well as the frequency and nature of details and interfaces may have been more noticeable with a generally less frequent occurrence of problematic details and interfaces.

TABLE 3.4
BUILDING FORM COMPLEXITY

BUILDING FORM COMPLEXITY	
Exterior Corners of Façade:	**Totals**
10 or less	3 (9 %)
11 to 20	19 (54 %)
21 to 30	10 (28 %)
More than 30	3 (9 %)
Roof Levels:	
1	4 (13 %)
2	8(23 %)
3	6(17 %)
4	11(32 %)
5	4(13 %)
6	0
7	2 (6 %)
Balconies:	
Fully recessed in façade	9 (26 %)
Partially recessed	16 (46 %)
Fully projecting beyond façade	6 (17 %)
Many decks over living space and exposed balconies	4 (11 %)

Overhangs

The *Low-Rise Survey* found that there was a strong relationship between the width of wall overhangs, which provide protection from rain and runoff, and the percentage of walls in low-rise buildings that were damaged by water ingress. The database uses input data to calculate an "Overhang Ratio" for wall and window assemblies. It is calculated as the horizontal projection of the overhang divided by the vertical distance between the overhang and the base of the assembly.

On a high-rise building, it is more difficult to provide a meaningful overhang because of the increased height of the buildings' walls. In addition, there is a cumulative effect due to water running on the surface of the building. Even a relatively small amount of water (per unit area) impacting on the building walls and windows can accumulate to a considerable quantity as it drains down the face of the building to the lower floor levels.

Figure 3.6 shows the distribution of overhang ratio for walls in the database. About 2/3 of the walls defined have no overhang at all. Only 4 walls have an overhang ratio greater than 0.1 (equivalent to 250mm (10") per storey of height); all of these walls are one storey or less in height, and none were damaged.

No relationship was found between the overhang ratio and the percentage of walls that were damaged by moisture exposure. Five of the 35 main wall assemblies (making up most or all of the height of the building) were not damaged; 3 of these walls had no overhang and the other two had very small overhang ratios, equivalent to an accent reveal band at the top of the wall.

FIGURE 3.6
DISTRIBUTION OF WALL OVERHANG RATIOS

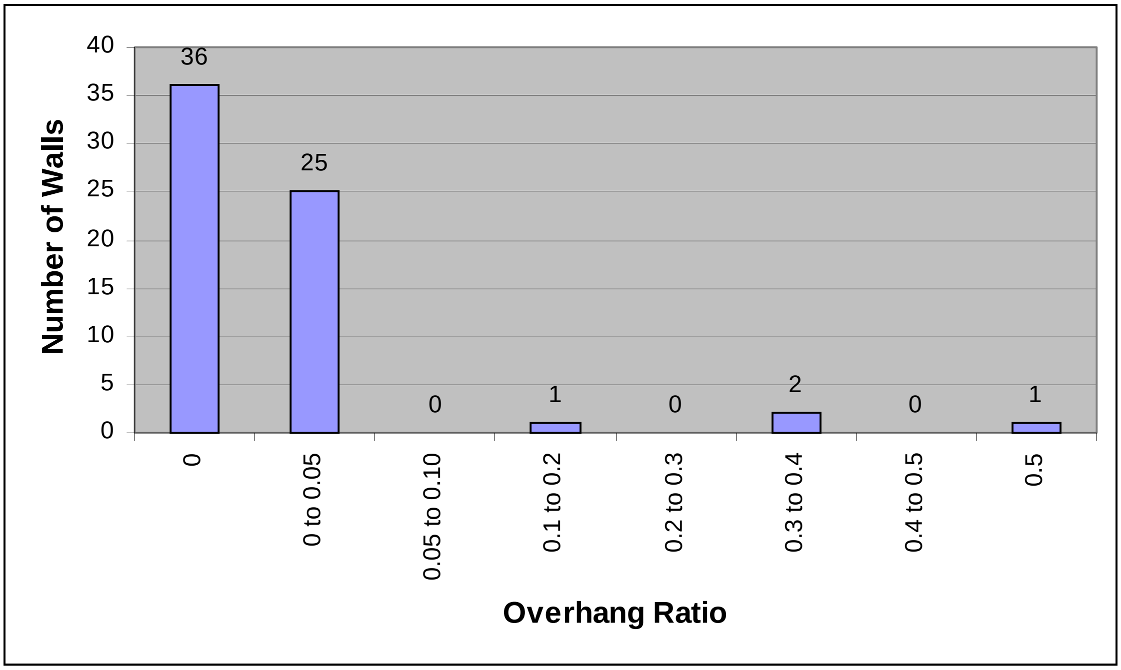


Figure 3.7 shows the distribution of window overhang ratio for the 42 window assemblies in the database. Typically, only one or two different types of window assembly are used on these buildings. 25 of the 42 window assemblies are essentially flush with the exterior wall face and have no overhang. The remaining 17 assemblies have small overhangs, some of which represent windows rebated within the surrounding wall assemblies, and some of which are protected by the overhangs within the wall above. No relationship was found between the overhang ratio and the percentage of windows that were damaged by moisture exposure.

A discussion of problems associated with windows assemblies and window to wall assembly interfaces can be found in Section 3.7 of this report.

FIGURE 3.7
DISTRIBUTION OF WINDOW OVERHANG RATIOS

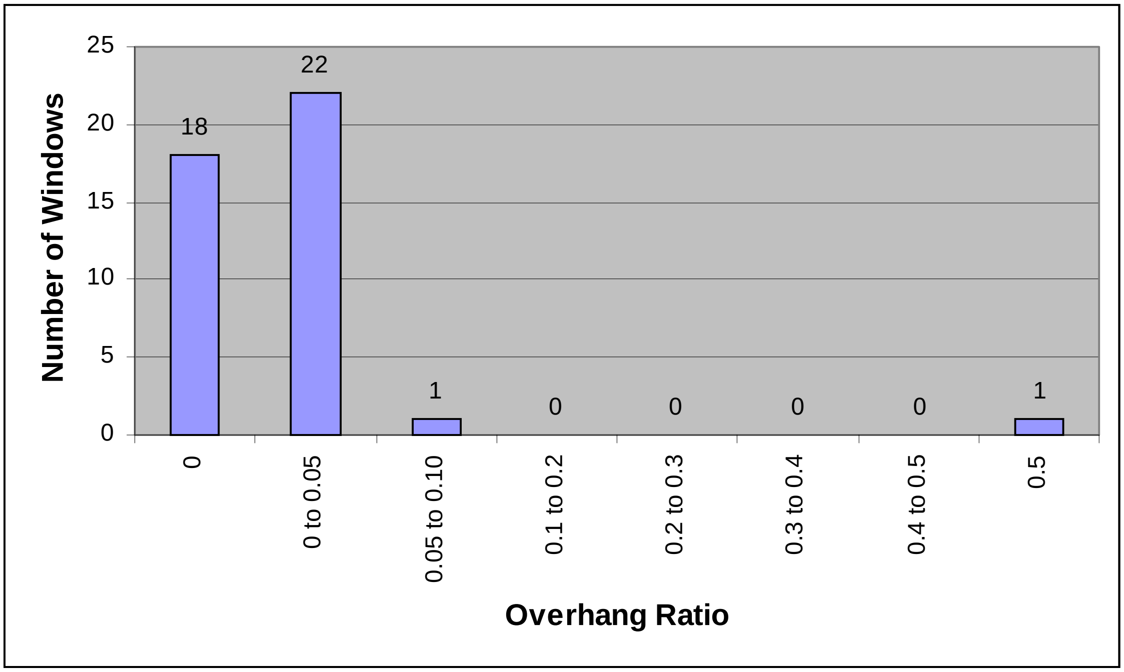
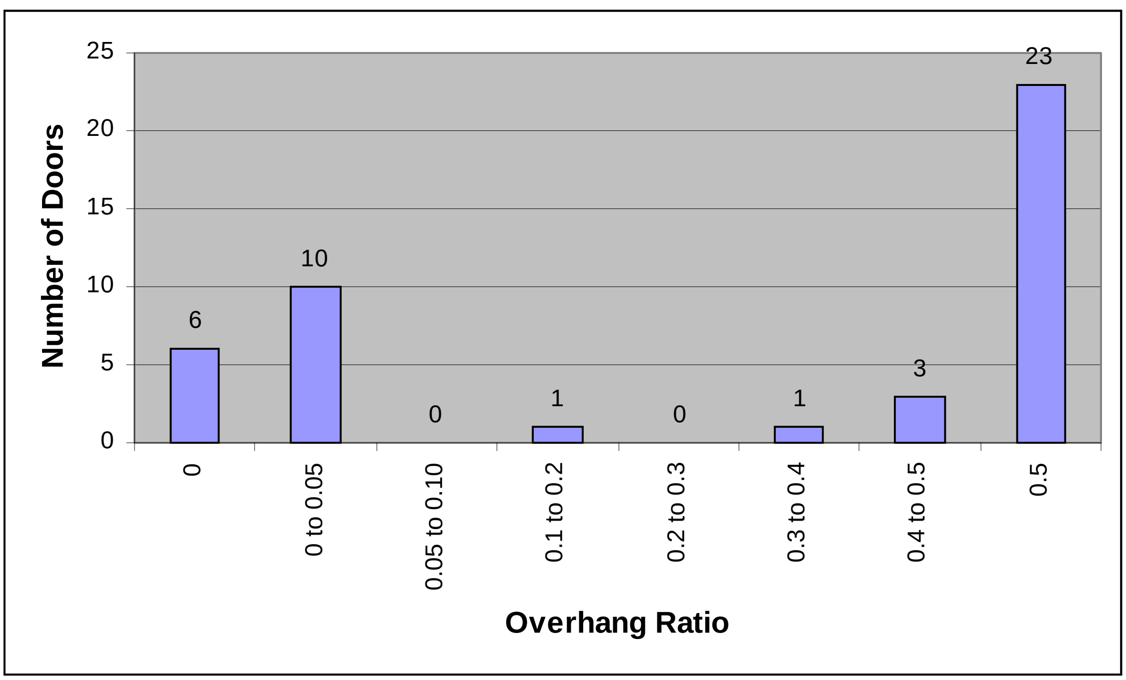


Figure 3.8 shows the distribution of door overhang ratio for the 44 door assemblies in the database. The overhangs on doors are typically large as a result of balconies being located in vertical stacks so that the balcony above shelters the door to the balcony below. More than half of the buildings provide this protection even to doors located on the top floor, which don't have a balcony above.

