DESIGN, INSPECTION, MAINTENANCE, LIFE CYCLE PERFORMANCE AND INTEGRITY OF BUILDING FACADES

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DEDICATION

To my wonderful parents for their never-ending love and support and my beloved sister for her patience and encouragement, without whom I could have never been able to achieve my goals both personally and academically. Also, I would like to dedicate this thesis to Léa Guilbeault, who lost her life in a catastrophic façade failure in Montreal, in 2009. May this thesis be a start for further research on facades’ life cycle performances and their maintenance needs, to eliminate the tragedies resulting from facade failures.
ABSTRACT

Facades mounted on the exterior of buildings protect the interior from aggressive environments, besides contributing to their aesthetics and technical performance. Unfortunately, despite some serious facade failures involving some deaths and injuries, their inspection and maintenance, which are essential for public safety, have been generally ignored.

On July 16, 2009, a large concrete facade element, weighing 320 kg, detached from the building structure of a Montreal hotel and fell on its exterior sidewalk cafe, instantaneously killing a young woman celebrating her birthday and injuring her husband. Some major U.S. cities, such as New York, Chicago and Boston have learnt from such tragedies, and nine American cities have enacted by-laws or ordinances requiring mandatory periodic facade inspections to ensure public safety. However, Canadian cities do not have similar stringent regulations to guide design, construction, maintenance and life-cycle performance of facades to ensure their safety over service life.

The National Building Code of Canada (NBCC) includes safety provisions for building components which implement environmental separation; however, the NBCC and other relevant CSA standards do not deal adequately with the maintenance, performance and durability issues related to the performance of these facades. This research program is an attempt to develop and recommend strategies to minimize these risks through mandatory inspection and maintenance programs, and to eliminate similar tragedies from occurring in the future.
ABRÉGÉ

Façades montées sur l'extérieur de bâtiments à protéger l'intérieur d'environnements agressifs, en plus de contribuer à leur esthétique et performances techniques. Malheureusement, malgré quelques ratés façade graves impliquant des morts et des blessés, leur inspection et d'entretien, qui sont essentiels pour la sécurité du public, ont été généralement ignorée.

Le 16 Juillet 2009, un élément de façade en béton grand, pesant 320 kg, détaché de la structure du bâtiment d'un hôtel de Montréal et est tombé sur son café sur le trottoir extérieur, tuant instantanément une jeune femme fête son anniversaire et blessé son mari. Certaines grandes villes américaines, comme New York, Chicago et Boston ont appris de telles tragédies, et neuf villes américaines ont adopté des lois ou des muntions qui nécessitent des inspections obligatoires périodiques façade pour assurer la sécurité du public. Toutefois, les villes canadiennes n’ont pas similaires réglementations strictes pour guider les performances conception, la construction, l’entretien et du cycle de vie des façades pour assurer leur sécurité pendant la durée de vie.

Le Code national du bâtiment du Canada (CNBC) comporte des dispositions de sécurité pour les éléments de construction qui mettent en œuvre la séparation de l’environnement, mais les normes du CNB et autres pertinentes de la CSA ne traite pas de manière adéquate les questions de maintenance, de performance et de durabilité liés à l’exécution de ces façades. Ce programme de recherche est une tentative d’élaborer et de recommander des stratégies pour minimiser ces risques par l’inspection obligatoire et des programmes de maintenance, et d’éliminer les tragédies semblables ne se reproduisent à l’avenir.
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This thesis is the conclusion of a long journey in academic research. During this journey, many people contributed either directly or indirectly to this work.

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# TABLE OF CONTENTS

ABSTRACT .............................................................................................................................................. iii
ABRÉGÉ ................................................................................................................................................ iv
ACKNOWLEDGMENTS ......................................................................................................................... v
TABLE OF CONTENTS ........................................................................................................................ vi
LIST OF TABLES .................................................................................................................................... xii
LIST OF FIGURES .................................................................................................................................. xiii

Chapter 1 General Overview of Building Facades ................................................................. 1
  1.1 Definition ....................................................................................................................................... 1
  1.2 Application of Facades ..................................................................................................................... 1
    1.2.1 Aesthetics ................................................................................................................................... 1
    1.2.2 Environmental Separation ......................................................................................................... 1
    1.2.3 Structural Resistance to Environmental, Seismic and Gravity Loads 2
  1.3 Building Facades through History .................................................................................................... 2
  1.4 Classification of Building Facades According to Their Material .................................... 2
    1.4.1 Brick Facades ............................................................................................................................. 2
    1.4.2 Glass Facades ............................................................................................................................. 4
    1.4.3 Metal Facades ............................................................................................................................. 5
    1.4.4 Stone Facades ............................................................................................................................. 8
    1.4.5 Wooden Facades ......................................................................................................................... 9
    1.4.6 Concrete Facades .................................................................................................................... 10
  1.5 Summary......................................................................................................................................... 14

Chapter 2 Characteristics of Concrete Façade Components ............................................. 16
  2.1 Sustainability and Durability of Concrete ....................................................................................... 16
  2.2 Sustainable Development in Concrete Facade Engineering .................................................. 18
  2.3 Durability Considerations ............................................................................................................... 19
  2.4 Damage Modes in Precast Concrete Facades ............................................................................. 20
2.4.1 Chemical Damage................................................................. 20
  2.4.1.1 Leaching............................................................................. 20
  2.4.1.2 Alkali–Silica Reaction (ASR).............................................. 20
  2.4.1.3 Delayed Ettringite Formation.......................................... 21
  2.4.1.4 Carbonation....................................................................... 22
  2.4.1.5 Acid Attack......................................................................... 23
  2.4.1.6 Chloride Attack................................................................. 23
  2.4.1.7 Decalcification................................................................. 23
2.4.2 Physical Damage.................................................................... 24
  2.4.2.1 Freeze-Thaw...................................................................... 24
  2.4.2.2 Surface Wear...................................................................... 25
  2.4.2.3 Thermal Damage............................................................... 25
2.5 Characteristics of Reinforcing Steel...................................... 26
2.6 Failure Modes of Steel Reinforcement or Connections in Concrete Facades............................................................. 27
  2.6.1 Corrosion.................................................................................. 27
  2.6.2 Fracture................................................................................... 29
2.7 Summary.................................................................................... 30

Chapter 3 Service Life of Concrete Facades................................. 31
  3.1 Service Life of Concrete Facades............................................. 31
  3.2 Durability Design Approaches.................................................. 31
  3.3 Durability Design Formulation by Lifetime Safety Factor Method. 33
  3.4 Determining Lifetime Safety Factor.......................................... 33
  3.5 Design Service Life..................................................................... 38
  3.6 Summary.................................................................................... 39

Chapter 4 Risks in Concrete Facades.......................................... 40
  4.1 Risks to Be Considered in Concrete Facade Design..................... 40
    4.1.1 System Selection................................................................. 41
      4.1.1.1 System Detailing............................................................. 41
5.6 Prevention of Accumulation and Ingress of Surface Water ............... 59
5.7 Moisture Protection ........................................................................ 59
  5.7.1 Protective Material and Component Properties ............................. 59
  5.7.2 Required Moisture Protection ..................................................... 60
5.8 Sound Transmission ........................................................................ 60
5.9 Summary ....................................................................................... 61

Chapter 6 Maintenance Strategies .......................................................... 62
  6.1 General Principles for Maintenance Strategies ................................. 62
  6.2 Design for Maintainability ............................................................... 62
  6.3 Preventive Maintenance .................................................................. 63
    6.3.1 Concrete Façade Inspection - A Brief History ............................. 63
    6.3.2 Conducting Façade Inspections for Unsafe Conditions ............... 64
    6.3.3 Considerations in Performing Concrete Building Façade Inspection ................................................................................. 65
      6.3.3.1 Movement of Materials ...................................................... 67
      6.3.3.2 Thermal Movements .......................................................... 67
      6.3.3.3 Moisture Movements ......................................................... 67
      6.3.3.4 Elastic Deformations .......................................................... 68
      6.3.3.5 Creep Effects ................................................................. 68
      6.3.3.6 Corrosion ................................................................. 69
      6.3.3.7 Unstable Soils ................................................................. 69
    6.3.4 Procedures for Performing Concrete Building Façade Inspection 69
      6.3.4.1 Inspection Process ............................................................ 69
      6.3.4.2 Precast Concrete Façade Investigation ................................. 72
      6.3.4.3 Reporting ................................................................. 74
    6.3.5 Facade Cleaning - Preparation ................................................... 75
      6.3.5.1 Water Cleaning Methods ............................................... 77
      6.3.5.2 Chemical Cleaning Methods ............................................ 78
      6.3.5.3 Abrasive Cleaning Methods .............................................. 79
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4</td>
<td>Corrective Maintenance</td>
<td>80</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Repair Considerations</td>
<td>81</td>
</tr>
<tr>
<td>6.4.1.1</td>
<td>Cause and Extent of Deterioration</td>
<td>81</td>
</tr>
<tr>
<td>6.4.1.2</td>
<td>Repair Objectives</td>
<td>82</td>
</tr>
<tr>
<td>6.4.1.3</td>
<td>Environmental and Logistical Limitations</td>
<td>83</td>
</tr>
<tr>
<td>6.4.1.4</td>
<td>Temporary Support and Shoring</td>
<td>84</td>
</tr>
<tr>
<td>6.4.1.5</td>
<td>Cost Versus Service Life</td>
<td>85</td>
</tr>
<tr>
<td>6.4.1.6</td>
<td>Selection of Repair Materials</td>
<td>85</td>
</tr>
<tr>
<td>6.4.2</td>
<td>Patching Techniques and Materials</td>
<td>88</td>
</tr>
<tr>
<td>6.4.2.1</td>
<td>Identifying Delaminated Areas and Extent of Required Concrete Removal</td>
<td>88</td>
</tr>
<tr>
<td>6.4.2.2</td>
<td>Concrete Removal/Rough Demolition</td>
<td>89</td>
</tr>
<tr>
<td>6.4.2.3</td>
<td>Saw Cutting Patch Perimeter and Surface Preparation</td>
<td>90</td>
</tr>
<tr>
<td>6.4.2.4</td>
<td>Reinforcing Steel Repairs</td>
<td>90</td>
</tr>
<tr>
<td>6.4.2.5</td>
<td>Final Preparation</td>
<td>91</td>
</tr>
<tr>
<td>6.4.2.6</td>
<td>Form and Pouring Technique</td>
<td>92</td>
</tr>
<tr>
<td>6.4.2.7</td>
<td>Substrate Wetting, Patch Placement, and Finishing</td>
<td>92</td>
</tr>
<tr>
<td>6.4.2.8</td>
<td>Curing and Form Removal</td>
<td>93</td>
</tr>
<tr>
<td>6.4.2.9</td>
<td>Surface Grinding</td>
<td>93</td>
</tr>
<tr>
<td>6.4.2.10</td>
<td>Coating Application</td>
<td>93</td>
</tr>
<tr>
<td>6.4.3</td>
<td>Repairing Cracks in Concrete</td>
<td>94</td>
</tr>
<tr>
<td>6.4.4</td>
<td>Quality Assurance</td>
<td>95</td>
</tr>
<tr>
<td>6.4.4.1</td>
<td>Initial Sounding and Identification of the Patch Area</td>
<td>95</td>
</tr>
<tr>
<td>6.4.4.2</td>
<td>Rough Demolition</td>
<td>95</td>
</tr>
<tr>
<td>6.4.4.3</td>
<td>Final Surface Preparation</td>
<td>95</td>
</tr>
<tr>
<td>6.4.4.4</td>
<td>Form Removal</td>
<td>96</td>
</tr>
<tr>
<td>6.4.4.5</td>
<td>Final Inspection</td>
<td>96</td>
</tr>
<tr>
<td>6.5</td>
<td>Summary</td>
<td>96</td>
</tr>
</tbody>
</table>
Chapter 7  Facade Failure: A Case Study................................................................. 97
  7.1  The Peel Street Incident.............................................................................. 97
  7.2  Coroner’s Report: Analysis and Cause of the Incident............................... 99
    7.2.1  Definition of Building Situation.......................................................... 99
    7.2.2  Partial Details of the Incident............................................................. 100
    7.2.3  Summary of the Case ............................................................................ 104
  7.3  Lessons Learnt............................................................................................. 105
  7.4  Summary..................................................................................................... 109

Chapter 8  Summary and Conclusions................................................................. 111
LIST OF REFERENCES........................................................................................... 114
LIST OF TABLES

Lifetime safety factors determined by a normally distributed degradation function [31].............................................................. 37
Considerations of systems for façade wall selection [58].................. 41
Considerations of wall selection – finishes [58]............................. 42
Summary of facade risks [58].......................................................... 49
LIST OF FIGURES

Figure 1-1 Brick veneer over reinforced cast-in-place concrete [7] .................. 3
Figure 1-2 Brick veneer over reinforced concrete block [8] .......................... 3
Figure 1-3 Brick veneer over steel studs [9] ............................................. 4
Figure 1-4 Typical glass façade detail [11] ................................................. 5
Figure 1-5 An example of steel façade detail [14] ....................................... 7
Figure 1-6 Stone veneer over reinforced concrete block [16] ....................... 9
Figure 1-7 Timber façade [17] ................................................................. 9
Figure 1-8 Concrete block veneer over steel stud [19] ................................. 10
Figure 1-9 Concrete block veneer over concrete structure [20] ................. 11
Figure 1-10 Typical concrete sandwich panel system. It must be noted that in
this section steel reinforcement is not illustrated [22] ................................ 13
Figure 1-11 Anchorage systems used to attach precast concrete panels to
building structure [23] ........................................................................... 14
Figure 2-1 Molecules of surface-active agents [35] ...................................... 24
Figure 2-2 Corrosion process [46] ............................................................. 28
Figure 3-1 Relationship between mean service life and target service life [53]
............................................................................................................. 34
Figure 3-2 Lifetime safety factor in terms of degradation process [53] ....... 35
Figure 6-1 Engineer conducting façade inspection via industrial rope
access[63]. ............................................................................................. 66
Figure 6-2 Detailed façade inspection including sounding for delamination
being conducted from a telescoping boom lift [63] ................................. 72
Figure 7-1 The scene where a slab of concrete fell from the 18th floor of a
downtown hotel killing a woman and injuring her husband in Montreal
Thursday, July 16, 2009 [74] .................................................................. 97
Figure 7-2 Visual survey on the incident scene [78] .................................. 99
Figure 7-3 Front-view of panel at issue located on 18th floor ...................... 100
Figure 7-4 Photo of the Hotel façade showing the place of fallen concrete panel [79]...........................................................................................................................................100

Figure 7-5 At left: Upper south corner of the panel. A rebar can be distinguished that was formerly welded to a plate which is now detached from the panel. Corrosion traces indicate the place where once the plate stood. At right: plate remained attached near the window of 18 floor. The arrow points to a deposit of slag at welds [79]. .......................................................................................................................................101

Figure 7-6 The lateral coating did not allow the welding of the two attachments on this side. The picture shows the brick was used as a coating material [79]. .......................................................................................................................................102

Figure 7-7 Panel at issue ...........................................................................................................................................103

Figure 7-8 Anchoring of the south bottom corner of panel is intact although it is twisted [79]. ...........................................................................................................................................104
Chapter 1  General Overview of Building Facades

1.1  Definition
The word “Façade” comes from French language, meaning "frontage" or "face" [1]. A façade is, in general, the exterior of a building occasionally with a special architectural treatment, usually the front but it can also be on the sides and rear of the building.

1.2  Application of Facades
1.2.1  Aesthetics
As façade of a building sets the tone for the rest of the building itself, from a design standpoint, in architecture, the facade is often the most important building component [2].

1.2.2  Environmental Separation
Along with the aesthetic considerations, facades have a major role in protecting the exterior walls of a building from direct impact of aggressive environment to enhance the durability of the building structure and to enable it to perform well throughout its lifecycle [3]. A façade works as an extra heat, moisture and sound insulator. For example it allows the excess humidity from inside the building to migrate to the outside, while at the same time it does not permit the humidity from the exterior environment to penetrate to the inside. Generally the performance of the facades enhances the building durability in practice and promote its functions to provide air-tightness, thermal performance (heat losses and solar gains), daylight access, acoustic behaviour, and resistance to fire.
1.2.3 Structural Resistance to Environmental, Seismic and Gravity Loads

Building facades must be designed to carry gravity loads. In addition, they must be able to resist environmental loads (wind, rain,) and other mechanical loads such as seismic and blast loading [4]. The components should be designed and selected for adequate durability without extensive maintenance over the service life. However, the probability of achieving this target depends on building type, size and intended building usage.

1.3 Building Facades through History

Facades are directly related to the architecture of buildings and as a result, have changed throughout history through evolution of architectural styles. The earliest facades were mostly constructed with stone, wood, brick and even clay depending on the climatic conditions surrounding the building. Using different materials and construction methods to suit a variety of functions and climates, led to appearances of different architectural renderings and highly varying forms of facades. Concrete was first used in Roman architecture during the 1st century [5]. The invention of roman concrete caused a revolution in the construction industry, which led to appearance of different architectural styles. Years later, steel was employed as another material used both in buildings and facades, and presently, there are numerous types of materials and construction styles used in facades.

1.4 Classification of Building Facades According to Their Material

1.4.1 Brick Facades

Brick facades hold up well to the elements and are relatively inexpensive, with minimal repair costs [6]. Consequently, they are favored for both residential and commercial buildings. Brick facades can be ordinary, or decorative. They do not tend to be as complex as marble facades. They can be molded, shaped and engraved more easily. Also it is possible to add some diversity to brick facades by using colored brick. Figures 1.1 to 1.3
show details of brick facades over, cast in place concrete, and reinforced concrete block and steel studs.

Figure 1-1 Brick veneer over reinforced cast-in-place concrete [7]

Figure 1-2 Brick veneer over reinforced concrete block [8]
1.4.2 Glass Facades

Glass facades are mostly by used in commercial structures, but have also been utilized in modern construction [6]. They allow not only natural light and heat to enter the building structure, but also admit cold air, which occurs when the façade is not sealed. The University of California Berkeley's Center for the Built Environment claims that, by using high performance glazing products, it is possible to incorporate larger areas of transparent glass in a building façade. However, it should be pointed out, that as this surface area increases, it becomes more difficult to accurately predict its effect on energy performance and temperature-dependent comfort levels.

In modern theory, glass was idealized as a material whose transparency “dissolved” the separation between the inside and the outside [10]. In fact, it was a material that permitted light to pass through it while prevented entry to air, bugs, and most projectiles. Transformation of curtain walls from two-dimensional surfaces to three-dimensional, vertical terrains is an important modern development. Presently, glass is explored using a
number of procedures, from casting and bending to silk screening, and other surface improvements.

Advocate of computers has facilitated and helped evolve production of both architectural designs and construction elements such as materials, systems, etc. and more complex and varied designs have become a reality. One example is a folded glass facade, which takes the previously modular mechanism of glass and steel and make them more ductile. Detail of a typical glass façade can be seen in Figure 1.4.

![Diagram of typical glass façade detail](image)

**Figure 1-4 Typical glass façade detail [11]**

### 1.4.3 Metal Facades

Metal facades offer extensive design scope by using many different materials that are suitable for the intended purpose and also the wide range of treatments to which they can be exposed [12]. Availability of metals in forms of strip, sheet, panel or single form, enables them to be
pressed and punched, or be manufactured as mesh and fabric-like materials.
In 1912, architects were provided with a new building material by development of stainless steel which had the combination of high strength, good resistance to corrosion, workability and a modern appearance [13]. For 100 years, the external weatherproof component of many of the world’s tallest buildings have been provided in stainless steel. Stainless steel cladding can remain shiny and free of stains, despite the heavy environmental pollution, especially from the traffic. Accumulations of airborne contaminants can be prevented by natural rainwater washing of the surface. Stainless steel cladding can endure the effects of the aggressive environment without any apparent damage. An intelligent designer can adjust the moveable elements of cladding according to the angle of the sun. Figure 1.5 illustrates an example of a steel façade.
Figure 1-5 An example of steel facade detail [14]
1.4.4 Stone Facades

Unquestionably, the most enduring architectural applications are constructed with stone [15]. The compressive strength of most stones far exceeds any loads that can be imposed on these facades. The technology of building in stone provides bearing walls and columns to carry loads from floors and roofs. This method has not changed over time, except in style and complexity until the arrival of steel and reinforced concrete building structures in the mid-twentieth century. Walls do not need to be massive at the base; thinner and lighter curtain walls evolved and with the same weight on the foundations, and several more stories could be implemented in the building.

Stone is still excavated in the same old way as in the past. Lacking flexibility of the new industrial materials, has led stone façades to become comparatively expensive to the extent that after the Second World War its share of the market declined noticeably. For prestigious buildings, however, the use of cut stone continued, particularity in lobbies and/or at least around the main entrance, if not for the main façade.

Stone, has some great advantages over most other building materials. It does not have to be manufactured. Also, it has a recognised to be resistant to aggressive weathering conditions. In addition, no other material can duplicate textures and colors of the various available stones exist. New techniques have been developed, both in preparing and in construction of the stone, because usage of stone (even at a premium level) in facades is very desirable due to its excellent properties. Presently, stone is cut into thin slabs that are used in a diverse ways to face precast concrete panels and light metal frames. One of the major economic factors in this adaptation is that one quarry block can clad larger surface area of wall. Stone façades are durable and eye-catching, and represent a considerably economical alternative to solid stone construction.
1.4.5 Wooden Facades

Presently, various solutions for the design of façades are offered by the use of numerous types of wood with their unique qualities, such as color, durability, hardness, visual structure, etc. (Figure 1.7) [17]. Wooden façades are appropriate for both residential buildings as well as for larger buildings. Since wood is a natural material, it is subject to ageing and it can decay subjected to an aggressive environment. The use of properly treated wood is essential to ensure an extended lifespan for wooden façades.
Concrete was introduced in the first century by ancient roman constructors. This revolutionary material which freed the romans from limitations of brick and stone is being used as the most popular construction material today. Precast concrete was introduced in the early twentieth century and has been widely used commencing in the 1960s [18] in construction of bridges, industrial buildings, facades of building structures, and others. It is expedient to use prefabricated panels for facade systems to save time, along with better quality control on materials and fabrication. Presently, a pre-casting organization provides the designer
with choice of numerous shapes, colors, textures, and finishes for precast concrete systems. As a result, the key to the use of precast concrete for facades involves assessment of samples. Before pre-casting of the panel at the plant, a majority of review and approval processes are conducted in addition to the quality control and field testing.

Typically, an assemblage of metal components and anchors is used for each precast panel to be independently connected to the building structure. Joints around each of the precast panels are usually filled with a sealant. Figures 1-8 and 1-9 provide some typical details of concrete blocks with steel and concrete wall structures.

Figure 1-8 Concrete block veneer over steel stud [19]
Another form of concrete façade is a sandwich panel system which provides an appealing functional and energy efficient façade system, which is easy to construct, and provides a long economical life [21]. It also offers
structural efficiency, fire resistance along with appropriate acoustic qualities and vibration control. Figure 1-10 illustrates section of a typical concrete sandwich panel facade system.