FIGURE 3.8
DISTRIBUTION OF DOOR OVERHANG RATIOS



Only one door assembly problem was reported in the database. This problem was more related to poor drainage of the adjacent deck, rather than to water ingress through the door assembly itself. Typically there are a relatively small number of unprotected doors at upper levels of each building that may fail but their repair is not costly enough to qualify as a problem. The lack of problems found to be associated with door assemblies should not be misinterpreted; the lack of problem occurrence emphasizes the substantial value of large overhangs since by their nature doors are susceptible to moisture ingress if exposed to direct rainfall.

3.4 Mechanical Ventilation

Data concerning mechanical system configuration was collected in order to analyze the potential relationship between envelope problems and ventilation arrangements within the buildings. This information often is not reported as part of a building envelope condition assessment or investigation of a specific problem; thus we were able to confirm this information in only about 60 % of the buildings in the study group. The profile of suite ventilation is provided in Table 3.5.

TABLE 3.5
BUILDING VENTILATION PROFILE

DO SUITES HAVE HUMIDISTAT CONTROLLED EXHAUST FAN ?			
Yes	11 Buildings	31%	
No	13	37%	
Don't Know	11	31%	
SUITE EXHAUST DUCTWORK:			
Formed in Floor slab	25	71 %	
Chases below floor slab	4	11 %	
Central shafts to rooftop	2	6%	
None	0		
Don't Know	6	17 %	
VENTILATION PARAMETERS:			
	YES	**NO**	**Don't Know**
Systemic High Humidity	6 (17 %)	26 (74 %)	3 (10 %)
Individual Makeup Air	1 (3 %)	26 (74 %)	8 (23 %)
Ensuite Dryers	24 (68 %)	7 (20 %)	4 (11 %)
Range Hood Fan:	**Recirculating**	**Exhaust**	**Don't Know**
	0	26 (74%)	9 (26%)
Suite Entrance Doors:	**Undercut**	**Weather-strip**	**Don't Know**
	10 (29%)	0	25 (71%)

Starting with the 1992 BC Building Code, individual suites within residential buildings were required to have a ventilation system that would control humidity within the suite. Most mechanical designers responded by providing one bathroom fan controlled by a humidistat. The humidistat continuously measures humidity of the air in the suite and turns the fan on when humidity exceeds its setting. In theory, buildings having this type of controlled ventilation system should have fewer problems caused by high interior humidity levels. Eleven of the 24 study group buildings (11 buildings had insufficient information) were confirmed to have this type of system. However, no correlation could be established between buildings with high interior humidity and the existence of the humidistat-controlled fans. Six buildings reported widespread high humidity; 2 of those had humidistat controlled fans and for 2 others information was not available. Eleven buildings had humidistats. Only two of these reported widespread high humidity. In many buildings it was common to find some of the humidistats not used or disconnected.

Exhaust ducts carry exhaust air from the fan to its discharge point outside the building. The fan may be a bathroom fan, a kitchen hood fan, or a dryer exhaust fan. In high-rise buildings using concrete slab floor construction, the ducts are often cast into the floor slab. In order to fit within the slab without interfering with reinforcing steel and other services, the ducts must be very thin, which requires them to be very wide in order to provide adequate cross-sectional area. Concerns related to in-slab ducts include:

- The ducts are often too long and contain too many direction changes for the fans that are installed to be able to provide their rated ventilation capacity. Thus excess humidity cannot be ventilated and remains in the suite. This is especially a problem with dryer vent ducts because they tend to become restricted by lint build-up in the duct and the exhaust grille.
- The duct joints are often unsealed, and no slope is provided to drain condensate or water driven into the exhaust grilles back to the exterior grille of the duct. Water that collects in the duct can leak through the joints and the concrete slab and stain ceilings and furnishings below.
- The ducts are often damaged during construction, so that their section is reduced or even blocked.
- The ducts are very difficult to investigate or repair if problems are found.

Twenty-five of the 29 buildings in the study group for which this information was available had ducts cast into the floor slabs. Twenty-four of the 31 buildings in the study group for which ensuite dryer information was available did have ensuite dryers; this therefore appears to have become a typical amenity in high-rise residential buildings. Only one of the buildings had separate in-suite ventilation supply; the others rely upon leakage into the suite from the corridor, which is dependant on lack of entrance door weather-stripping and on air pressure difference between the corridor and the suite. Looking at the known information for the 6 buildings in which systemic high humidity inside the suites was reported, all had in-slab ducts and 5 had ensuite dryers. All six buildings reported other moisture related problems indicating a possible relationship between exterior moisture sources and elevated interior humidity levels. However, 25 of the 29 buildings that did not report high humidity also had other moisture related problems.

Although the sample size is too small to draw definitive conclusions, the study results with respect to ventilation indicate that the relationship of interior humidity levels to ventilation provisions in high-rise residential buildings in the coastal climate area of BC deserves closer study.

3.5 Wall and Window Assemblies and Components

A total of 65 wall assemblies records and 86 window/door assemblies records are defined for the 35 buildings. There is considerable variation in the components and materials of wall assemblies, but very little variation in the types of window and door assemblies.

Table 3.6 describes the profile of wall assemblies and components for the study group buildings.

TABLE 3.6
PROFILE OF WALL ASSEMBLIES AND COMPONENTS

Wall Assembly:		
Buildings with 1 Wall Assembly:	10	29%
Buildings with 2 Wall Assemblies:	15	43%
Buildings with 3 Wall Assemblies:	7	20%
Buildings with 4 Wall Assemblies:	1	3%
Total	65	1.86/building
Wall Assembly – Exterior Moisture Control Strategy:		
Face Seal:	56	86%
Concealed Barrier:	3	5%
Drained Cavity:	5	8%
Rainscreen:	1	2%
Pressure Equalized Rainscreen:	0	0%
Wall Assembly - Support Structure:		
Steel Stud Backup	48	74%
Concrete Block Backup	2	3%
Anchored to Primary Structure	13	20%
Don't Know	2	3%

Wall Assembly - Cladding:		
Stucco	24	34%
EIFS	15	21%
Brick	6	9%
Concrete	8	11%
Concrete Block	3	4%
Metal Panels	3	4%
Curtain Wall	0	0%
Window-wall	8	11% *(represents opaque sections of window-wall, vision areas included as windows)*
Other (2 mansard roofs and 1 glass panel balcony railing wall)	3	4%
Wall Assembly – Secondary Exterior Moisture Protection Layer:		
SABM	1	2%
Building Paper	18	28%
Housewrap	10	15%
Liquid-Applied	2	3%
None	30	46%
Other	0	0%
Frame/Glass/Seal	2	3%
Don't Know	2	3%
Wall Assembly - Sheathing:		
Cement Bd.	0	0%
Glass Fibre Faced Gypsum Board	10	15%
Exterior Gypsum Board	37	57%
None	16	25%
Other	0	0%
Don't Know	2	3%

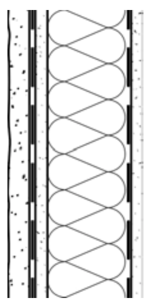
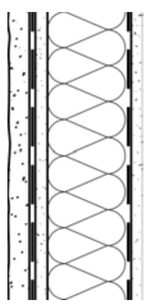
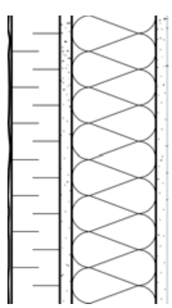
Wall Assembly - Cladding Fasteners:		
Screws, Minimal or no Corrosion Protection (Electroplated zinc, paint)	45	69%
Screws, hot dip galv., coated for exterior use, proprietary coating system, stainless	5	9%
Adhesive	3	5%
Anchored – Mass steel or concrete	5	8%
No fasteners	2	3%
Don't Know	5	8%
Wall Assembly - Insulation:		
Glass Fibre Batt	49	75%
Type 2 polystyrene (not EIFS)	3	5%
Type 4 polystyrene	0	0%
Rigid glass fibre	0	0%
Other	0	0%
None	11	19% (typically mechanical room walls)
Don't Know	2	3%
Wall Assembly – Air Barrier:		
Polyethylene with sealed joints	28	43%
Not Designed	33	51%
Airtight Drywall Approach	0	0%
Exterior Membrane	1	2%
Compression Gaskets	0	0%
Don't Know	3	5%
Wall Assembly - Vapour Barrier:		
Polyethylene Sheet	53	81%
Self Adhesive bituminous membrane	0	0%
Trowel applied	0	0%
Interior paint	6	9%
Don't Know	4	6%
Frame/Glass/Seal	2	3%

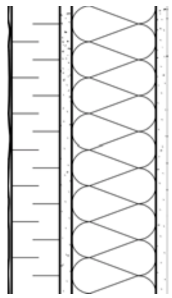
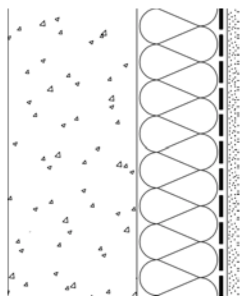
Specific comments with respect to the components of wall assemblies are:

- Cladding – stucco, EIFS, concrete, window/wall (opaque sections), and brick together make up 90 % of the total, but there are also examples of concrete block and metal panels.

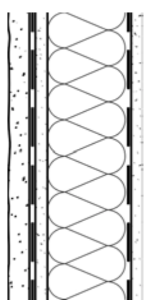
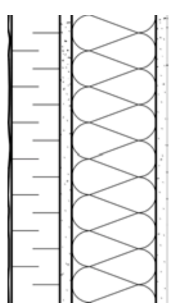
- Moisture Protection – nearly half of the wall assemblies rely solely on a face seal and do not have a secondary exterior moisture protection layer. Most of the remainder use either building paper or housewrap, although there are examples of all types defined. Most of the EIFS walls and all of the cast-in-place concrete walls did not provide a secondary exterior moisture protection layer.
- Sheathing – nearly 60 % of the walls used exterior grade gypsum board sheathing. The remainder were split between glass-fibre faced gypsum board (having much better moisture resistance), and no sheathing in the case of cast-in-place concrete and window/wall assemblies (sheathing not typically required).
- Air Barrier – where the condition assessment report specified that a polyethylene air barrier was shown on the design drawings, or the vapour barrier was found to be sealed at laps and joints with floor slabs and columns, we accepted it as an intention to use a combined air/vapour barrier relying on the polyethylene sheet with sealed joints. Where no air barrier was shown on the drawings and/or no effort was made to seal vapour barrier joints, we considered the wall assembly air barrier as “Not Designed”. These two were split fairly evenly, with a slight majority going to “Not Designed”.