Presently, framing facade systems are commonly used in building structures. In these systems, concrete precast panels are attached to building frame by welding the steel elements embedded in the facade to the anchors embedded in the building structural system (Figure 1-11).
As with other façade systems, concrete facades would deteriorate during their service life due to aggressive environmental conditions and applied forces (both mechanical and environmental). The principal deterioration modes are corrosion of the embedded anchors, improper welded connections, and damage to concrete due to freezing and thawing cycles. Since most of the tragic accidents and façade failures have occurred in concrete facades, this research focuses mainly on concrete façades, their failure modes, enhanced design, maintenance, repair and rehabilitation. The first step to prevent these failures is to examine characteristics of materials used in concrete facades, which is covered in Chapter 2 of this research.

1.5 Summary

Facades have changed over time with evolution of architectural styles and the variety of materials that can be used in building facades. Independent of the material selected for building facade, the facade must satisfactorily fulfill its major functions which are environmental separation and structural resistance to any applied loads.
Normally, it is the responsibility of the architect to select the cladding material for an appealing aesthetic appearance and to specify the performance criteria [18]. The structural engineer then designs the structure to support the cladding, provides the details for façade connections and sealants, considers and estimates the effects of structural movement on the cladding. The manufacturer produces the cladding in accordance with the specified structural design and connection details and provides the water tightness, performance and durability requirements of the cladding.
Chapter 2  Characteristics of Concrete Façade Components

2.1  Sustainability and Durability of Concrete

Sustainability generally implies no remaining negative environmental, economic and social impact on for the future generations [24]. As a result sustainable development means (development that meets the needs of the present without compromising the ability of future generations to meet their own needs)[25].

Construction materials are manufactured from some mixture of raw materials, with considerable consumption of energy, which produce related wastes [26]. To enhance sustainability in manufacture of construction materials, it is important to minimize the energy input into their production and reduce any resulting waste to a minimum. Also, energy is consumed during the construction process, along with production of some waste. Several important issues are related to the construction process, such as the amount of each manufactured material used, possibility of using materials with lower environmental impact, amount of consumed energy and the waste produced and the impact of this waste on the environment. Presently, as part of global and regional efforts to make construction activities more sustainable, construction phase is receiving increasing attention.

Sustainability is directly influenced by the service life of a structure. A structure may be demolished and rebuilt when it deteriorates. Adaptability of design to repair and renovation further influences the sustainability, which have their own environmental impact. Decommissioning and demolition are the final stage in the life of a structure which involves, consideration of parts of the structure that can be reused, or the portion of the materials that can be recycled, the environmental impact of the waste produced during the demolition process, materials that must be discarded as waste, and their environmental impact.

Concrete is a versatile, durable and most widely used construction material in the world [27]. Compared with wooden construction, concrete provides
higher fire resistance and can gain strength over time. Concrete structures can have a long service life. By chemically combining water and cementitious materials a kind of glue is produced that binds the materials together and creates an extremely versatile material that can be molded into an variety of shapes and produces a durable structural material that does not decay, rust, or burn [28]. Concrete is a unique material with many qualities; however, there are a number of limitations in improving the sustainability of construction. These include the following positive attributes:

- Concrete is typically locally derived, manufactured and placed. It can be recycled and used as aggregates.
- Concrete consumes CO₂ from the atmosphere during service.
- It is usually reinforced by recycled steel.
- The ingredients need little processing and produce little waste
- Concrete is remarkably resistant to fire, progressive collapse, seismic, wind or blast loads
- Concrete saves on artificial lighting by being reflective,
- It will not decay or rust and is extremely durable
- It enables considerable reductions in heating and cooling costs by offering an exceptional thermal mass
- It provides aesthetics in architectural applications
- It is flexible in design choices and can fit perfectly into any surroundings
- It offers acoustic attenuation

However, concrete has some limitations such as:

- It needs components, such as Portland cement and reinforcing steel, whose manufacture necessitates considerable expenditure of energy and consequently results in a considerable emission of CO₂.
- Concrete construction requires experienced staff to properly place it, particularly in modern high-tech structures and applications.
- Designers and engineers must possess the specialty required to design for optimum structure sustainability.
2.2 Sustainable Development in Concrete Facade Engineering

As mentioned earlier, the concept of sustainability is associated with reasonable consumption of natural resources to benefit the present society without compromising their resource for future generations [29]. Sustainable development in civil engineering, concentrates on well-organized use of natural resources at design, construction and operation phases of a project. This efficiency is reliant on the positive impact of the structure on the public and the environment [30]. This objective can be reached by emphasizing on preservation measures, consumption of renewable resources, reduction of waste, recycling of used materials and preparation of more comprehensive environmental and economic valuations by using tools such as life-cycle costs analysis [31].

To ensure safety and serviceability of a facade during its service life, a comprehensive analysis of the life-cycle performance and costs of the project is necessary. This analysis includes not only the preliminary costs of design and construction, but also the “future” costs of maintenance, repair and replacement of the facade. The design alternatives for the lowest life-cycle costs need to be improved considerably to design a durable façade that fulfills the principles of sustainability [32].

A façade design must be engineered to ensure that the structure does not reach any of its probable limit states, such as the ultimate and serviceability limit states, while fulfilling the functional, economic, environmental, and other needs during its defined service life.

Durability of a facade needs consideration of diverse probable mechanisms of deterioration during the design process; these deterioration can be inhibited by the prevailing environmental conditions near the facade.

The concepts of the basic three R’s in sustainable development, (reduce, reuse and recycle), must be pursued in all phases of a project [31]. Reducing includes reduction of natural resource consumption and a reduction in waste generation. This suggests that the construction of a new structure must be undertaken only when it is essential. Reusing means that any element in the structure may be suitable for application in other structures with different characteristics. Recycling implies transformation
or process of some of the structural elements to create new elements or components with different characteristics. It is necessary to incorporate sustainability and durability principles in facade design, meaning being capable of visualizing how construction materials will perform over time under specific and aggressive environmental conditions, and thereby defining the complete performance of the structure over its service life. In new approach to facade design, before defining the project for execution, innovation is needed in facade design to plan, then to reconsider the plan and develop the possible solutions for improved service life performance.

2.3 Durability Considerations

Durability and sustainability issues have normally not been taken into consideration in the past facade design practice in North America and in many other regions of the world [31]. This has resulted in premature deterioration of facades, which has become a serious global problem, creating negative social, economic and environmental impacts. This premature deterioration of facades in particular and infrastructure in general, is directly related to some current practices, such as delayed maintenance, unawareness of the impact of aggressive environmental conditions on the facade, poor workmanship and overall lack of quality control during the design construction and operation phases of the project.

From structural design viewpoint, all provisions in the standards about the required quality of construction materials are based on a series of recommendations originating from current design practices for non-structural element, and the existing codes and manuals. Currently, sufficient knowledge is available for the different mechanisms of deterioration that may occur in facades. However, the requirements accepted by different national codes about the essential actions to guarantee durability of construction materials against the degradation forced by the aggressive environmental conditions, are quite diverse. Most of these code provisions agree in two major aspects, finding the local exposure conditions, and the absolute need for low concrete transport
property such as permeability to impede ingress of aggressive agents, such as chloride and CO₂.

2.4 Damage Modes in Precast Concrete Facades

Precast concrete façades can be damaged by two main processes: physical and chemical; however, concrete panels used in façades, due to their location in buildings, type of applied forces, environmental conditions and the nature of manufacturing and assembly, may not be subjected to all of the possible deterioration mechanisms in concrete. For example, chemical deterioration due to sulphate attack which can cause a major problem in bridges and sewage or water canals, may not be a threat to concrete façades. Also, there are physical mechanisms of failure, such as fatigue, which is related to the reinforcing steel and steel connections in panels, which could be neglected due to a lower risk involved with their very low probability of the failure taking place.

2.4.1 Chemical Damage

2.4.1.1 Leaching

Leaching is the process of dissolution of soluble components of a material by a liquid [33]. Leaching in concrete which is a hardened mixture of cement and aggregates, occurs as hydroxide compounds of cement (usually calcium hydroxide) are gradually dissolved in water that occupies the pores. [34]. In environments where the concrete is in contact with water, dissolution of cement component of the concrete occurs, as dissolved and ionized calcium ions migrate into concrete. The amount of dissolved salts in the water and the temperature of the water can influence the degree of leaching [35]. While leaching itself is not a damage mechanism, but it can illustrate the high permeability of concrete which can threaten the durability of concrete.

2.4.1.2 Alkali–Silica Reaction (ASR)

The expansive alkali–silica reaction (ASR) takes place over time in concrete between the highly alkaline cement paste and reactive non-
crystalline (amorphous) silica, in many common aggregates [36]. The nature, amount and particle size of reactive forms of silica, adequate alkali and adequate moisture concrete within the concrete are three essential ingredients for ASR expansive reaction. This expansive deterioration can be prevented if any one of these ingredients is removed from the concrete. Another method for controlling ASR is to modify the pH of the pore solution (expansion at 200 days is lower in less acid soluble alkali content) [35]. The mechanism of ASR causing the deterioration of concrete can be described in four steps as follows:

- During hydration of cement alkali ions are released, which results in an increase in hydroxide ion concentration in pore solution.
- Aggregate integrity is destroyed by initial hydrolysis of the siliceous fraction of the aggregate in the highly alkaline pore solution.
- Swelling of alkali silica gel by absorption of water causes localized swelling, internal pressure and finally cracking.
- As more water is imbibed, alkali silica gel becomes liquefied and the liquidated gel is expelled through the cracks.

The nature of the silica involved affects the duration of time between concrete casting and the appearance of the ASR damage.

2.4.1.3 Delayed Ettringite Formation

In the 1980s, a new deterioration mechanism of concrete was reported that was named “Delayed Ettringite Formation” or DEF, which is known as the formation of ettringite within the concrete cement paste after the concrete has hardened [37]. Experiments have shown that during the hardening process of concrete, if it is exposed to high temperatures and subsequent moist conditions, it exhibits expansion and cracking [36]. These observations may be explained as follows.

DEF occurs when concrete is excessively heat-cured (temperature higher than 70 °C), which causes ettringite (calcium sulphaaluminate hydrate or $\text{3CaO.Al}_2\text{O}_3.3\text{CaSO}_4.32\text{H}_2\text{O}$) in Portland cement products to become fully or partially decomposed during the first hours of hydration. If the concrete is
subsequently exposed to moisture for months or years, ettringite re-forms and causes expansive forces that will lead to concrete cracking. Generally, at temperatures higher than 70 °C, any ettringite formed upon hydration will become thermodynamically unstable and will decompose to hydrated calcium monosulphoaluminate (AF$_m$) and will release sulfates to the pore solution. At high temperature, the sulfates released by the cement become available to the pore solution because they do not react completely with the tricalcium aluminate (3CaO·Al$_2$O$_3$ or simply C$_3$A for simplicity). It is true that sometimes the destructive mechanism of ettringite formation in hardened concrete occurs due to appearance of sulphate (from gypsum in aggregates or by adding gypsum plaster to the mix); however, this internal sulphate attack is not considered as DEF [37]. If ASR cannot be avoided in the concrete mixture, use of a higher reinforcement content, or provision for subsequent post-tensioning can minimize the expansion due to ASR to lower acceptable levels.

2.4.1.4 Carbonation
Carbonation is to formation of calcium carbonate from reaction of carbon dioxide from air with calcium hydroxide in the concrete hydrated cement paste[38]. Carbonation is a gentle and constant process that progresses from the outer surface inward and slows down with an increasing diffusion depth. Carbonation increases the mechanical strength of concrete, but it also decreases its alkalinity, which is essential to provide an alkaline environment around the reinforcing steel bar to prevent its corrosion. Below a pH of 10, the thin layer of surface passivation on the steel surface, dissolves and corrosion is promoted. Consequently, carbonation is detrimental to a concrete structure. Carbonation can be tested by applying a phenolphthalein solution, a pH indicator, over a freshly fractured surface. Non-carbonated and thus alkaline areas of the fractured surface will convert to a violet color while carbonated areas will have the same color as before.
2.4.1.5 Acid Attack
Leaching of calcium hydroxide [Ca(OH)$_2$ or CH] can be accelerated by hydrogen ions as[35]:

$$\text{Ca(OH)}_2 + 2\text{H}^+ \rightarrow \text{Ca}^{2+} + 2\text{H}_2\text{O}$$

If the hydrogen ion concentration is high, C-S-H will be attacked as:

$$3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + 6\text{H}^+ \rightarrow 3\text{Ca}^{2+} + 2(\text{SiO}_2 \cdot n\text{H}_2\text{O}) + 6\text{H}_2\text{O}$$

This attack is normally restricted to the surface of concrete. Compounds soluble in the given acid dissolve almost immediately. Generally, this reaction develops insoluble calcium salts which build up and shelter the concrete from additional carbonated attack.

2.4.1.6 Chloride Attack
To shorten the setting time of concrete, chlorides, especially calcium chloride, were used as the part in cold climate countries. However, calcium chloride and to a lesser extent, sodium chloride, leach calcium hydroxide and cause chemical changes in Portland cement that leads to strength loss; chlorides also attacks the reinforcing steel embedded in most concrete structures [39].

2.4.1.7 Decalcification
Purified water can wash out the calcium ions in concrete, resulting in a concrete structure which is quite brittle [40]. Condensed steam usually used for cleaning of facades can be a common source of purified water. Purified water leaches out more calcium ions than unpurified water, since undistilled water already contains some calcium ions, and cannot dissolve additional ions.
2.4.2 Physical Damage

2.4.2.1 Freeze-Thaw

Porous materials, containing moisture, are vulnerable to damage under repeated cycles of freezing and thawing [35]. Freeze-thaw damage occurs through attrition, meaning that one cycle causes very little damage and it takes many cycles before the damage increases to significant levels. Damage is caused by internal tensile stresses which appear due to the combination of several factors. There is a 9% volume increase in transition from water to ice. In case the pores are completely filled with water, the concrete can split [41]. As a result, an adequate amount of pores that are not filled with water, should be available to allow the water to expand and thus prevent the damage caused by frost. This is the reason that while casting, air-entraining admixtures (AEA) are added to concrete. An air content in the range of 2-8% by volume of concrete depending on the maximum aggregate size, is needed for an acceptable freeze-thaw protection [35]. AEAs contain surface-active agents which are molecules with one end tending to dissolve in water (hydrophilic), while the rest is repelled by water (hydrophobic). With the hydrophilic groups in the water and their hydrophobic portion in air, surface-active agents tend to align at the air-water interface (see Figure 2.1).

![Figure 2-1 Molecules of surface-active agents](image)

Figure 2-1 Molecules of surface-active agents [35]
### 2.4.2.2 Surface Wear

Surface wear is a damage involving progressive mass loss from a concrete surface due to repetitive attrition cycles and relative motion between concrete surface and a contacting surface or substance [35]. Surface wear is divided into three primary mechanisms: abrasion, erosion and cavitation. For building facades, it is normally abrasion which refers to dry attrition as another solid objects moves along or rubs against the concrete surface. The area of contact between two solid surfaces, compared with the actual area of contact, is very small and is limited to points of contact which are surface asperities. [42]. The load will be transmitted to the surface through these points of contact and can cause large localised forces. The material’s inherent surface properties such as hardness, strength, ductility, etc. are very important factors for surface wear resistance; however, the opposing surface properties such as surface finish, load, speed, temperature and etc. are equally important.

### 2.4.2.3 Thermal Damage

Since concrete has a low thermal conductivity, for fireproofing of steel structures one usually uses a layer of concrete [35]. However, concrete itself can be damaged by fire. Concrete experiences normal thermal expansion at temperatures up to about 300 °C [43]. Above that temperature, shrinkage takes place due to loss of moisture inside the concrete; however, the aggregates continue to expand, which causes internal stresses. Major structural changes in the concrete at temperatures up to 500 °C, consist of carbonation and hardening of pores. At 573 °C, due to phase change, quartz experiences rapid expansion, and at 900 °C, calcite initiates decomposition and shrinks. The hydrated cement decomposes and calcium oxide yields at 450-550 °C. At about 600 °C, Calcium carbonate decomposes. When structure cools, calcium oxide rehydrates. This expansive procedure can cause damage to material that resisted fire without falling apart. Noticeable degree of carbonation from reabsorbed carbon dioxide were observed in concrete buildings that were exposed to fire and were standing for several years.
Normally, concrete easily maintains its integrity up to temperatures of above 100°C. The parts of the concrete structure that are open to temperatures above 300 °C will most likely develop a pink color depending on the water/cement ratio of the concrete. The concrete will become light grey over approximately 600 °C, and it turns yellowish-brown over 1000 °C. It is reasonable to recognize all pink colored concretes during inspection as damaged that should be removed.

Also, fire will produce gases that can be dangerous to the concrete when they come into contact with water, and also harmful to living beings.

2.5 Characteristics of Reinforcing Steel
Over the years, steel has been used traditionally for reinforcing concrete structures, because of the low tensile strength concrete, which leads to cracking. A reinforced concrete structure is designed, based on the assumption that steel and concrete act together to resist all induced actions [44]. The fact that steel is a ductile material and has a coefficient of thermal expansion that is almost equal to that of concrete, makes steel the finest material as reinforcement in concrete structures. Another advantage of using steel as reinforcement is that it bonds well with concrete.

Not only strength, but also the durability of the structure is influenced by the steel rebar quality. Durability is the capacity of a structure to fulfill the required safety and serviceability standards during its design life; it is reliant on the condition of concrete and the steel reinforcement. The principal reason for impairment of concrete durability is corrosion of reinforcement. Corrosion can be either due to chloride ingress into the concrete or due to its carbonation. Chemical configuration of reinforcement plays an important role in this respect.

Improvement of strength by cold working, or by changing chemical composition, for example, increase in carbon content, has detrimental impact on steel ductility and weldability. Therefore, optimum balancing of the requirements is necessary to achieve an optimum balance between strength, ductility, durability and the cost of steel reinforcing bars.
2.6 Failure Modes of Steel Reinforcement or Connections in Concrete Facades

The applied forces to structural elements induce forces and movements within the system [44]. Steel connections are used to hold the precast concrete panels on a building. These connections are impacted by gravity and lateral loads. The lateral loads include wind and seismic loads, while the only applied gravity load on these attachments is the weight of the façade material. The Structure may fail in many ways due to the action of these induced forces. Moreover, aggressive environmental elements, particularly moisture, salts, acids (chlorides and CO₂), have great impact on durability of steel connections and/or reinforcement. Therefore, an important role is played by reinforcement in design and construction of safe and durable structures for strength and serviceability.

2.6.1 Corrosion

The ASTM vocabulary describes corrosion as “the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces deterioration of the material and its properties”[45]. Exposure of steel rebars to moisture and oxygen, which may take place either by carbonation or chloride attack; triggers the corrosion of steel.

At the anode, when corrosion takes place (see Figure 2.2), the iron in the steel reinforcement “dissolves” in the pore water and releases electrons [46]. The process of losing electrons is called oxidation.

\[ \text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^- \]

At the cathode, when water and free electrons are present, oxygen is altered from a neutral molecule to an anion. This process is known as reduction.

\[ 4\text{e}^- + 2\text{H}_2\text{O} + \text{O}_2 \rightarrow 4\text{OH}^- \]
As the products of anode (Fe\(^{2+}\)) and cathode (OH\(^{-}\)) react, producing ferrous hydroxide (Fe(OH)\(_{2}\)) is produced.

\[
\text{Fe}^{2+} + 2\text{OH}^{-} \rightarrow 2\text{OH}_2
\]

Ferric hydroxide (Fe(OH)\(_3\)) is formed by further oxidation of ferrous hydroxide.

\[
4\text{Fe(OH)}_2 + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{Fe(OH)}_3
\]

From exposure to the environment, due to dehydration, ferric hydroxide converts to ferric oxide, Fe\(_2\)O\(_3\), known as rust.

\[
2\text{Fe(OH)}_3 \rightarrow \text{Fe}_2\text{O}_3\cdot\text{H}_2\text{O} + 2\text{H}_2\text{O}
\]

Dehydrated ferric oxide, Fe\(_2\)O\(_3\), has a volume almost twice that of the original iron in the steel reinforcement. Ferric oxide swells even more and becomes porous when it becomes hydrated, leading to an increase in volume that could be two to ten times that of the original steel reinforcement volume. The expansion of corrosion products of steel may cause mechanical stresses that can lead to the development of cracks in the concrete cover, causing delamination and disruption of the concrete structure [47]. Spalling can also take place if the rebars are poorly installed and are located too close to the concrete surface.

When the steel corrodes, bond between the steel and the concrete is lost due to formation of rust and subsequently, the concrete delaminates and
spalls[48]. A loss of 15 to 20 in the steel rebar mass, can lead to a loss of bond to the extent of 80 to 85% [49]. Corrosion makes the steel brittle especially pitting corrosion in the surface of reinforcing steel which not only reduces the cross-sectional area of the steel but also creates a notch effect which leads to triaxial tension at the pit and leads to loss of strength and [50].

Resistance of steel rebars against corrosion relies on the chemical composition of steel [44]. The pore solution in concrete with a very high pH, leads to the formation of a protective iron oxide film around the steel bar during the process of hydration of cement, which protects the steel from corrosion. When pH of concrete decreases (usually by carbonation or by chloride attack) around the steel, this protective film is destroyed locally, exposit the “bare” steel surface and the corrosion process initiates [35].

Although good quality concrete is needed for corrosion resistance in RC structures, the quality of rebars also has an important influence on initiation of corrosion [44]. Though no absolute corrosion resistant reinforcing steel exists; however, one type may have lower corrosion potential than the other. Non-ferrous reinforcement has been used in some structures recently.

2.6.2 Fracture

Fracture is physical separation of a consistent piece into separate pieces due to applied loads or environmental causes [35]. Steel fractures can be two types, ductile or brittle. The cross-sectional yielding occurs at 45° to the stress axis in the case of a ductile fracture. Ductile steels are favoured as construction materials, because they provide warning (yielding, necking) before failure, while brittle steels provide no such warning. The brittle fracture of steel occurs on a flat plane, perpendicular to the stress direction.
2.7 Summary
This chapter examines the characteristics of materials used in concrete façade systems (concrete and steel), as the first step to prevent premature deterioration and failure in concrete façades. To design for the optimum performance of a façade system, along with having familiarity with compatibilities of materials used, it is important to deal with the various deterioration mechanisms and prevent or mitigate them. Pre-cast concrete panels used in façade systems can be damaged both chemically and physically. Chemically, major damage can be caused by delayed ettringite formation, carbonation and chloride attack, while freeze-thaw cycles cause the most damage by physical attack. For steel, used as reinforcement, or as connections in concrete façade systems, the most threatening failure mechanism is due to corrosion; therefore, suitable measure must be adapted to prevent or considerably delay initiation of corrosion activity.
Chapter 3  Service Life of Concrete Facades

3.1  Service Life of Concrete Facades
One defines service life as the time interval during which a structure functionality is preserved with no unpredicted or extraordinary maintenance or repair [51]. For facades, the expected service life is equal to the service life of the building. Recently, owners and designers have been paying increasing attention to service life expectations during the project’s design phase, and service life expectations are normally determined, to be from 50 to 75 years. While trying to assess the consequence of different design options on service life, designers are making decisions to optimize service life performance.

Many parameters may affect the service life of a concrete structure. Among these parameters, some are environmental and cannot be controlled by the designer and the owner. Presently, some design tools are available to assist designers with durability design against aggressive environment. Numerical modeling is now employed to estimate time to corrosion of steel rebar embedded in concrete, which is considered as the primary mechanism leading to concrete deterioration. These numerical models are used to test the various design options over the service life and beyond for the various environmental conditions, allowing designers to make rational decisions to maximize the service life at a reasonable cost.