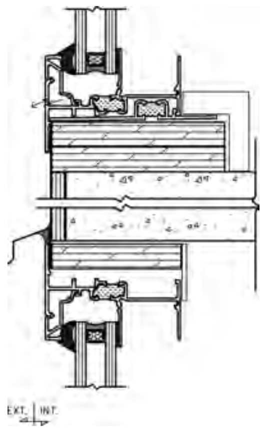
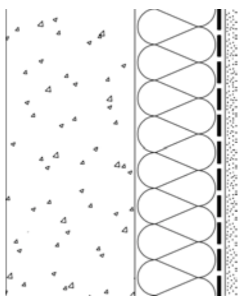
The 5 most common wall assembly types were as follows:

	**7 examples (11% of total):** Stucco, Sheathing paper, Exterior gypsum board, No designed air barrier
	**5 examples (8 % of total):** Stucco, Sheathing paper, Exterior gypsum board, Polyethylene with sealed joints
	**5 examples (8 % of total):** EIFS, No secondary exterior moisture barrier, Exterior gypsum board, No designed air barrier

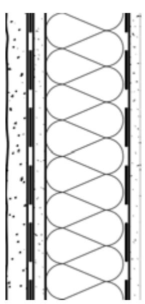
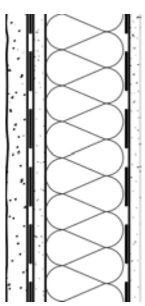
	**5 examples (8 % of total):** EIFS, no secondary exterior moisture barrier, exterior gypsum board, polyethylene with sealed joints
	**5 examples (8 % of total):** Concrete, No secondary exterior moisture barrier, No sheathing, No designed air barrier

Among the 5 common cladding types (making up over 90 % of all wall claddings), there were 28 different types of assemblies. This indicates that a fairly wide range of options and choices were considered in the design of these buildings. However, if the “air barrier” variable is left out, more popular assembly types emerge:

	**13 examples (20 % of total):** Stucco, Sheathing paper, Exterior gypsum board
	**10 examples (15 % of total):** EIFS, No secondary exterior moisture protection layer, Exterior gypsum board

	**7 examples (11 % of total)** Window-wall
	**6 examples (9% of total):** Concrete, No secondary exterior moisture protection layer

Most buildings have one or two assemblies that cover the large majority of the total wall area (main wall assemblies), while there may be other assemblies that are used in small areas for architectural effect. These main assemblies can be identified in the database because assessors labeled wall assemblies in order of decreasing proportion of area. The three most common main wall assembly types of the 35 buildings in the database are:

	**12 (34 % of total):** Stucco, Sheathing paper, Exterior gypsum board
	**4 (11 % of total):** Stucco, Housewrap, Exterior gypsum board

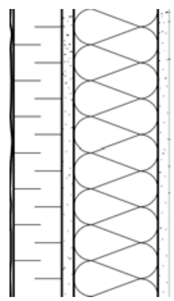
	**8 (23 % of total):** EIFS, No secondary exterior moisture barrier, Exterior gypsum board

Table 3.7 Summarizes wall records by cladding type and occurrence of problems

TABLE 3.7
WALL PERFORMANCE BY CLADDING TYPE

Cladding Type	No. of Wall Records	No. of Main Wall Records	Walls Involved in Problems
Stucco	24	20	19 (79%)
EIFS	15	12	10 (67%)
Brick	6	0	1 (17%)
CIP Concrete	8	1	1 (13%)
Concrete Block	3	0	2 (67%)
Window Wall	8	2	5 (63%)

Table 3.8 summarizes wall records by rain penetration control strategy and occurrence of problems.

TABLE 3.8
WALL MOISTURE CONTROL STRATEGY PERFORMANCE

Rain Control Strategy	Total Wall Records	Main Wall Records	Walls Contributing to Problems
Face Seal	56	32	35 (63%)
Concealed Barrier	3	0	0
Drained Cavity	5	1	0
Rainscreen	1	0	0

The main wall assemblies of the 4 buildings that did not have any problems are all assemblies that are not common within the study buildings. One consists of stucco, building paper, and exterior gypsum board, but contains a strapped drainage cavity separating the stucco from the building paper. Two contain no secondary moisture protection layer but use glass-fibre faced gypsum board as sheathing. The other problem-free building uses cast-in-place concrete with a painted exterior.

In all but one of the 31 buildings that had problems, the problem(s) damaged the main wall assembly. We also find an interesting relationship between the type of sheathing used and the damage sustained, as follows:

- On 6 buildings the main wall assembly used glass-fibre faced gypsum board sheathing; 3 of these were not damaged or were on no-problem buildings.
- 26 main wall assemblies used exterior grade gypsum board sheathing; only 1 of these was not damaged, and it was on a "drained cavity" design wall.
- Of 10 wall assemblies using glass fibre faced gypsum board sheathing, only 4 were involved in problems.
- Of 37 wall assemblies using exterior grade gypsum board sheathing, 28 were involved in problems. Of the 9 that were not involved in problems, 5 were cavity wall assemblies, 2 were metal panel assemblies, and 2 were too small for damage to them to qualify as a problem for this study (although failures and damage to one were described in the investigative report).

Table 3.9 summarizes window records by frame type and contribution to problems.

TABLE 3.9
WINDOW PERFORMANCE

Window Frame Type	Total Window Records	Windows in High Humidity Buildings	Windows Contributing to Problems
Aluminum, no thermal break	14	2	11 (79%)
Aluminum, thermally broken	6	1	2 (33%)
PVC	1	0	1 (100%)
Not Known	17	4	15 (88%)

All window types are contributors to problems. The determination of the precise nature of the failures within window assemblies exceeded the scope of this project. It is not possible to draw any conclusions with respect to frame type and the contribution to high humidity conditions because of:

- The small sample size for high humidity buildings.
- The fact that a non-thermally broken frame can potentially function as a dehumidifier within suites by providing a condensing surface and drainage path for condensate to the exterior.
- The generally less air tight nature of older construction meant that ventilation (air leakage) may have contributed more significantly to moderating humidity levels than in more air tight recent buildings.

3.6 Details

Table 3.10 shows the occurrence of details on the 65 wall assemblies defined in the database. The role of details in contributing to problems of water ingress into the walls of these buildings is significant.

TABLE 3.10
STATISTICS ON WALL DETAIL TYPES

Wall Assembly - Details:	**Wall Assemblies having this detail**	**How many of these details contributed to a problem?**
D1 – Flat roof parapet or urb above	44 (68%)	**12 (27 %)**
D2 – Soffits above	21 (33 %)	2 (10 %)
D3 – Roof / Wall junctions	34 (52 %)	**10 (29 %)**
D4 – Saddle	38 (58 %)	**26 (68 %)**
D5 – Deck / Wall junctions	29 (45 %)	**12 (41 %)**
D6 – Balcony / Wall junctions	49 (75 %)	**23 (47 %)**
D7 – Patios	15 (23 %)	6 (40 %)
D8 – Movement/Control joints within wall	30 (46 %)	**23 (77 %)**
D9 – Wall flashings	10 (15 %)	5 (50 %)
D10 – Cornices or reveals	11 (17 %)	5 (45 %)
D11 – Dryer vents	23 (35 %)	**11 (48 %)**
D12 – Fireplace vents	8 (12 %)	3 (38 %)
D13 – Other vents and air inlets	31 (48%)	**19 (61 %)**
D14 – Guardrail attachment	39 (60 %)	**18 (46 %)**
D15 – Electrical fixtures	24 (37 %)	3 (13 %)
D16 – Scuppers	21 (32 %)	8 (38 %)
D17 – Water, power, gas lines	2 (3 %)	0
D18 – Gutters and rainleaders	4 (6 %)	3 (75 %)

Note: Window and door interface details are considered to be an interface between two different assemblies and therefore do not appear in the above table.

The high rates of failure of nearly all types of details occurring on high-rise walls indicates that it is not so much the type of detail that occurs as the interruption to wall assembly continuity caused by any detail, that results in problems.

We found 189 instances of details that contributed to a problem, for an average of over 3 different types of details contributing to each reported problem. For several types of detail, over half of their occurrences contributed to problems. Details that appear to be significant contributors to problems due to both their frequency of occurrence and problematic nature are highlighted and bolded in Table 3.6.

3.7 Assembly Interfaces

Table 3.11 presents the data in the database relating to interfaces between wall and/or window assemblies. There are records describing 131 different interfaces in terms of design geometry, materials used, and performance. Interfaces can occur between parts of the same wall assembly (in panelized wall assemblies), between two different wall assemblies, between a wall assembly and a window assembly, or between two window assemblies. Each interface is divided into three orientations as follows:

- HEAD orientation – Assembly 1 is located above Assembly 2
- SILL orientation – Assembly 1 is located below Assembly 2
- JAMB orientation – Assembly 1 is located beside Assembly 2

Some interfaces do not occur in some orientations; for example the interface of a stucco wall (assembly 1) above a brick wall (assembly 2) will have no data for the Sill and Jamb orientations because they do not exist.

TABLE 3.11
PROFILE OF WALL/WINDOW ASSEMBLY INTERFACES

Statistic Description	**Totals**	**Comments**
Buildings with 1 or 2 interfaces	6 (17 %)	
Buildings with 3 interfaces	12 (36 %)	
Buildings with 4 interfaces	6 (17 %)	
Buildings with 5 or more interfaces	11 (31 %)	
Interfaces between wall types	38 (29 %)	16 same wall assembly (panelized walls or control joints) 22 different wall assemblies
Interfaces between walls and window/doors	91 (69 %)	
Interfaces between window/door types	2 (2 %)	

Interface Rain Control Strategy	**Head**	**Sill**	**Jamb**
Face Seal	Total 77 (73 %) Failed 42 (55%) Problem 32 (42%)	Total 70 (79 %) Failed 51 (73 %) Problem 40 (57%)	Total 116 (98 %) Failed 58 (50 %) Problem 45 (39%)
Face Seal with drip edge	Total 19 (18%) Failed 7 (37%) Problem 5 (26%)	Total 14 (16%) Failed 11 (79%) Problem 7 (50%)	Total 0 (0 %) Failed 0 (0 %) Problem 0 (0 %)
2 – stage seal:	0	0	0
Drained Cavity	0	0	1
Drained and Vented Cavity	0	0	0
Flashing only	5	3	0
Don't Know	2	1	1

End Dam:		**Head**	**Sill**
An end dam would be expected in details where the interface is not planar – i.e. one assembly is recessed or expressed more than ½" out of the plane of the other, and where heads or sills intersect jambs.	Total: No End Dam: Sealant:	33 13 (40%) 19 (58%)	22 8 (37%) 13 (59%)
Continuous Membrane		0	0
Molded plastic or soldered metal pan		0	0
Don't know		1	1

Joint Material:	**Head**	**Sill**	**Jamb**
Silicone Sealant	0	1 (1 %)	1 (1 %)
Polyurethane Sealant	52 (49 %)	40 (45 %)	70 (59 %)
Unknown Sealant	12 (11 %)	8 (9 %)	15 (13 %)
Other Sealant	3 (3 %)	5 (6 %)	3.5 (3 %)
Flexible Membrane	0	0	0
Compressed Material (Gasket, Rod)	0	0	0
Flashing	21 (20 %)	14 (16 %)	5 (4 %)
None	11 (10 %)	13 (15 %)	16.5 (14 %)
Don't Know	7 (7 %)	7 (8 %)	7 (6 %)

Joint Profile:	**Head**	**Sill**	**Jamb**
Planar	71 (67%)	64 (73 %)	77 (65%)
Projecting	26 (25 %)	17 (19 %)	33 (28 %)
Recessed	5	4	6 (5 %)
Don't Know	2	2	2 (2%)

Air Barrier Continuity:	**Head**	**Sill**	**Jamb**
Sealant	58 (55%)	40 (45 %)	49 (42%)
Compressed material	0	0	0
Flexible Membrane	5 (5%)	5 (6%)	7 (6%)
None	22 (21%)	21 (24 %)	22.5 (19 %)
Don't Know	21 (20 %)	15 (17 %)	25 (21 %)

Table 3.12 presents information related to assembly interfaces and reasons for failures or success.