3.2  Durability Design Approaches
National building codes are mainly focused on structural design that considers mechanical loads and resistances, regardless of the severe durability problems in concrete systems; and despite the hard work of the researchers over past few decades, these investigations have had little influence on developing an acceptable practical method of design for durability [52]. However, there are a few methods that are used presently, to design a structure for durability. In 1996, Sarja and Vesikari [53], proposed a technique known as the service life principle or the lifetime safety factor method, which ensures safety and serviceability of the system
by checking that the service life is more than or, at least, equal to the minimum specified design. This method was developed based on the assumption that the system reaches its design life when the maximum tolerable damage level is reached; the risk of attaining the allocated damage limit is considered probabilistically.

There is another design approach that practices the “performance principle” meaning that the probability of failure is found by considering time-dependent performance and loading functions [52]. Performance is established as the various capacities (bending, shear, etc.) for different loading conditions, serviceability issues, such as deflections, resistance to degrading environmental conditions and aesthetic appearance. In this method, partial safety factors for material capacities and loadings, and the lifetime safety factor, defined as the ratio between the design service life and the target service life, are used. This design procedure contains combination of mechanical design and durability design along with the final design. Sarja and Vesikari [53], introduced selected performance and service life calculation models in their proposed design method. However, the influence of preventive and remedial maintenance in attaining and enhancing the service life has not been considered [52].

In 2003, Schiessl et al. [54] established a new service life concept for concrete structures, which minimizes the costly repairs and optimizes the structure economically, by taking into account the design, construction, and operational phases. In this method the designer is able to design for a fully probabilistic service life of a structure, with respect to the different expected aggressive exposure conditions. This method permits the owner, the designer, the contractor, and the manager to achieve a suitable service life for a new structure along with evaluating the performance of a standing facility for durability, or its remaining service life. To increase the reliability of performance of a structure over the planned service life, one requires recourse to perform repair and rehabilitation work.

Another framework was proposed by Siemes [55], in 1996, for reliability-based durability design for elimination or prevention of deterioration reactions, establishment of single and multiple-barrier protection systems.
To create a reliability-based design method, one must establish the failure probabilities for each of the three strategies and their limiting targets [52].

### 3.3 Durability Design Formulation by Lifetime Safety Factor Method

The service life of a facade changes according to the macro- and micro-environmental circumstances that define the type and severity of the deterioration mechanisms of the materials comprising the different structural members of the facade. Furthermore, the quality of the construction materials and the exposure degree of the different members to the aggressive conditions may vary significantly [31]. Therefore, it would be preferable to treat performance and service life of a structure stochastically. To produce a reliable design in this stochastic procedure, the designer takes into account the real nature of structural performance [53]. While the various available equations for load, resistance and service life are relatively complicated, due to the large number of deterioration factors affecting the performance of the structure, the application of this approach becomes considerably complicated. Therefore, it is appropriate to apply the lifetime safety factor method. Although this method is based on safety and reliability, the formulation of the procedure is deterministic. The design service life is then obtained by the product of the target service life and a lifetime safety factor, as the following [53]:

\[ t_d = \gamma_t t_g \]  \hspace{1cm} (1)

where:
- \( t_d \) = design service life.
- \( t_g \) = target service life.
- \( \gamma_t \) = lifetime safety factor.

### 3.4 Determining Lifetime Safety Factor

The lifetime safety factor is described by the following equation:

\[ \gamma_t = \frac{\mu(t_L)}{t_g} \]  \hspace{1cm} (2)
where $\mu(t_L)$ denotes the mean service life obtained from a distribution of probable service life values of the structure, and $t_g$ is the target service life of the project required particularly for design purposes [31].

![Figure 3-1 Relationship between mean service life and target service life [53]](image)

The distribution of service life values in (Figure 3.1), illustrates the relationship between the target service life, the failure probability, and the mean service life. The mean service life, $\mu(t_L)$, can be recognised as the intersection point of the degradation curve and the “limit state of durability”, as shown. The lifetime safety factor, $\gamma_t$, is required to be greater than one, to guarantee that the mean service life is greater than the target service life. It is known that the lifetime safety factor relies on the maximum permissible failure probability. This is well known that, lower values of maximum allowable failure probabilities necessitate larger values of lifetime safety factor, which is also affected by the form of the service life distribution [53].

The durability of a facade can be presented in terms of the deterioration process that is existing in the structural system because of the degrading impacts of the environmental loads which affect different structural members (Figure 3.2).
It is apparent from Figure 3.2 that the point where the degradation curve intersects the maximum degradation, $D_{\text{max}}$, represents the design service life, $t_d$, that must be longer than the target service life by a factor denoted by the lifetime safety factor $\gamma_t$ [31]. The range $[D_{\text{max}} - D(t)]$ in (Figure 3.2) represents the safety margin. The lifetime safety factor can be determined by using a stochastic method, assuming a normal distribution of degradation around the mean value, with the standard deviation being proportional to the mean. Following these assumptions, it is possible to obtain the following expression for the lifetime safety factor [53]:

$$\gamma_t = (\beta \nu_D + 1)^{1/n}$$

where:
- $\beta$ = reliability index.
- $\nu_D$ = coefficient of degradation rate.
- $n$ = degradation rate exponent.

The required reliability index $\beta$ and the probability of failure, $P_f$, for a regular design as determined by Eurocode 1 are [53]:

For the ultimate limit state (ULS):
- $\beta = 3.8$ (serious consequences of a durability failure) $\rightarrow P_f = 7.2 \times 10^{-5}$. 

Figure 3-2 Lifetime safety factor in terms of degradation process [53]
$\beta = 3.1$ (no serious consequences of a durability failure) $\rightarrow P_f = 9.7 \times 10^{-4}$.

For the serviceability limit state (SLS):
$\beta = 2.5$ (serious consequences of a durability failure) $\rightarrow P_f = 6.2 \times 10^{-3}$.
$\beta = 1.5$ (no serious consequences of a durability failure) $\rightarrow P_f = 6.7 \times 10^{-2}$.

The degradation rate exponent, $n$, will affect the determination of the lifetime safety (Equation 3) in the following way:

$n = 1$ $\rightarrow$ represents a linear degradation.

$n = 0.5$ $\rightarrow$ represents a retarding degradation.

$n = 2$ $\rightarrow$ represents an accelerating degradation.

The calculation of different values of the lifetime safety factors for different values of the parameters mentioned previously, are shown in Table 3.1 [31].
Table 3.1 Lifetime safety factors determined by a normally distributed degradation function [31]

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Safety class (consequence of durability failure)</th>
<th>Probability of durability failure (after $t_g$), $P_f$</th>
<th>Safety index (after $t_g$), $\beta_t$</th>
<th>Lifetime safety factor, $\gamma_t$, with $V_D$ of 0.4</th>
<th>0.6</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate limit</td>
<td>1. Serious</td>
<td>7.20E-05</td>
<td>3.8</td>
<td>6.35</td>
<td>10.76</td>
<td>16.32</td>
</tr>
<tr>
<td></td>
<td>2. Non-serious</td>
<td>9.70E-04</td>
<td>3.1</td>
<td>5.02</td>
<td>8.18</td>
<td>12.11</td>
</tr>
<tr>
<td>Serviceability</td>
<td>1. Noticeable</td>
<td>6.20E-03</td>
<td>2.5</td>
<td>4.00</td>
<td>6.25</td>
<td>9.00</td>
</tr>
<tr>
<td>limit</td>
<td>2. Not noticeable</td>
<td>6.70E-02</td>
<td>1.5</td>
<td>2.56</td>
<td>3.61</td>
<td>4.84</td>
</tr>
<tr>
<td></td>
<td>1. Serious</td>
<td>7.20E-05</td>
<td>3.8</td>
<td>2.52</td>
<td>3.28</td>
<td>4.04</td>
</tr>
<tr>
<td></td>
<td>2. Non-serious</td>
<td>9.70E-04</td>
<td>3.1</td>
<td>2.24</td>
<td>2.86</td>
<td>3.48</td>
</tr>
<tr>
<td>Serviceability</td>
<td>1. Noticeable</td>
<td>6.20E-03</td>
<td>2.5</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>limit</td>
<td>2. Not noticeable</td>
<td>6.70E-02</td>
<td>1.5</td>
<td>1.6</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>1. Serious</td>
<td>7.20E-05</td>
<td>3.8</td>
<td>1.59</td>
<td>1.81</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td>2. Non-serious</td>
<td>9.70E-04</td>
<td>3.1</td>
<td>1.50</td>
<td>1.69</td>
<td>1.87</td>
</tr>
<tr>
<td>Serviceability</td>
<td>1. Noticeable</td>
<td>6.20E-03</td>
<td>2.5</td>
<td>1.41</td>
<td>1.58</td>
<td>1.73</td>
</tr>
<tr>
<td>limit</td>
<td>2. Not noticeable</td>
<td>6.70E-02</td>
<td>1.5</td>
<td>1.26</td>
<td>1.38</td>
<td>1.48</td>
</tr>
</tbody>
</table>
3.5 Design Service Life

Aggressive environments can intensely deteriorate and drastically decrease the integrity and performance of different members of a facade. Corrosion of fasteners and joints is perhaps one of the most serious deterioration mechanisms that can occur in most facades of North America [31]. Therefore, the use of a degradation rate exponent of about 2 could closely describe the behaviour of a reinforced concrete component exposed to such aggressive environments. 

Reliant on the degree of exposure against certain environmental conditions, the deterioration mechanisms can escalate. Thus, high values of \( \nu_D \) can be used to define the lifetime safety factor. Moreover, it should be noted that poor durability performance of a structure might cause serious resistance and serviceability concerns which must be considered reasonably in the durability design process.

Taking into account any premature failure of a structure that would cause serious economic and social consequences on the surrounding properties, facilities and can even cause fatalities, a reliability index \( \beta = 3.8 \) was derived for ULS [53]. Accordingly, the lifetime safety factor at ULS for this structure can be calculated as:

\[
\gamma_t = (3.8 \times 0.8 + 1)^{1/2} = 2.01
\] (4)

Therefore, the design service life for the ultimate limit state implies that:

\[
t_{d,ULS} = 2.01 \times 50 \text{years} = 100 \text{years}
\] (5)

Knowing that any premature serviceability failure of the structure would indicate serious consequences for the use of the structure, a reliability index \( \beta = 2.5 \) is accepted for SLS. Accordingly, one determines the lifetime safety factor at SLS for this structure as:

\[
\gamma_t = (2.5 \times 0.8 + 1)^{1/2} = 1.73
\] (6)

Consequently, the design service life for the serviceability limits state results in:
\( t_{d, ULS} = 1.73 \times 50 \text{ years} \approx 85 \text{ years} \) \hspace{1cm} (7)

3.6 Summary

Due to the severe durability problems in concrete systems, it is necessary to design them for durability, rather than simply focusing on evaluation of the resistance of the structure to mechanical and environmental loads [52]. The objective of performing durability design of a structure is to ensure that at the end of the service life, the materials and the elements would have the predicted characteristics. Prediction of design life of a structure depends on selection of proper materials and performing an integrated design of the structure along with the planned maintenance, to ensure that service life of the structure will not go shorter than the lifetime of the materials used due to their performance under aggressive environmental conditions.