TABLE 3.12
WALL/WINDOW ASSEMBLY INTERFACE FAILURES

Interface failure:	**Head**	**Sill**	**Jamb**
Total interfaces	106	88	118
Interfaces that failed	52 (49 %)	65 (74 %)	58 (49 %)
Interfaces that failed and contributed to a problem	39 (37 %)	49 (56 %)	45 (38 %)
Reasons for Failure:			
Inappropriate design	47/52	56/65	46/53
Construction defective	3	3	2
Unforeseen loads	0	0	0
Lifetime exceeded, no mtce plan provided	1	4	4
Lifetime exceeded, mtce plan ignored	0	0	0
Reasons for Success:			
Appropriate design & construction	18/34	4/13	16/38
Protected location	21	9	22
Failures that contributed to Problems:	36/49	45/60	41/53

It is clear from Table 3.11 that the design approach for over 90% of the interfaces recorded on these 35 buildings is a face seal made by applying a sealant compound between two substrates. It is also clear from Table 3.12 that inappropriate design is the primary contributor to failures. Inappropriate design can mean a lack of design for an interface condition or it can mean design of an interface that had no reasonable expectation of fulfilling its function in the expected environmental conditions.

For example, a typical face sealed interface (caulked joint) is located at the outer edges of the two substrates and is therefore fully exposed to the outdoor environment. This approach exposes the joint to extremes of temperature, sunshine, water, wind pressure, and thermally induced joint movement and therefore reduces the durability of the joint from its already low expected lifetime of 10 years. The majority of assessments concluded that most interface joint geometries made no attempt to optimize the joint performance by providing a good width to depth ratio, by minimizing three-sided adhesion, and by ensuring tolerances were such that the expected substrate movements resulted in sealant movements within the elastic range. The result is a high proportion of face sealed joints that have failed; well over 50% of joints have failed in a group of buildings whose average age is less than 10 years. Many of these joints have been left in the failed condition for long enough that water ingress through the failed joints has resulted in a problem.

Table 3.13 presents an analysis of the relative failure rate of interfaces between non-planar assemblies compared to interfaces between planar assemblies. A non-planar interface occurs when one of the assemblies is out of plane of the other assembly by at least ½". For example rebated windows meet the surrounding wall assembly a couple of inches inside the rough window opening; the surface of the window is inside the surface of the wall. Non-planar interfaces are more difficult to design and construct because at least one surface (the sill or head) will collect rain and runoff. End-dams are required to prevent water on this surface from entering the wall or window structure at the corners.

TABLE 3.13
PLANAR VERSUS NON-PLANAR ASSEMBLY INTERFACES

	Head	**Sill**	**Jamb**
Planar Interface Failures	47/71 (66%)	50/64 (78%)	49/77 (64%)
Non-Planar Interface Failures	5/33 (15%)	15/22 (68%)	9/39 (23%)

The data lead us to the conclusion that use of non-planar geometry decreases failure rate of head and jamb joints substantially, and decreases failure rate of sill joints only slightly. Possible explanations of this finding are as follows:

- The rebated interfaces are protected from direct water runoff by their location within the wall opening; only wind-driven rain reaches these interfaces
- The geometry of non-planar interfaces are more demanding and require more attention to design and construction.

Other than the increased use of sill and head flashings on non-planar interfaces, there is no data to indicate that the joint materials, geometry, or other design aspects are improved over planar interfaces; the greater protection from runoff provided by the joint location in the recessed opening therefore appears to explain the result.

3.8 Analysis of Problems

It is important to understand that the definition of “problem” used in this study was established in order to exclude work that might be considered renewals. The problem threshold is intended to represent failures in the envelope assemblies or details that require suite owners to spend at least twice as much as they would spend on normal renewals over the expected life of a building envelope. In practical terms, any envelope failure that required more than $400/(suite-year) to repair was considered a problem.

Table 3.14 presents the database statistics relating to costs of the problems encountered on the study group of buildings.

TABLE 3.14
HIGH-RISE ENVELOPE PROBLEM COST STATISTICS

Average Problem Cost	$1,052,000	$12,474/suite	$1,364/(suite-year)
Average Cost of fixing all problems in a building	$2,019,000	$24,360/suite	$2,664/(suite-year)

For two buildings in the database, problems are described for which repair pricing estimates were not available. These situations were evaluated as likely qualifying as problems, and have been left in the database pending further information. However, the two buildings have been excluded from analyses of repair costs.

Regression analysis was carried out in order to determine the importance of variables such as building size and age on the cost of repairs as a result of envelope failures on the high-rise buildings in the study group. Figure 3.9 shows the relationship of Repair Cost/(Suite x Years) to the age of the building. The cost statistic represents the amount of money that each suite owner would have had to put aside each year since the suite was new, in order to pay for the repairs that were required to deal with all envelope problems in the building. The logarithmic correlation of this statistic to the age of the building was over 60%, representing a moderate level of explanation (60% of the variation in cost is explained by the variation in age of the buildings). Since the cost statistic is already normalized for the age of the building, it appears that factors such as different cladding systems and different building heights used on newer buildings also play a role in making the cost greater for newer buildings.

FIGURE 3.9
COST/(SUITE x YEAR) VS. AGE OF BUILDING

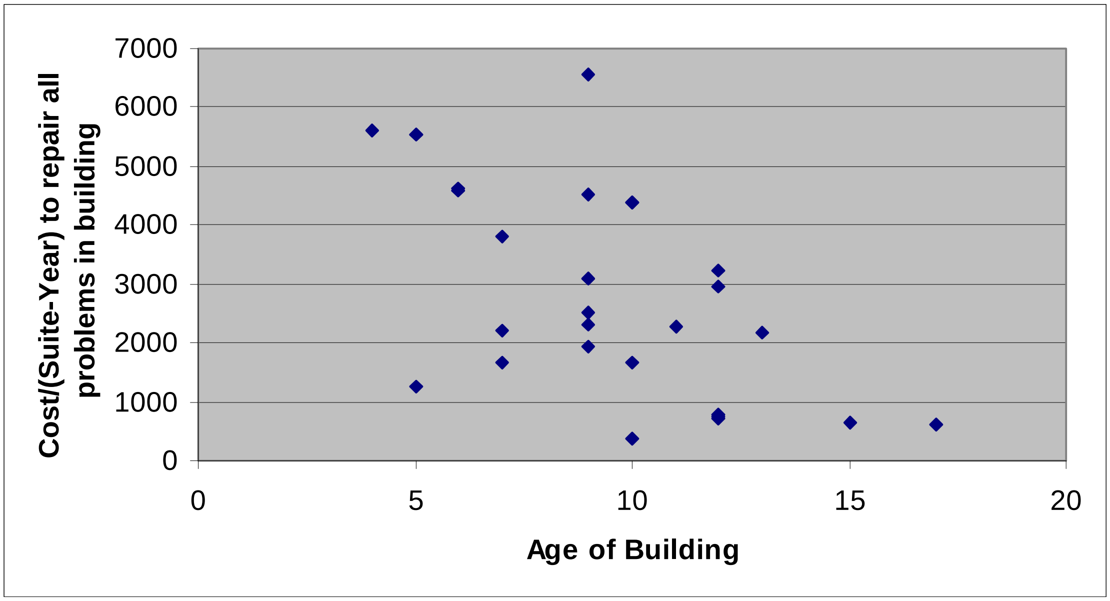
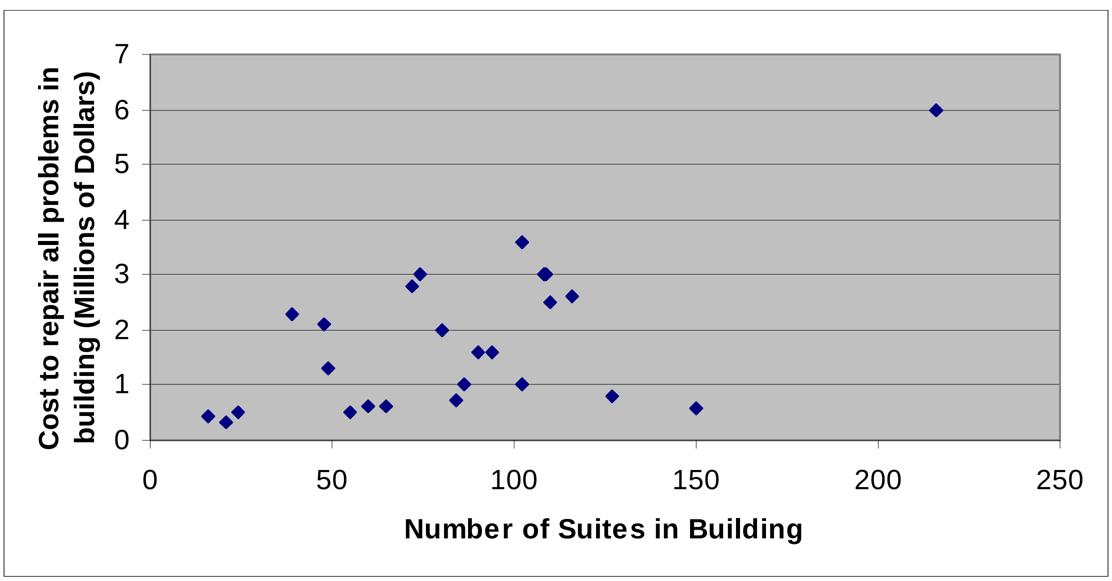


Figure 3.10 is a scatter chart showing the relationship between cost of repairs and size of building. As expected, a moderately good correlation coefficient over 0.70 was found for the linear relationship of these variables. The total cost of repairs is closely related to the size of the building.