It must be noted that there are no perfect methods for precise prediction of the service life of a structure because of the differences between the “testing” conditions and “real” service life conditions; however, quality assurance and control are useful for checking the performance of the structure and for developing a reliable framework for an appropriate feedback to the designer.
Chapter 4  Risks in Concrete Facades

It is quite complex to analyze a building façade due to a variety of materials involved, and their varying performances, along with the different probabilities of failure associated with them. The safety and ease of maintenance of facades are directly related to their resistance performance against weathering conditions. It must also minimize the life cycle costs, including cleaning, repair and replacement of the facade. Several basic risk factors affect these life cycle costs and maintainability of the façade, which should be considered from the design stage to construction, maintenance, operations, throughout the building life cycle to achieve optimum maintainability with a minimum level of risk. In this study, risk factors that affect the level of safety and maintainability of the concrete facades are categorized as follows:

- Design (water-tightness, resistance to applied forces, control of water flow, ease of access, downtime costs, material performance and etc.)
- Construction quality
- Maintenance quality (both preventive and corrective maintenance, including cleaning, inspection, repair, rehabilitation, decommissioning and deconstruction of facades).

4.1 Risks to Be Considered in Concrete Facade Design

Design of a facade system is one of the most challenging phases of building design both architecturally and structurally [56]. Due to the advances in technology and materials, a variety of system options are now available to both the owner and the designer that results in additional cost and performance choices. However, despite all of these industrial progresses, it is important to design and implement these systems accurately. Manufacturing, design, construction and maintenance must be integrated in such a way that facades perform as required by life cycle performance. Façades are mainly designed to perform functions such as atheistic and energy efficiency; consequently professionals involved with implementing
these functions must coordinate their work throughout the conception, design, construction and operation phases.

4.1.1 System Selection

Excluding the “unwanted” weather components from the indoor environment created for occupants, is the principal function of a facade [57]. Consequently, in choosing a wall system, its components should fully undertake this primary function of weather protection. As in Table 4.1 summarizes different wall systems which provide different performance against weather elements

Table 4.1 Considerations of systems for façade wall selection [58]

<table>
<thead>
<tr>
<th>Reinforced Concrete (RC) wall ($f'_c &lt; 35$ MPa)</th>
<th>Low grade concrete has more void spaces and higher porosity and transport property.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC wall ($f'_c &lt; 35$ MPa)</td>
<td>High grade concretes are denser with lower void ratio.</td>
</tr>
<tr>
<td>Semi Pre-cast Concrete) PC / PC wall</td>
<td>Factory produced and quality controlled with elaborate jointing and water drainage possible.</td>
</tr>
<tr>
<td>Stick system</td>
<td>Water tightness mainly depends on the workmanship quality in sealing joints on site.</td>
</tr>
<tr>
<td>Unitized system</td>
<td>Factory produced and quality controlled. In-built water barriers improve water-tightness.</td>
</tr>
</tbody>
</table>

4.1.1.1 System Detailing

Staining and water penetration are two important defects arising from poor detailing and implementation of system features in high-rise buildings [57]. Humidity and water penetration are the main cause of most façade failures from an aesthetic perspective, ranging from the disagreeable view of staining and efflorescence to the structural flaws, such as cracks and corrosion of the joints caused by water penetration. Large numbers of discontinuities (joints), accompanied by lack of water tightness, that have higher probability of water infiltration can be an example of poor detailing. The façade integrity improves by reducing the
number of required joints when the grid size is maximized. Although it may be good practice in façade detailing, but it can result problems in component manufacturing, handling and construction. Table 4.2 indicates some considerations for façade wall finishing.

Table 4.2 Considerations of wall selection – finishes [58]

<table>
<thead>
<tr>
<th>Masonry/ RC/ PC wall:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water based emulsion paint system</td>
<td>High water vapor permeability and low water resistance.</td>
</tr>
<tr>
<td>Cement based paint / water repellent coat</td>
<td>Offers good surface protection by sealing and filling the porous areas.</td>
</tr>
<tr>
<td>Plaster with admixtures</td>
<td>Polymers as admixture can improve the water resisting properties of plastering mortar.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curtain wall / cladding (drainage system):</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Drained and ventilated</td>
<td>Allows rapid evacuation and its evaporation of rainwater.</td>
</tr>
<tr>
<td>Pressure equalized</td>
<td>The system includes outer rain-screen to stop initial flow of rainwater, an inner chamber to equalize pressure with the outside, and an inner seal to arrest any water that has seeped in.</td>
</tr>
</tbody>
</table>

4.1.1.2 Material Factors

In designing for maintainability, materials for façade systems must be selected based on their ability to resist degradation from normal surface wear to spalling, wear and tear [58]. As a durable material, that is compatible with its adjacent materials and requires little maintenance throughout its lifespan, it has a minimal maintenance cost. This choice of facade materials is very important in maintainability. The effective durability of a building facade with varied facade components can be attained by using the following equation [58]:
where \( D_{TF} \) is defined as the effective durability of façade, \( SL_i \) is the service life of \( i^{th} \) facade element and \( n \) is the number of facade elements.

### 4.1.2 Durability Issues

To analyze durability of a façade system, evaluation of durability of the various components can be used [59]. Certain components made from a variety of materials with different characteristics, with their modes of failure and durability can comprise building façades [60]. To have a durable system, all relevant design aspects of façade systems must be considered. Different detailing is needed for different façade systems. Weather protection, material compatibility and structural and wind loads are the most common design parameter. Water infiltration is the main durability issue in curtain walling systems, conventional concrete and masonry façades.

The main area of failure is normally at the joints, where may cause premature deterioration of the elements. Another characteristic disturbing the durability of systems is compatibility of materials. A single material or a selection of different wall materials that are directly exposed to an external environment may be used in the surface of a façade. Therefore how well each wall surface material works independently, as well as integrally in withstanding the external weathering agents are the factors that influence the performance and durability of the facade. Another significant parameter for system integrity and durability are wind loads, and requires consideration of wind loads that are likely to act on the façade over its service life; this can lead to the desired performance of façade, against the wind loads in all façade systems.
4.1.3 Environmental Risks

As mentioned earlier, environmental conditions and building locations (industrial, urban, rural or coastal zones) can influence the facades due to variable durability characteristics of façade materials in each zone [58]. Facades are always challenged by the environmental forces ranging from moisture effects, thermal expansion and contraction to degradation from salts or pollutants in the air, freeze-thaw cycles, and breakdown of sealants or other materials from exposure to ultraviolet rays [61]. It is useful to note that environmental risks have been categorized under design risks because strategies toward prevention or delaying of any environmental risks must be considered in the design process.

4.2 Construction Risks

Correct installation of façades with a high standard of workmanship is usually essential for integrity, durability and overall performance of the facades. Prefabrication in the form of unitized or panelized systems should be adopted for decreasing any onsite imperfections. Design deficiencies such as poor tolerances of panels delivered to site as compared to those on the drawings, may cause some workmanship issues. [62] Therefore selection of appropriate materials for components that have the capability to resist the weathering effects, are factors that influence the system durability. The performance of the façade system should be evaluated by testing before installation onsite. In a majority of cases, the concrete façade are made in precast concrete. Very rapid speed of assembly and excellent quality control are the advantages of precast concrete construction; however, heavier components, small margin for error, difficulty of connections, need for bracing during on-site assembly of the structure and limited facade design flexibility are the limitations of these systems.

4.2.1 Measures for Quality Improvement

There are a number of factors that can lower the quality of construction and decrease the service life of a constructed structure; however, most of
these factors are inter-related [62]. As a result, the actions for enhancing the quality of construction can be defined by considering the relationship between design and construction and the responsibilities of the different parties involved.

4.2.2 Relationship between Design and Construction

Design and construction of a structure are closely related activities. If a design can be built for use at the site without much difficulties then it is a successful design [62]. With good workmanship and quality control at the construction site, the safety, strength, serviceability, and durability specified in a design can be attained. However, good workmanship and quality control, are possible only if the specifications are clearly defined, and member and connection details are simple and executable at the site. The consultant must deal with an integrated design and consider all engineering disciplines, by using the relevant codes and standards in addition to providing adequate construction details and specifications. It should be noted that an efficient and competent workforce must be available, to implement the job at site. A well-managed program together with sufficient sampling and testing facilities must be available to the contractor. Such a program must include tests on the steel joints and bars as well as on the concrete panels. The present codes provide a basis and requirements for testing and approval of the materials to be used. All of these provisions must be recognized and followed by qualified field and laboratory workers.

Inspection and supervision play an important role in maintaining and improving the quality of construction. The owner and the consultant should have plans for these activities during construction. The owner must also conduct a program for supervision and quality assurance, independent of the contractor’s quality control measures.
4.3 Risks Involved in Lack of Facade Maintenance

4.3.1 Material Maintainability

Planned cleaning and inspection work must be performed periodically to ensure that a facade performs its functions adequately throughout its useful economic life, [57]. Hence, facade materials must fulfill aesthetic and functional performance requirements, without imposing excessive costs for maintenance, repairs and rehabilitation. Materials that necessitate minimal visual and instrumented inspections for defects are desirable for a maintainable façade.

4.3.2 Facade Maintainability

Ease of future maintenance should be considered during the design stages of a façade [57]. Wherever possible, all decisions made regarding the selection of materials and elements, should ensure that the constructed building components perform as required with minimal maintenance costs.

The ease of performing cleaning, repair and replacement work to a building façade is reliant on the accessibility and flexibility of the façade. Lack or difficulties of accessibilities can make the work costlier and dangerous for the workers. The accessibility of the building facade is dependent on the complexity of the facade shape, involving strange corners and complex building features which would necessitate elaborate and costly access systems.

In addition, the wall components should be designed to simplify removal work for minimizing the down time losses during repair and replacement.

4.3.3 Role of Regular Inspection

A piece of building façade detaching and falling can have disastrous consequences for the pedestrian and others, [63]. Many Cities around the world have been subjected to detachment of facades that have caused severe injuries or deaths to the public users and pedestrians. It has been stated on March 2000, there was a façade failure in North America every three weeks.
To prevent future damage to properties and pedestrians, caused by façade failures, nine major US cities, including New York and Chicago, promulgated by-laws requiring building owners to inspect their facades periodically. In US, there are over 15,000 buildings subject to local municipal by-laws in these cities. These laws are known as facade ordinances, aimed of identifying unsafe conditions, such as loose facade elements or materials, that may fall and cause damage, or injury to properties or pedestrians. Some cities have severe requirements for personnel required to perform the inspections; they require licensed architects or engineers, to perform hands-on inspection of all facades, while other cities only necessitate visual inspection of street-facing facades.

4.3.4 Facade Cleaning

A building’s façade should be cleaned, to maintain its aesthetics [64]. Building facades differ in the amount of care and attention needed for keeping them clean, safe and serviceable. To determine the level of cleaning effort required to attain the desired appearance, building’s location, function, geographic and atmospheric conditions are important. While aesthetics is the apparent and main reason for cleaning a building façade, it also exposes the surface for possible evaluation and repair. It is almost impossible to evaluate the condition of a façade when it is covered in dirt. To determine the areas requiring patching, repairs or resealing, the façade should be cleaned of any and all components that prevent its suitable evaluation.

Removing damaging pollutants such as sulfur and nitrogen oxides, and acid rain pollutants from the façade, which accelerate façade degradation, is another motivating reason for façade cleaning. The main cause of façade degradation is moisture that accelerates the façade decay, if it is coupled with soluble salts from polluted rainwater, or with atmospheric gases. When the soluble salts dissolve in water, they travel deep into the facade panel through inter-connected pores or cracks. Moisture evaporation results in recrystallization of the salts which cause large pressures inside
the panel and breaks it from within. Furthermore, corrosive liquids such as carbonic acid, sulfuric acid and nitric acid are formed by reaction of atmospheric gases such as carbon dioxide, sulfur dioxide and nitrogen oxides with dirty, wet surfaces. These acidic liquids react with different components in the façade panel and can result in the creation of hardened surface crusts and dissolution of cementing binders that keeps the facade together. A serious progressive deterioration is caused, by continuing formation of these solid surface crusts together with the washing away (leaching) of cementing binders.