FIGURE 3.10
COST VS. NUMBER OF SUITES



The relationship between cost/(suite x year) and the number of suites in the building shown in Figure 3.11 is quite poor, with a correlation coefficient of 0.23 for a linear relationship. Thus, the cost/(suite x year) has little relationship to the size of the building – a suite in a small building costs about as much to repair as one in a large building.

FIGURE 3.11
COST/(SUITE X YEAR) VS. NUMBER OF SUITES

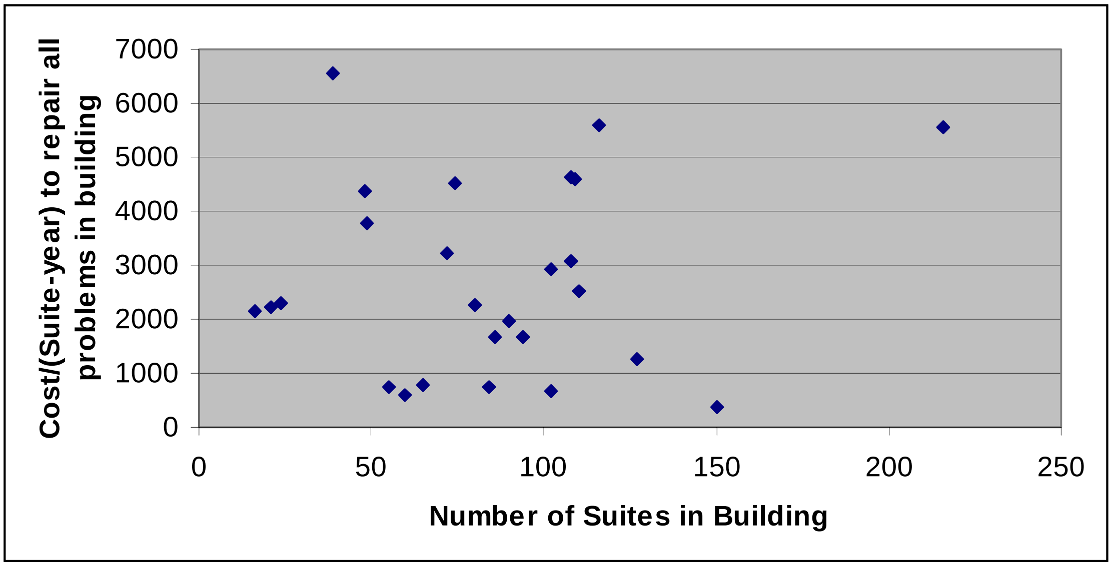


Table 3.15 shows a breakdown of problems by the assemblies and details that were involved. A high incidence of problems (46%) were found which are attributed solely to failures at an interface between assemblies. A further 40 % of the problems were attributed to wall assemblies where numerous defects, including defects at the interfaces between the wall assembly and adjacent assemblies, contributed to the problem.

TABLE 3.15
PROBLEM DETAIL AND INTERFACE STATISTICS

PROBLEM DETAILS AND INTERFACES - Problem involved:	Totals
A Wall Assembly only (includes multiple defect contributions)	24 (40%)
A Window/Door Assembly only	4 (7%)
A Detail within a Wall or Window/Door Assembly	4 (7%)
An Interface between 2 wall assemblies	7 (12%)
An Interface between wall and window/door assemblies	21 (34%)

The assessment of buildings for this study were typically based on one or more condition assessment reports for the building. In these previous reports, where damage was found to be extensive, reporting of the exact scope and extent of the defects causing the damage was limited. The repair typically involved the replacement of the entire wall assembly and its details and interfaces with other assemblies; there is no need to determine which assemblies, interfaces, or details are still performing and which have failed. Often the damage caused by a defect in one type of interface is not large enough, on its own, to qualify as a problem, but when combined with the many other defects qualifies as one problem for which the solution is to replace the entire wall assembly.

Leakage through windows and through interfaces between windows and wall assemblies generally does not damage the window assemblies themselves. Only 3 problems were reported which damaged window assemblies, and all three were in window/wall assemblies. However, defects in window assemblies or in interfaces between windows and walls are a factor in causing 25 of the 60 problems reported.

We can conclude that failures at interfaces of assemblies and details are responsible for the majority of the problems reported in the study group.

Table 3.16 presents statistics related to damage to components and materials within assemblies caused by these failures.

TABLE 3.16
DAMAGE TO HIGH-RISE ENVELOPE ASSEMBLIES

Assemblies Damaged:								
Walls	56							
Windows/ Doors	4							
Layers Damaged:	**Corrosion**	**Wetting**	**Fastener Damage**	**Mould**	**Stains**	**Other**	**None**	**Don't Know**
Cladding	1	18	5	4	11	8	16	0
Sheathing Paper:	0	5	0	1	13	0	34	6
Sheathing:	0	35	0	12	10	0	11	1
Fasteners /Adhesives:	52	1	1	0	0	0	4	1
Support Structure:	52	0	0	1	1	0	4	1
Insulation:	0	0	0	11	42	0	9	1
Air Barrier:	0	1	0	0	0	0	55	2
Polyethylene:	0	0	0	0	0	0	56	2
Drywall and Finishes:	0	0	0	33	25	0	11	1
Furnishings:	0	0	0	2	3	0	51	2

It is clear that the great majority of the damage is corrosion of metal components of the assembly, and wetting, staining and mould growth on sheathing and insulation. The high proportion of damaged walls in which corrosion of fasteners and of steel stud support structure is reported is a serious concern since each fastener represents a concentration point for transfer of loads from the envelope assembly to the primary structure of the building. Two of the buildings included in the study group suffered full or partial detachment of cladding as a result of extensive corrosion of fasteners. It is clear that the levels of corrosion resistance typically used for fasteners and support structure in these buildings is inadequate to cope with the environment they are exposed to once the walls are wet.

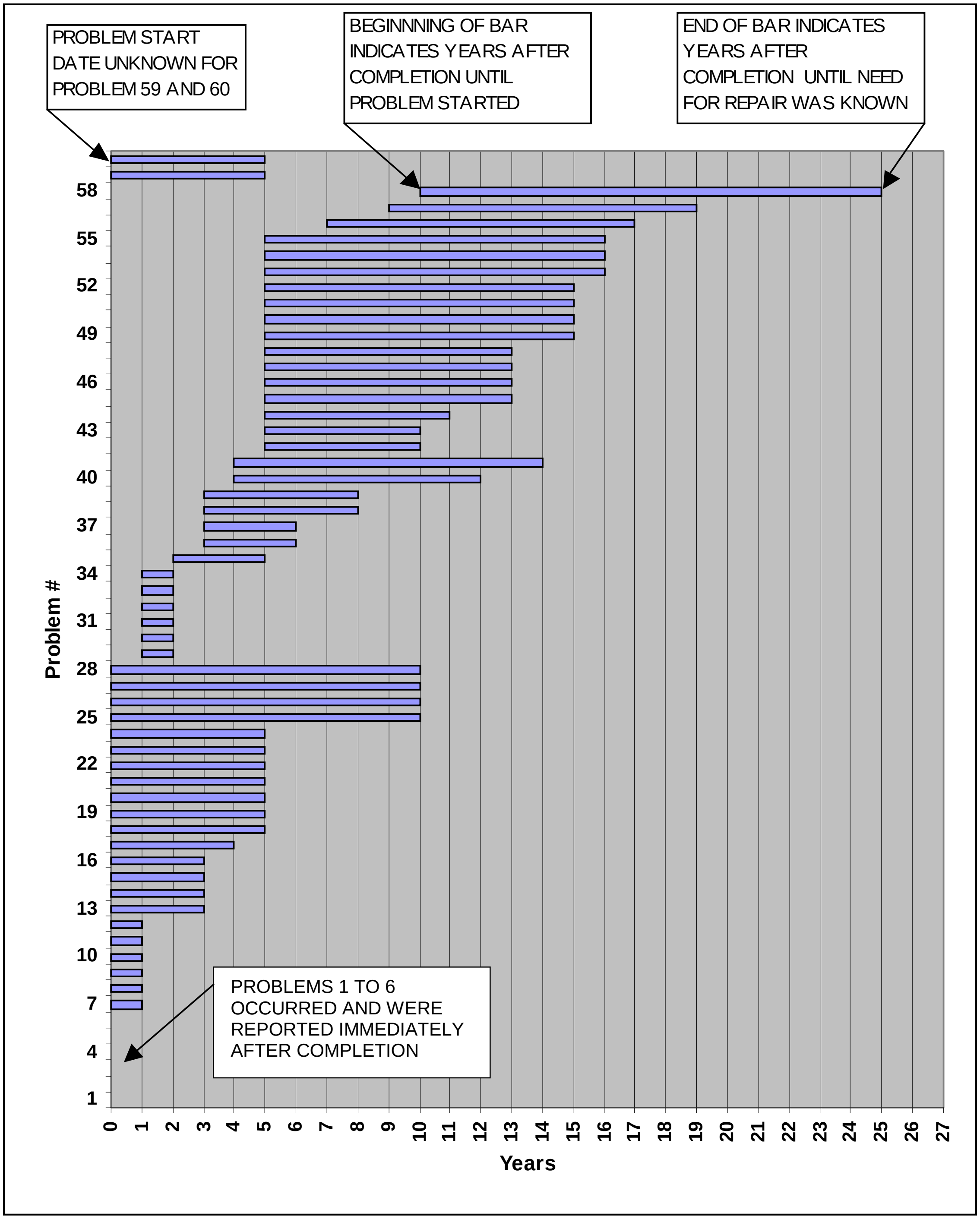
The significance of the damage reported to sheathing is less clear. It is known that wetted exterior gypsum board suffers loss of paper strength, debonding of paper from the gypsum core, and swelling of the core causing pullover of the board over fastener heads. There is very limited data available on the relationships between time of wetting and level of wetting of exterior gypsum board and other sheathing materials, and the above failure mechanisms. However there are problems reported in the database which involve partial or full detachment of the exterior sheathing and cladding, and some of the exterior gypsum board failure mechanisms described were found in those cases.