Façade cleaning unseals a building's pores and permits the normal perspiration of moisture. Moisture imprisoned within a facade panel, remains there if a waterproofing coating prevents its departure. Façade cleaning to remove the waterproofing coating, is a key activity to repair the building in which moisture is the principal cause of panel decay.

4.4 Summary
Risk factors influencing safety and maintainability of concrete façade systems are mainly categorized in the three phases of design, construction and maintenance of the façade. Design aspects are mainly related to selection of a proper system to withstand mechanical and environmental loads, and detailing of the system to resist the aggressive environment and also be energy efficient.

To minimize construction risks, supervision over standards of workmanship to ensure its safety and also performance of field tests to evaluate compatibility of materials and the assembled structure, to meet the design needs, is mandatory.

Risk mitigation in maintenance is related to both preventive and corrective maintenance, including cleaning, inspection, repair, rehabilitation, decommission and deconstruction of facades. Table 4.3 presents a summary of risks in facades.
Table 4.3 Summary of facade risks [58]

<table>
<thead>
<tr>
<th>Risk groups</th>
<th>Risk factors</th>
<th>Items to be considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Wall selection</td>
<td>Type of finishes and joints</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Type of wall system</td>
</tr>
<tr>
<td></td>
<td>Wall details (shape, grid, joint)</td>
<td>Proper details to drain water and prevent staining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Size and detailing, type, spacing, size, detailing and exposure</td>
</tr>
<tr>
<td></td>
<td>Wall maintainability (Accessibility and flexibility)</td>
<td>Building shape, provision for access and coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wall complexity, removability (panel), down time and access system</td>
</tr>
<tr>
<td></td>
<td>Window selection</td>
<td>Exposure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Panel, frame and drainage system</td>
</tr>
<tr>
<td></td>
<td>Window detail</td>
<td>Details for protection, drainage and louvers</td>
</tr>
<tr>
<td></td>
<td>Window maintainability (Accessibility for cleaning)</td>
<td>Method of opening</td>
</tr>
<tr>
<td></td>
<td>Material selection (Durability issue)</td>
<td>Service life</td>
</tr>
<tr>
<td></td>
<td>Material detail (Performance)</td>
<td>Resistance to weathering interface compatibility</td>
</tr>
<tr>
<td></td>
<td>Material maintainability (Cleanability and ease of inspection)</td>
<td>Cleaning requirement (methods, frequency) Maintenance requirements</td>
</tr>
</tbody>
</table>
| Environment       | Environmental issues, topography and orientation | Environmental conditions
|                   |                                   | Pollution levels, Parks, expressways, major roads, light traffic roads, coastline       |
|                   | Building age                       | As the building ages risk of failure is higher                                         |
|                   | Building height                    | Less than 6 stories, 6 -15 stories, 15-30 stories, More than 30 stories                |
| Construction      | Construction quality               | Construction and workmanship quality                                                   |
| Maintenance       | Maintenance practice (Method and efficiency) | Maintenance inspections, equipment and chemicals used for cleaning
|                   |                                   | Frequency of inspection and cleaning                                                   |
Chapter 5  Concrete Facade Durability Design Aspects

Advances in technology and materials have facilitated a large number of system choices that provide owners and designers with additional costs and performance options [56]. While the industry welcomes new choices, proper designs and executions stays as important as ever, and this statement holds for all types of buildings.

Although the ability of architects and engineers to precisely predict performance of an advanced façade system has been enhanced significantly, there are substantial limitations that inhibit widespread use of the systems. These solutions necessitate extensive engineering analysis with state of the art tools such as computational fluid dynamics to estimate air flow and ray-tracing to assess day lighting performance. Due to some time and cost limitations, these useful techniques are not employed as extensively, since one would need to realise the full operation of a façade system. These stand-alone tools have yet to be unified in order to derive an integrated method to reliably model control strategies and impact of the actions of the occupants. The design process which leads to properly implementing these facade systems, requires a higher level of design team integration at the beginning of the process to enable all of the key disciplines to coordinate efficiently.

The Standing Committee on Environmental Separation (SC-ES) in Canada, prepares recommendations for environmental separation needs in the National Model Construction Code Documents that are related to the following items:

- Structural and environmental loads impacting environmental separators and assemblies exposed to the outdoor,
- Heat transfer (different from fire resistance),
- Air transfer,
- Water vapour diffusion,
- Precipitation, surface water, and moisture ingress,
- Sound transmission.
These provisions are mostly included in Part 5 of Division B of the National Building Code of Canada (NBCC) [65]. The overview provisions in NBCC that must be considered while designing environmental separators in general and concrete facades in particular, are categorized as follows:

5.1 Resistance to Load and Deterioration

5.1.1 Load Analysis

Structural loads or actions are characterized as forces, deformations, or accelerations applied to a structure or its elements [66]. It is known that loads can result in stresses, deformations, and displacements in structures [67]. One is able to assess the effects of loads by using the different available methods of structural analysis. Designers also have to deal with the possibility of excessive or extraordinary loads causing structural failure, unless such a possibility is seriously controlled by design.

5.1.1.1 Determination of Structural Loads and Effects

According to NBCC, materials, components, or assemblies that separate different environments and are exposed to the exterior, or their connections, are needed to be designed to resist structural loads. These loads are to be determined in accordance with Part 4 of NBCC [65]. “Excluding those reported in Article 4.1.8.18 of NBCC, structural loads and their related effects include:

- Dead loads transferred from structural elements,
- Wind, snow, rain, hydrostatic, and earth pressure loads,
- Earthquake effects for post-disaster buildings, depending on their intended function,
- Live loads due to use and occupancy,
- Loads due to thermal or moisture-related expansion and contraction, deflection, deformation, creep, shrinkage, settlement, and differential movement.” [65]

It is worth noting that earthquake effects must be considered in seismic design of each of the building materials, components, and assemblies, and
at their interfaces; these are covered in Article 4.1.8.18 of NBCC to address life safety and structural protection of buildings.

5.1.2 Resistance to Deterioration

As reported in NBCC [65], materials that are used in building components and assemblies separating naturally unlike environments, as well as assemblies that are exposed to the outdoor, should fulfil the following two conditions:

- "Being compatible with adjoining materials,
- Being resistant to any mechanisms of deterioration that can possibly occur, provided the particular nature and function of the materials, and their geographic location and climatic exposure conditions" [65].

A partial list of environmental loads that need to be considered, consist of sound, light and other types of radiation, temperature, moisture, air pressure, acids, and alkalis. The sound-related requirements can be found in Part 3 of NBCC.

The mechanisms of deterioration consist of:

- "Structural (such as impact and air pressure),
- Hydrothermal (for instance, freeze-thaw cycles, differential movement due to thermal expansion and contraction, and ice lensing),
- Electrochemical (e.g., oxidation, electrolytic action and galvanic action),
- Biochemical (such as biological attack and intrusion by insects and rodents)" [65].

One can find information on the effects of deformations in building elements, in Effects of Deformation of Building Components in Structural Commentaries on NBCC.

It is possible to determine resistance to deformation based on field performance, accelerated testing, or compliance with guidelines, as provided by the evaluation agencies approved by the authority having jurisdiction.

Building components are to be designed with adequate knowledge of the length of time interval during which they are expected to perform their intended function effectively. The actual service life depends on the
materials used in design, as well as the surrounding environment. The designers are expected to consider the following factors: each component function together with the notions of premature failure, accessibility for maintenance, repair, and replacement purposes, and the cost of repair or replacement.

In cases where maintenance, repair or replacement is expected with a high probability, for certain elements prior to the building being subjected to a major retrofit, special attention should be focused on providing necessary access to those elements.

Where the use of a building, space, or service, is subject to a significant change, the impact of the changes on the environmental separators should be assessed to prevent premature failures that could possibly create hazardous conditions.

5.2 Heat Transfer

Section 5.3 of NBCC seeks levels of thermal resistance that are required to optimize the amount of condensation on or within the environmental separators, and to guarantee proper thermal conditions for the building use. According to energy regulations, if these conditions exist, the levels of thermal resistance required for energy efficiency or call up energy performance levels should be specified [65].

5.2.1 Required Resistance to Heat Transfer

According to NBCC [65], in cases where a building component or assembly is subject to an intended temperature differential, the element or assembly should consist of materials to suppress heat transfer, or a means to dissipate heat that has been transferred. Materials to resist heat transfer are not required to be illustrated in cases where uncontrolled heat transfer will not have adverse impact on any of the following:

- “Health or safety of the building users,
- Projected use of the building,
- Process of building services” [65].
Therefore, wherever there is an intended temperature difference across the building assembly, the heat flow must be controlled. The use of the term “intended” implies that whenever the interior space is separated from exterior space, temperature differentials would occur. However, it should be noted however that in many cases, such as adjacent interior spaces, there is an intended, although not substantial temperature difference. In these cases, the provisions to control the heat flow might be little, or no more than what would have been provided by any standard interior separator.

5.2.2 Properties to Resist Heat Transfer, or Dissipate Heat
Taking into consideration the conditions on either side of the environmental separator, materials and elements installed to serve the required resistance against heat transfer, or the means employed to dissipate the transferred heat, shall provide adequate resistance or dissipation, as follows:

- “Minimize the surface condensation on the warm side of the component or assembly.
- Minimize condensation within the component or assembly and in union with other materials and elements in the assembly.
- Fulfill the interior design thermal conditions for the intended occupancy, in conjunction with the systems installed for air conditioning of the space, and
- Minimize ice blocking on sloped roofs” [65].

5.2.3 Use of Thermal Insulation, or Mechanical Systems for Environmental Control
The level of thermal resistance needed to considerably avoid condensation on the warm side of an assembly or within it (at the vapour barrier), and to allow the maintenance of appropriate indoor conditions, depends on several items:

- “The habitation,
- Air temperature of the exterior,
- Air temperature of the interior and relative humidity,
- The capacity of the heating system, and
- The means of delivering heat” [65].

For controlling the condensation on the interior surface of an exterior wall, the interior surface must stay above or at the dew point of the interior air. As an example, if temperature and relative humidity of the interior air are 20°C and 35% respectively, the dew point will be 4°C. If the interior air temperature is 20°C with relative humidity 55%, the dew point will be 11°C.

In locations with mild temperature on the exterior, the interior RH during the heating season is estimated around 55%. Assuming exterior temperature is -7°C, the materials in the environmental separator would be required to provide a mere RSI (R-value using the SI units, R-value is used to measure a material’s thermal conductivity and resistance) 0.082 for condensation on the interior surface to be avoided.

Exterior temperatures are, significantly lower for most of the regions of the country. In these cases, insulation or increased heat delivery to the environmental separator are required to maintain interior temperatures of the vapour barrier above or at the dew point.

It would generally be impractical to directly deliver heat over the entire surface of the environmental separator. On the other hand, for indirect heat delivery, interior air temperatures must be raised above the comfort level. It should be noted that increased heat delivery would normally entail excessive energy costs. Besides controlling condensation, interior surface temperatures must be sufficiently warm not to cause occupant discomfort because of excessive heat lost through radiation process. Thus, installation of insulation may be necessary, even where condensation control is not required, depending on the occupancy of the spaces.

5.3 Air Leakage

A separating component or assembly may separate interior conditioned space from exterior, interior space from the ground, or environmentally different interior spaces. Where a separator performs, the position and
properties of the materials, components or assemblies are such that air leakage is controlled or venting to the exterior is permitted to:

- “Provide fairly acceptable conditions for occupants of the building,
- Maintain proper conditions necessary for the intended use of the building,
- Minimize the accumulation of condensation and the diffusion of precipitation into the building component or assembly,
- Not compromise the procedure of building services” [65].

To provide the principal resistance against air leakage, an air barrier system shall be installed. This system is not required, where uncontrolled air leakage will not have any adverse effect on:

- “Health or safety of the building users,
- Projected use of the building,
- Process of building services” [65].