Many of the reported problems involved mould growing on the organic paper facer of exterior gypsum board sheathing. As this paper is known to be a good substrate for some types of fungi that can produce toxic or allergenic airborne compounds, this is cause for concern relating to the health of building occupants.

Figure 3.12 shows the distribution of “Time to Start” and “Time to Report” for the 60 problem reports in the database. Time to Start indicates when the damage resulting in the need to repair started, whereas Time to Report indicates when the owners generally became aware that repairs would be required (not when the first symptoms of damage were reported). Note that nearly half of the problems were considered to be inherent design or construction defects that were allowing water ingress since the time of the original construction of the building. In the majority of cases, there is a time lag of a few years before a problem relating to water ingress through the envelope assemblies is reported. This indicates that assessments of envelope performance issues during the years immediately after construction are failing to identify the problems. This may be due to:

- Time lag for symptoms to become readily noticeable
- Inadequate assessments
- A reliance on the original project team to correct ‘defects’ in the original design and construction such that they are not initially perceived to be problems by the owners.

FIGURE 3.12
TIME TO PROBLEM OCCURRENCE AND REPORTING



3.9 Nature of Problems

This study confirmed that the nature of the problems experienced in high-rise buildings are similar in many ways to those identified for buildings in the *Low-Rise Survey*. The predominant moisture source (exterior), path (details), and sensitive assemblies (face seal) are common to both types of buildings. However, the performance problems in high-rise buildings manifest themselves quite differently than in wood frame low-rise buildings. In high-rise buildings the key damage issues are:

- Damage to interior finishes
- Deterioration of exterior gypsum board due to softening of the core and mold growth on the paper facing
- Corrosion of metal components of the cladding attachment system including the steel studs (secondary structure), clips, metal reinforcing and fasteners

The damage issue that usually drives the need to rehabilitate is deterioration of the structural attachment system. The structural attachment concern is related to the extent of corrosion of metal components and softening and resulting loss of bearing resistance in the exterior sheathing. The assessment of the adequacy of the structural attachment of the cladding is critical to determination of the need to rehabilitate. Appendix B provides a greater discussion of the mechanism of deterioration as well as providing a protocol for assessment of structural attachment.

Once the adequacy of the structural attachment system has been verified and the moisture source controlled then it is often possible to leave corroded components in place. This is less likely to be possible with decay of wood components in wood frame construction, and is not generally recommended since the decay impacts the primary structure and the mold and resulting decay can continue to grow at relatively modest levels of moisture.

Although mold is present in many of the damaged wall assemblies (predominantly on the interior face of the exterior gypsum board) it is not clear that its presence necessarily drives the need for a rehabilitation program. This may be due to the role of the polyethylene sheet within most wall assemblies limiting the mold to the stud space and limiting its migration to the interior spaces.

4. CONCLUSIONS

4.1 General

It should be re-emphasized that conclusions drawn from this study are not necessarily representative of the general population of high-rise buildings constructed in coastal British Columbia during the study period. The buildings chosen for the study represent a sample of buildings selected from team member files. Extrapolating the results to reach similar conclusions regarding the overall population of buildings is not statistically valid. For example, it is not possible to address issues related to what extent water problems exist in the general population based on the results of this study. However, the findings and conclusions regarding causal relationships (for example, the relationships between building design and construction practices and the occurrence of failures and problems) are valid for similar buildings within the general population of high-rise buildings.

Ideally an examination of a moisture related problem for the purposes of this study would include the examination of many issues throughout the design, construction, operation and maintenance phases of a project's life. However, due to the limited funds available, very little information is available to the team to establish why the design evolved the way it did, why the as-constructed details were as they were found during the investigation, or what the maintenance and operations history was. The investigation necessarily focused on symptoms of a failure or a problem for which relationships with specific assemblies, interfaces, details and features of the building could be examined. Thus, it is beyond the scope of the current study to examine the question of why the design, construction, operations and maintenance activities were undertaken as they were. This study only links specific aspects of the results of these activities (as-designed or as-constructed assemblies) with the problems observed.

The sample size for many aspects of this study is large enough to reach many well-supported conclusions. However, when this sample size is broken down to facilitate comparison of discrete variables, the actual sample size in some cases becomes too small to permit significant conclusions to be drawn. This lack of adequate sample size and its impact on the data analysis has been noted where appropriate.

4.2 Specific Conclusions

Several themes emerge from the analysis of the data. In some instances these conclusions are interrelated, however, independently they represent specific opportunities for improvement in performance:

Building Form Complexity

1. Complexity of the exterior facades of buildings, as defined in this study, was not found to be a significant causal factor in the occurrence of failures or problems. This is contrary to the study team's expectations but may possibly be explained by the predominant impact of virtually all assembly interfaces and details on the occurrence of failures and problems (See Item 5 & 6 below). This may have masked a less significant contribution due to increased building form complexity creating more details that are potentially problematic.

Building Exposure Conditions and Overhangs

2. No relationship could be found between overhang ratio and the occurrence of damage in wall assemblies. This likely reflects the general lack of meaningful overhangs on the buildings in the study group. Given the small overhang ratios, other factors are more significant causal factors.

3. No relationship could be found between door assemblies and the occurrence of problems. This reflects the low exposure conditions that exist for most door assemblies on a typical high-rise building. Although the doors on upper levels of the buildings in the study (no overhang protection provided by balconies) had experienced failures their limited numbers prevented them from being considered problems as defined in the study.

Mechanical Systems

4. Mechanical ventilation provisions in high-rise buildings are not adequately controlling interior moisture conditions. This may be attributable to a variety of factors including unusual sources of moisture from the exterior (water infiltration), unusual sources of moisture from the interior (high occupant load or use characteristics, disconnection of humidistat), inadequate fans and controls, and possibly to problematic in-slab duct configurations.

Assembly Interfaces and Details

5. Exterior moisture penetration at details within wall assemblies are significant contributors to moisture problems in high-rise buildings. It appears to be not so much the type of detail as it is the interruption to the wall assembly continuity caused by any detail that has caused the problems.

6. Exterior moisture penetration at wall to wall assembly interfaces and at wall to window assembly interfaces are significant contributors to moisture problems in high-rise buildings.

7. The use of non-planar geometry at interfaces (one assembly is out of plane with respect to the adjacent assembly) between assemblies improves performance. This is related to the protection provided in instances where one assembly overhangs another and the inherent need to use flashing at many non-planer interfaces. Conversely, there was a reliance on non-ideal caulked joints for planer interfaces.

Assemblies, Components and Materials

8. Window assemblies are significant contributors to problems, although the nature of the failures was not determined within the scope of this study. It was also not possible to assess the relative contribution of window assembly failures vs. failures at the window assembly to wall interface.

9. The majority of the damage caused by the moisture problems that necessitated repairs was found to be corrosion of concealed metal components of the wall assemblies. Metal components include steel studs, fasteners, anchors, and reinforcing mesh (stucco). The levels of corrosion resistance used are inadequate for the in-service conditions in many instances.

10. Significant levels of damage occurred to exterior gypsum board. Wall assemblies containing glass fibre faced gypsum board showed lower extent and severity of damage.

11. Most of the face seal wall assemblies, other than the mass concrete wall assemblies, were found to be damaged and involved in problems.

12. Most of the wall assemblies incorporating an exterior drainage cavity were not damaged. None of these wall assemblies experienced problems.

5. RECOMMENDATIONS

The results of this study clearly indicate that there are opportunities for improvement in many aspects of the design and construction process that will impact positively on the performance of envelope assemblies. The recommendations range from fairly philosophical in nature, encompassing issues relating to the building code, to general aspects of the design and construction process, to prescriptive requirements for elements of the envelope.

Standards and Guidelines

1. At present there is very little prescriptive guidance within building codes, standards and other guideline documents with respect to the environmental loads to be considered in meeting objectives outlined within Part 5. There is a need to better define appropriate exterior and interior design temperature and humidity conditions, but in particular there is a need to define exterior moisture exposure conditions (wind and rain) as well as a process for evaluating these loads in design. The determination of exterior exposure conditions is fundamental to selecting assemblies and developing appropriate assembly interfaces and details.

2. Durability as an issue appears to have been largely ignored during the design and construction of the study group of buildings. The current 1998 BC Building Code refers to S478 Guideline on Durability in Buildings, a non-mandatory guideline. There is a need to better articulate specific durability requirements for the building envelope, and reflect reasonable maintenance and renewal requirements. Durability expectations for components and materials that make up the building envelope are also not well articulated within current standards and guideline documents. The use of mandated durability requirements together with identification of durability expectations for many of the materials and components used in particular environments may meet this need.

3. Guidance and standards exist for the corrosion resistance of metal components within masonry wall assemblies. Similar guidance and standards should be developed and mandated for appropriate corrosion resistance of metal components used in all wall assemblies. These standards and guidelines should reflect relative durability requirements for materials, components and assemblies. As a related item there is a need for further research with respect to the durability of corrosion resistant coatings in installed conditions.

Assemblies

4. Wall assemblies should be selected and designed to reflect exposure conditions for each building and possibly wall regions within buildings that have differing exposure conditions. In particular, rainscreen wall assemblies should be used for the high exposure situations that are typical of non-combustible high-rise buildings. These assemblies must meet performance expectations with respect to moisture control currently required by Part 5 of the building code, but must also reflect reasonable durability, maintenance and renewal expectations.

5. Window assemblies should be selected and designed to reflect exposure conditions for each building and possibly wall regions within buildings that have differing exposure conditions. In particular, rainscreen window assemblies and sub-sill flashing should be used for the high exposure situations that are typical of non-combustible high-rise buildings. These assemblies must meet performance expectations with respect to moisture control currently required by Part 5 of the building code both as manufactured and installed components, but must also reflect reasonable durability, maintenance and renewal expectations.

Assembly Interfaces and Details

6. Interfaces between assemblies and at details are clearly the focal point for water ingress and resulting damage. Both the design and construction of these details can improve. With clarity with respect to durability requirements and use of better wall and window assemblies it is likely that the development and construction of the interfaces will improve. However, there are some specific measures that could be taken to bring greater attention to the need to provide adequate interface details:

   - Add a new module to the AIBC's Building Envelope Education Program dealing with interface details
   - Encourage education and training of all members of the design and construction team with respect to assembly interfaces and details
   - Require mandatory testing of mock-ups on the building as it is constructed to confirm performance of interface details
   - Develop design guide for detailing of assembly interfaces and details

Mechanical

7. Mechanical ventilation and air flow within high-rise residential buildings to control interior humidity levels requires both more research and more consistent application of principles. Although some aspects of this issue are well understood (such as flow in ducts, and exterior wall air tightness levels), there is a need to develop guides that integrate more recent research and knowledge of

air flow and pressure differences within buildings and relative levels of air tightness of interior wall and floor assemblies to arrive at appropriate ventilation strategies.

Prior to more definitive research and/or guidance being developed there are some specific recommendations that could be considered on a project by project basis:

- Careful assessment of system static pressure drops. Avoid long lengths of ducts
- Keep duct runs as straight as possible
- Avoid use of small opening screens/grilles for dryer exhaust ducts as they plug with lint easily
- Match system pressure losses with exhaust fan curves
- Consider the use of dryer exhaust booster fans for long runs
- Consider the use of lint filter boxes within suites to prevent lint build-up within the exhaust system
- Consider use of continuous vertical exhaust systems as found in some hotels. These systems ensure a continuous removal of high humidity in the suites plus ensuring an adequate and measurable amount of outside air as required by ASHRAE standards.

Materials

8. This study noted a difference in performance between paper-faced exterior gypsum board and glass fibre faced gypsum board sheathing. The use of glass fibre faced gypsum board and other more moisture resistant products should be encouraged if not mandated for high-rise construction. As a minimum these products provide greater assurance of acceptable performance through the wetting that is likely to occur during the construction period. Paper-faced exterior gypsum board should not be used as exterior sheathing in high-rise building construction.

   There is also a need to have better data with respect to performance of gypsum board products in wet environments. This will assist the industry in evaluating the implications of particular situations.

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APPENDIX A

Guideline for Assessment of Structural Attachment of Cladding

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GUIDELINE FOR ASSESSMENT OF STRUCTURAL ATTACHMENT OF CLADDING

A-1. Background

Moisture problems in wood frame buildings impact the primary structure by causing decay of the wood sheathing and framing. This decay is often the primary reason that a comprehensive rehabilitation program is initiated in these buildings. In high-rise buildings, or those of non-combustible construction a moisture source is unlikely to significantly impact the primary structure of the building. The exceptions to this general rule may include parking garage structures or steel frame structures where a larger quantity of moisture over long periods of time can have an impact on the primary structure. In particular, post-tensioned concrete slab systems typically have their anchorage zones located at exterior walls and are susceptible to severe damage due to wetting from exterior sources.

The most prevalent structural impact of moisture in high-rise residential buildings is on the attachment of the cladding to the primary and secondary structural system. Moisture damage can manifest itself in softening and loss of strength and stiffness in gypsum sheathing products, corrosion of steel studs, and corrosion of fasteners that attach the cladding and window assemblies to the building. The implications of this damage in the worst-case scenario can result in the cladding and window elements being unable to resist the intended design loads. This loss of attachment capacity does not necessarily result in failure or collapse, although clearly the risk increases. In order for failure to occur the assemblies must be subjected to loads that exceed the resistance of the attachment. Due to margins of safety that are inherent both in the determination of loads and in the assessment of capacity, collapse or other catastrophic failures rarely occur. However, there have been examples of cladding falling from high-rise buildings due to the presence of damage and loads that approach the design values. See Photos A-1 and A-2.

Photo A-1: Stucco cladding fell from north side of this high-rise building during high winds in late November 1998. The yellow indicates new sheathing in the area where cladding fell.

Photo A-2: Wet gypsum board sheathing, corrosion of steel studs and fasteners result in lower capacity of attachment. When combined with high winds (considerably below design loads) failure occurred.

A-2 Mechanisms of Deterioration

The following sections describe the typical structural function of various elements within the exterior wall, the implications of deterioration on future structural attachment performance of these elements, and the need for rehabilitation.

Steel Stud Corrosion

Steel studs provide lateral and vertical support for the cladding. Corrosion of the steel studs affects the fastener holding strength and flexural strength and stiffness of the studs. The flexural stiffness of the stud wall is determined by stud gauge, size and spacing. As a design parameter, steel stud stiffness controls out-of-plane deflection of the steel stud framing and is selected to control flexural movement of the cladding.

Corrosion of the studs reduces the effective stiffness of the studs, which increases deflection and consequently increasing stress on the cladding and potentially a variety of fasteners used in the assembly of the building envelope. Corrosion of the steel stud flange reduces the material thickness and thereby reduces the pull-out capacity of screws. Complete corrosion of a steel stud flange is not likely to occur before pull-out of a fastening screw, therefore loss of fastener holding strength is more critical than loss of stiffness.

The failure of one or more fasteners will not necessarily result in imminent collapse or failure of the cladding attachment. With each fastener failure however, redistribution of support loads will occur and the significance of continued corrosion, and future fastener failures increases. Unlike more ductile structures, such as wood framing, it is not necessarily the case that fair warning will precede failure. Due to the progressive nature of the cladding support system, failure may involve more than one floor level.

Fastener Corrosion (Screws, Metal Clips and Girts)

Cladding in high-rise buildings is typically attached either to the primary structure or secondary steel stud structure with a combination of screws, metal clips and girts that transfer both the gravity load of the cladding and any lateral loads that may be acting. In some cases the cladding may bear on the primary or secondary structure thus negating the need to transfer any gravity loads.

The fasteners used to attach cladding should be corrosion resistant, however buildings have utilized fastener systems of widely varying corrosion resistance, including non-corrosion resistant metal. Some cladding (stucco) provides corrosion protection to the embedded reinforcing and the embedded portion of the screw through passive resistance. Unfortunately the exposed portion of a screw can be exposed to a very corrosive environment. The level of corrosion resistance of the fastener system is an important variable to be considered in assessing both the current structural attachment issue, as well as the longer term durability of the structural attachment.

Corrosion of the fasteners is an initial indicator of potential problems. Corroded fasteners with rust stains that appear on exterior surfaces are indicators of more serious concealed problems that may require immediate attention. Typically, if the fastening screw is adequately corrosion resistant, corrosion and loss of strength in the steel stud flange material will result in failure before corrosion of the fastener. It is important to note that non-corrosion resistant screws, or even some corrosion resistant screws, continually exposed to wet conditions, will corrode and eventually fail at the shank/head interface. Failure of the fastening system can result in loss of attachment for the cladding.

Sheathing Deterioration

The role and importance of the exterior sheathing is complex. The sheathing can provide lateral bracing for the steel stud framing, support for the batt insulation, support for the building paper, and some cladding materials. The sheathing is also a thermal barrier and provides bearing support for the fastener system that supports the cladding.

The fastening screws are installed through the sheathing into the steel studs. The bearing resistance of the sheathing supports the screws, preventing the screws from rotating under the weight of the cladding. Softening of the exterior gypsum sheathing due to elevated moisture content can result in lower bearing capacity of the sheathing and rotation of the screws. In the case of stucco cladding the wire lath typically rests behind the head of the lath screw, and consequently, bearing failure of the exterior gypsum sheathing could result in rotation of the wire lath fastening screw and disengagement of the lath from the screw head.

Cement board and glass fibre faced gypsum (GFFG) exterior sheathing products have greater resistance to wetting and its effects. This fact is supported by the results of this study. However, despite its improved behaviour in wet conditions, GFFG products sheathing is not intended for use in continually wet applications. GFFG sheathing that is exposed to water for prolonged periods of time eventually loses flexural, compressive and bearing strength. In addition, like all gypsum or cement based sheathing products it holds or stores moisture in immediate contact with metal components contributing to the potential for corrosion.

A-3 Approach

The primary purpose of this guideline is to provide a protocol for the consistent assessment of the structural attachment of elements of the building envelope to the primary and secondary structure of the building. In addition, some explanatory material is provided to assist in the understanding of the mechanisms of deterioration and failure that may occur, as well as a better understanding of assessment techniques and their limitations. The guideline is only intended to provide a protocol for the structural attachment issue. It is not intended to provide guidance with respect to the elimination of the source of moisture that may have caused the deterioration.

Most buildings contain more than one type of wall assembly. Structural attachment issues vary significantly depending on the type of wall assembly and therefore it will be necessary to assess each wall type independently.

The protocol consists of 3 sequential stages representing increasing levels of risk with respect to structural attachment. At the first stage, Risk Assessment, the apparent risk of an attachment problem is assessed based on knowledge of the building envelope’s assemblies, components and materials gained from the construction documents as well as visual observations. The visual examination is also used to identify symptoms of deterioration that may indicate an attachment problem. Based on the results of the risk assessment stage a decision can be made to proceed to Stage 2 or alternately no further action may be required if the risk is low.

In the second stage, Damage Assessment, the extent and severity of deterioration to all of the elements impacting the attachment of the cladding is documented. The tasks for this stage are more intrusive, possibly requiring moisture probes and exploratory openings. Based on the results of the damage assessment stage a decision can be made to proceed to Stage 3 or alternately if the risk is low, no further action may be required.

The third stage, Structural Assessment, involves the determination of the impact of the observed and documented damage on the structural capacity of the attachment. The outcome of this third stage would be a report that summarizes the structural inadequacies and provides a recommendations with respect to repairs required in order to address any structural inadequacies. It is anticipated that these recommendations must be considered in the context other repair or rehabilitation work required to address the moisture source.

The tasks in Stage 1 require building envelope expertise and knowledge, whereas the tasks in Stage 3 require structural engineering expertise. Individuals with either area of expertise could undertake the tasks in Stage 2 although a combination of both would be ideal.

If the decision is made not to proceed to a subsequent stage due to low risk or the absence of significant damage, it may still be necessary to undertake rehabilitation work to address a moisture source. The absence of a structural attachment problem at the time the assessment is completed does not provide an indication of adequate future performance.

Figure A-1 illustrates the three stages of the assessment of structural attachment process. The following sections describe each of these stages of assessment in more detail.

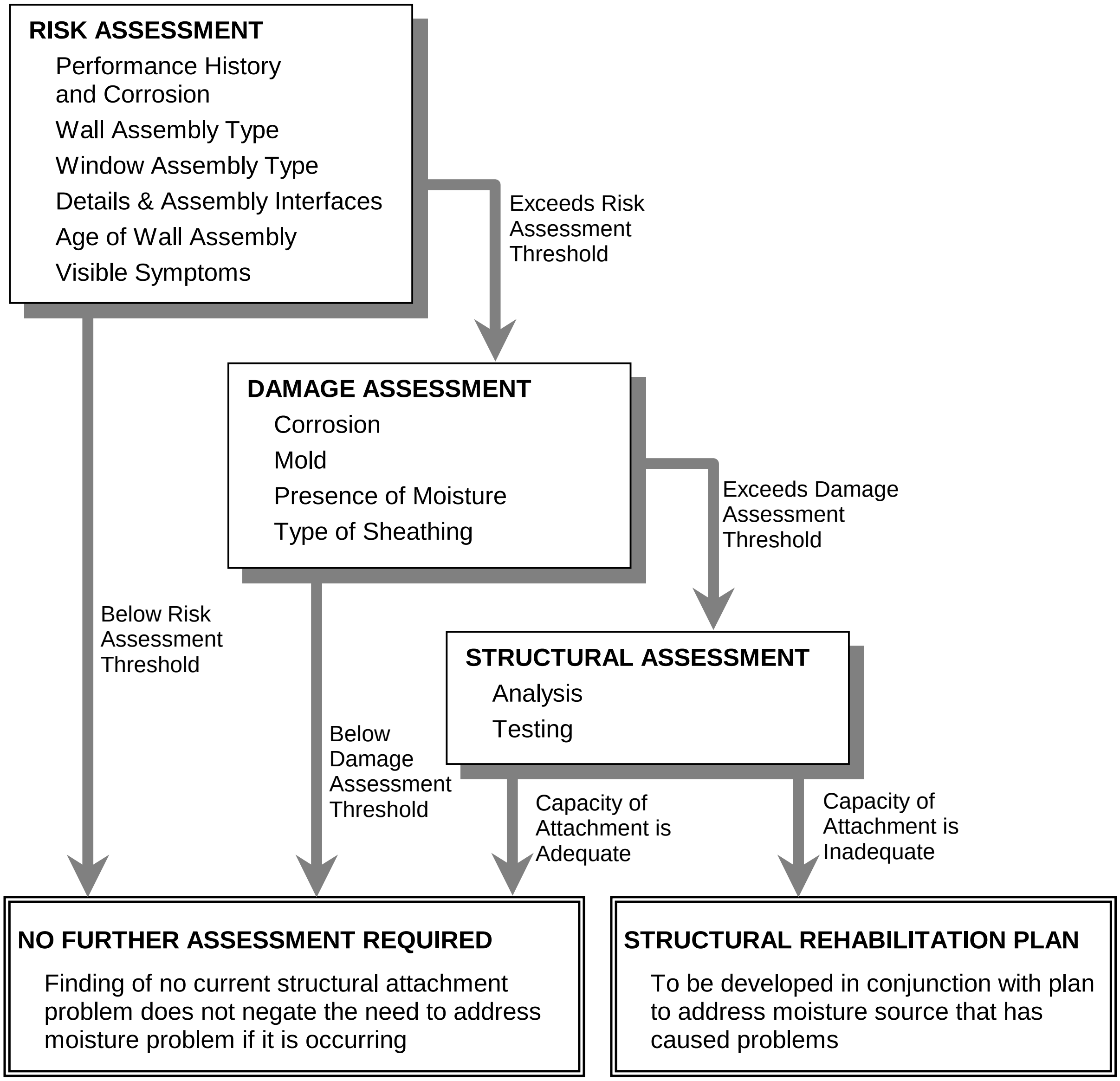

Figure A-1: Assessment of Structural Attachment of Cladding Process

A-4 Protocol For Assessment of Structural Attachment of Cladding

The following sections outline specifics steps of a protocol for assessment of structural attachment of cladding. The tasks for the first two stages involve the assigning of numerical values to categories representative of risk factors based on observations and knowledge of the building envelope. An importance value has been established for each factor as a relative indication of importance. The product of the risk values and the importance factors provides scores that are added to obtain an overall score for each stage. Thresholds have been established that trigger carrying the assessment to the next stage of assessment.

Stage 1: Risk Assessment

The occurrence and extent of moisture damage in building envelopes varies depending on the types of assemblies utilized, the quality of the design and construction of details, the durability of materials used and the age of the building. This initial stage is not intended to be an intrusive process (no exploratory openings or other testing).

Performance History and Corrosion

If the building has a documented history of systemic water penetration, staining or mold on interior surfaces then this would automatically trigger the more detailed and intrusive assessment associated with Stage 2, without the need for further evaluation of the other variables in Stage 1. Rust colour staining indicative of corrosion at particular locations is a key indicator of possible hidden damage. Since the corrosion of metal components has a direct consequence with respect to structural attachment capacity its presence automatically triggers a Stage 2 assessment.

Wall Assembly

This task involves the determination of the type of wall assembly based on the water penetration control strategy. Some types of wall assemblies have inherently better or worse drainage and drying characteristics if wetted.

Window Assemblies

Windows are primary contributors to moisture entering wall assemblies and the resulting damage to the structural attachment system. This factor recognizes the differences in risk provided by various window types and their connection to the adjacent wall assembly.

Details and Assembly Interfaces

Exterior moisture causing damage typically enters wall assemblies at details and assembly interfaces. This factor recognizes the varying frequency and quality of details.

Age of Wall Assembly

The extent of damage to components of the cladding attachment system is a function of age. This factor recognizes the fact that risk increases with age.

Visible Symptoms

Staining on interior surfaces is a possible indicator of concealed moisture. Alternately concentrated moisture runoff on the exterior surface can indicate an area where the exterior moisture control strategy is suspect.

Stage 1: Risk Assessment

If there is a history of moisture related problems or there is rust colour staining visible at base of wall, at through-wall flashing or other locations indicating possible corrosion of concealed metal components proceed to Stage 2.

Risk Factor:	**Risk Value (1)**	**Importance Factor (2)**	**Total Score (1 x 2)**
Wall Assembly Reflects relative performance risk associated with different types of water penetration control strategies: 0 – Rainscreen or Mass Concrete 1 – Concealed Barrier 2 – Face Seal with impervious cladding (window-wall, metal panel) 3 – Face Seal with permeable cladding		3	
Window Assemblies Reflects relative risk of water leakage from window assemblies entering adjacent wall assembly: 0 – Rainscreen window with sub-sill drainage 1 – Rainscreen window without sub-sill drainage or other window with sub-sill drainage 2 – Concealed barrier or face seal window with appropriate head flashing (slope and end dams) 3 – Concealed barrier or face seal window, poor perimeter details (head, sill & jamb)		2	
Details and Assembly Interfaces Reflects the presence and overall quality of the design and construction of details: 0 – Few details, all of good quality 1 – Many good quality details 2 – Many details of variable quality 3 – Many details or poor quality		4	
Age of Wall Assembly Reflects the age of the wall assembly: 0 – 0 to 2 years 1 – 2 to 5 years 2 – 5 to 10 years 3 – Greater than 10 years		1	
Visible Symptoms Reflects the extent and severity of visible staining on the interior (mold, water leakage) or exterior finishes (concentrated water runoff): 0 – None 1 – Minor 2 – Staining indicating concentration runoff at many locations 3 – Staining on the interior or exterior that would normally be indicative of moisture within the hidden components of the wall assembly		3	
Total Stage 1 Score: **If total from Stage 1 Risk Assessment is 25 or greater proceed to Stage 2**			

Stage 2: Damage Assessment

This stage involves more intrusive work to determine extent and severity of damage to structural attachment components. Exploratory openings from either the exterior or interior, and possibly drilling of holes through the cladding to obtain moisture content readings are generally required in order to obtain the necessary information regarding the condition of hidden components. In order to determine the extent of any observed moisture and associated damage it will be necessary to sample an adequate number of locations to reach conclusion regarding the overall pattern of wetness and damage.

Corrosion

At exploratory opening locations, observations and measurements should be made regarding the extent and severity of corrosion that has occurred. This includes all metal components on the load path for structural attachment.

Mold

Mold is an indicator of the current and past presence of moisture.

Presence of Moisture in Sheathing

The evaluation of the extent of moisture within exterior sheathing and the implication of this moisture on structural bearing capacity is a combination of measurement of moisture content and more subjective assessment of the condition of the materials. Section B-5 of this guideline provides information regarding the use moisture meters in determining moisture content within gypsum based sheathing products.

Type of Sheathing

The various non-combustible sheathing products accommodate moisture with lesser or greater softening and damage occurring.

Stage 2: Damage Assessment

Symptom of Damage:	Risk Value (1)	Importance Factor (2)	Total Score (1 x 2)
Corrosion Reflects presence and relative severity of corrosion on exterior flange of steel studs, cladding anchors and fasteners: 0 – None 1 – Minor 2 – Significant reduction in section at isolated locations 3 – Systemic reduction in section due to corrosion		6	
Mold Reflects presence of mold within the wall assembly as an indicator of moisture: 0 – No mold visible 1 – Minor amounts visible 2 – Significant amounts of mold visible but dry 3 – Significant mold visible and elevated moisture levels		2	
Presence of Moisture in Sheathing Reflects the presence of elevated moisture content within exterior sheathing: 0 – None 1 – Isolated locations above 1.4% MC 2 – Many locations above 1.4% 3 – Many locations are saturated and materials have visibly deteriorated (gypsum core, facing)		4	
Type of Sheathing Reflects the relative durability of different sheathing types: 0 – Cement board 1 – Glass fibre faced gypsum board 3 – Exterior gypsum board		2	
Total Stage 2 Score: **If total from Stage 2 Damage Assessment is 18 or greater proceed to Stage 3**			

Stage 3: Full Structural Assessment

The full structural assessment stage could involve analysis based on current condition of components, testing or a combination of both. Many factors must be considered in assessing the adequacy of the attachment system. These include:

- Determination of applicable vertical and lateral loads
- Severity and extent of corrosion
- Wall panel size
- Geometry of wall assembly
- Possibility that unintentional support paths exist (sealants, carried by adjacent cladding elements)
- Redundancy in fasteners and load paths

The report produced for this stage should describe current conditions, future prognosis, safety issues that require immediate attention as well as long-term rehabilitation recommendations.

A-5 Use of Moisture Metres with Gypsum Board

The use of moisture metres in gypsum board products requires knowledge of the specific material properties as well as the specific calibration curves for the instrument used to obtain measurements. Figure A-2 illustrates the relationship between the relative moisture scale on the metre and moisture content of exterior gypsum board. Unfortunately unlike wood moisture content thresholds, the moisture content for mold to initiate, support mold growth and to cause softening and non recoverable damage to the paper facing or gypsum core are not well established. Due to the composite nature of the material it is difficult to establish these relationships for gypsum sheathing products. The threshold numbers shown in Figure A-2 reflect conservative ranges based on the minimal information that is currently available. The thresholds are linked to mold growth since it is the paper facing that acts as a food source for the mold, and the paper on the sheathing is generally considered to be the weak link in the composite behaviour of gypsum sheathing.

FIGURE A-2:
MOISTURE CONTENT IN EXTERIOR GYPSUM BOARD (NOT GFRG) VS. RELATIVE SCALE READING FOR DELMHORST BD-10 AND BD-2100 METERS ONLY