An air barrier system in above-grade building components and assemblies that separates conditioned interior space from the exterior, will decrease the chance of condensation caused by air leakage, uneasiness from drafts, the penetration of dust and other pollutants, and intrusion in the performance of building services, such as HVAC and plumbing. It should be noted that serious health or safety threats can be implied by these difficulties, as defined in the following:

The most noticeable and also important troubles are currently due to degradation of the moisture-related material, such as rot and corrosion, which can result in the failure of the component connections. Furthermore, a wide range of health problems can be the consequence of the infiltration of dust and other pollutants. The pollutants may include fungus spores where the separator is subject to high moisture levels. Finally, interference with the performance of building services can result in unhealthy and hazardous conditions in many regions during the heating season.

In just a few buildings projected for human occupancy, the interior space is conditioned although an air barrier system is not required to be installed. This would rely, on the following parameters: the particular levels of
interior conditioning provided, the ventilation levels, protection provided for the workers, and the tolerance of the building to the accumulation of condensation and potential precipitation ingress.

For some industrial buildings, only limited conditioning is provided. For instance, radiant heating and ventilation levels can be adequate to decrease relative humidity to the desired level, i.e., a level at which condensation will not accumulate to a degree that is challenging. Conversely, some industrial buildings, due to the operational processes, operate at very high temperatures and ventilation levels. In such cases, the building envelope is maintained at temperatures at which condensation is avoided. In both examples, the occupants are protected from unacceptable levels of pollutants, by either the ventilation rates or protective gear in the work environment.

5.4 Vapour Diffusion

5.4.1 Required Resistance to Vapour Diffusion

Where a building component or assembly is exposed to a temperature differential and a water vapor pressure differential, the element or assembly should include a vapor barrier [65].

The principal resistance against water vapor diffusion is provided by installing a vapor barrier, which is not required if it can be shown that uncontrolled vapor diffusion does not affect any of:
- “Health or safety of the building users,
- Projected use of the building,
- Process of building services” [65].

5.4.2 Vapor Barrier System Properties and Installation

The vapor barrier shall have adequately low transport properties, and be positioned in the building component, or assembly to:
- Minimize moisture transfer by diffusion, to sufficiently cold surfaces within the assembly that would cause condensation at the design temperature and relative humidity, or
• Decrease moisture transfer by diffusion, to sufficiently cold surfaces within the assembly that would cause condensation at the design temperature and relative humidity, to a degree that will not allow adequate accumulation of moisture causing degradation or otherwise undesirably disturb any of:
  
  I.  “Health or safety of the building users,
  
  II.  Projected use of building,
  
  III.  Process of building services” [65].

5.5 Precipitation

In case a building component or assembly is exposed to precipitation, the element or assembly shall,

• Minimize precipitation ingress into the element or assembly, and
• Prevent precipitation ingress into interior space [65].

Protection from precipitation ingress is not necessary if it can be shown that such ingress has no adverse effect on any of:

• “Health or safety of the building users,
• Projected use of the building,
• Process of building services” [65].

5.5.1 Sealing, Drainage, Accumulation and Disposal

5.5.2 Sealing and Drainage

Materials, elements, assemblies, joints in materials, connections between elements or assemblies exposed to precipitation should be:

• Sealed to avoid precipitation ingress, or
• Drained to direct precipitation to the outside [65].

Sealing or drainage is not necessary if one can show that omitting them does not have harmful impact on any of:

• “Health or safety of the building users,
• Projected use of the building,
• Process of building services” [65].
5.5.3 Accumulation and Disposal
In cases where accumulation of water, snow or ice can occur on a building, provision is made to reduce the chance of hazardous conditions arising from such an event [65]. Moreover, in case that there is a chance of precipitation accumulation on sloped or horizontal assemblies, recommendations should be made for drainage conforming to Section 7.4 of NBCC. If downspouts are provided but not linked to a sewer, it should be required to,
- Avert the water from the building, and
- Avoid soil erosion.
All connections between vertical assemblies, and sloped or horizontal assemblies, are designed and constructed in such a way that the water flow from the sloped or horizontal assembly onto the vertical assembly, is minimized.

5.6 Prevention of Accumulation and Ingress of Surface Water
The building should be located where the building site is graded, or catch basins are installed, to prevent accumulation of surface water alongside the building [65]. The foundation walls should be constructed so that surface water does not enter the building or damage materials that are vulnerable to moisture.

5.7 Moisture Protection
5.7.1 Protective Material and Component Properties
If it can be shown that reduced protection will not cause harmful conditions, as delivered in Article 5.8.2.3. of NBCC, materials and elements installed to serve the needed moisture protection should fulfill the requirements of Article 5.8.2.3 [65]. Materials for construction, control, and expansion joints, joints installed between different building assemblies and elements penetrating the building assemblies that are installed to provide the needed moisture protection shall be capable of bridging construction.
In case the materials and joints that are installed to serve the needed moisture protection, are not capable of bridging construction, these junctions should be designed to preserve the continuity of moisture protection. Materials and elements installed to provide the needed moisture protection should have adequately low water transport characteristics to resist against moisture loads.

5.7.2 Required Moisture Protection
According to NBCC, the control of moisture ingress into the interior space from the ground is independent of the type of the building, the use of the space, or the space being conditioned or not [65]. This indicates that high humidity levels, with or without standing water, possibly undesirably affect both health of the building occupants and the durability of the building structure.

The assembly separating the subject interior space from the outside environment, cannot normally be depended for delivering adequate moisture protection for the occupants of the building. Depending on the construction of the separator, it may also be in danger of moisture-related degradations.

The exclusions to this necessity includes only those cases for which the subject interior space is unoccupied and the separator itself delivers the needed protection, and is resistant against a highly humid environment, or the moisture loads are limited enough as to not have undesirable effects on the building or its occupants.

5.8 Sound Transmission
According to ASTM E413, Classification for Rating Sound Insulation, “Sound Transmission Class (STC)” ratings should be determined, using the outcomes from measurements in accordance with

- ASTM E90, “Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements”, or

### 5.9 Summary
Design of a concrete facade is the most significant step towards implementing a sustainable and durable system since it influences the whole service life of the structure and it has direct impact on its construction and maintenance. Presently, poorly implemented construction works is the result of design inefficiencies; additionally maintainability issues arise from not predicting and considering a regulated planned maintenance at the design stage, to ensure the efficiency of maintenance work.

Along with aesthetics, a façade must be designed to separate the interior of a building from the aggressive exterior environment and it must also withstand the imposed mechanical and environmental loads. National Building Code of Canada has adopted provisions to enhance the performance of these façade including, structural and environmental loads on the facades, heat transfer, water and moisture diffusion and air transfer and other related issues.
Chapter 6  Maintenance Strategies

6.1  General Principles for Maintenance Strategies  
The service life of a structure begins when the construction work is completed. At this point, the external factors start to disturb the facade system, and several progressive degradation mechanisms begin to have a negative effect on the construction materials [31]. These external factors include mechanical and environmental loads along with aggressive environmental deteriorating mechanisms. The structural design for durability must consider and mitigate these external actions that produce continuous deterioration in each one of the structural elements. This can only be achieved through a durable structural design method, related to a defined service life for the facade. The maintenance techniques must be performed to guarantee the accomplishment of the design service life for every one of the facade elements from the foundation components to the superstructure.
The maintenance plan must consider various maintenance procedures to be implemented on the facade during its service life, including the necessary preventive and corrective maintenance.

6.2  Design for Maintainability  
The design process should enable maintenance operations to be performed in a practical and effective manner for the adapted maintenance strategy [31]. These include, for example, adoption of a simple geometry to facilitate easy access for inspection of the structural elements, access to hidden parts of the structure, particularly access to connecting steel joints; and the installation of any needed instruments for testing and developing information about the future behaviour and performance of the construction materials and components used in the structure.
6.3 Preventive Maintenance

In the stage of preventive maintenance all of the actions required to preserve the original conditions of the facade when it was initially exposed to loading and environmental conditions [31]. The cleaning activities for the different elements of the structure must be considered in preventive maintenance procedures which involve:

- Cleaning of the draining system for proper operation, and to avoid gradual development of deterioration sources (microclimates) produced by its malfunctioning.
- Cleaning of the expansion joints at the supports to clear the accumulated debris, dust and water-borne aggressive agents.
- Eliminating or cleaning the accumulated debris, dust and water carrying aggressive materials underneath the expansion joints.
- Cleaning the fixed and mobile bearings and to maintain them for suitable conditions to ensure their efficient and proper performance.
- Performing a complete washing process of the whole façade, including the windows or any critical zones which can accumulate salts and any other aggressive agents.

Managing these cleaning procedures to be performed from time to time is essential, as well as arranging guidelines for seasonal cleaning activities, particularly in the spring, by decreasing the aggressiveness of the microclimates acting on the various structural elements, especially during the most severe conditions of temperature and relative humidity that are found during the summer season.

6.3.1 Concrete Facade Inspection - A Brief History

The concept of ordinances and laws to protect the public from building facades is not new. In fact, it is well known that Hammurabi’s Code of Laws (1700 B.C.) had several requirements associated to the safety of buildings. However, the roots of “modern” facade ordinances date back to 1976 [68], when impact of moisture and building movements on façades were not fully known. Therefore, buildings constructed in this era do not involve modern detailing, such as expansion and contraction joints and flexible
connections, to minimize these effects. It is claimed that a piece of masonry falls from a building in the North America every three weeks. It is unfortunate that what prompted government authorities to impose certain restrictions on construction and inspection of facades, has been personal injuries, deaths, and property damage. In 1976, the first facade ordinance in the United States, was passed in Chicago. However, this ordinance was repealed on a technicality, that when the new laws were issued, the section on the facade regulation was eliminated, according to the 1996 proceedings of the Chicago Committee on High-Rise Buildings. After a long pause, in 1996, a new facade ordinance was approved in Chicago. The longest ongoing facade ordinance, was executed in 1980 in New York City. The most common aspect of the existence of these facade ordinances is that, they were established after serious injury or death to pedestrians. Some of the older ordinances have also been modified over time by high profile facade failures [68]. As reported in the June 29, 1984 edition of the Cincinnati Enquirer, Columbus, Ohio, a member of the city council, Ben Espy lost part of his leg when a large section of a building's cornice fell to the sidewalk. Three other pedestrians were also injured. The Columbus facade ordinance became famously known as the Espy Law. In the New York City incident, an 18-year-old college student died when a piece of masonry fell from a Manhattan building and struck her in the head in 1979. In 1974, in Chicago, a 48-year-old woman was killed after a masonry segment fell approximately 16 stories and hit her. After that, Chicago lost one of its residents-a mother walking with her daughter, when a piece of glass struck her in the head. Despite the lessons learnt from these disasters in several cities many other cities still do not have such an ordinance to protect the public.

6.3.2 Conducting Facade Inspections for Unsafe Conditions
Facade inspections should be executed by licensed architects or engineers who have sound knowledge of design and construction of building facades [68]. But more importantly, the facade inspector should be experienced in the field of stability and deterioration mechanisms relating to specific
materials and facade assembly which is being inspected. It is essential that the building owner consider the experience of the facade inspector because it affects people’s life. Being affected by a slow economy, some architects and engineers pursue facade inspection work besides their regular jobs. However, they are sometimes not technically competent in performing these inspection procedures and can be negligent in identifying the type of facade construction and the potential degradation mechanisms.

Periodic facade inspections are typically performed in three steps.

- **Step 1:** Reviewing the documented history of the façade services and preparing elevation drawings if they are not available.
- **Step 2:** Performing the inspection including three main surveys; a visual survey under proper lighting conditions, a close-up inspection of selected facade parts where the facade surface can be touched by the inspector, and probing select building facades to inspect for hidden deteriorations.
- **Step 3:** Analyzing and documenting the inspection results which can be submitted to the building owner and the local building authority.

### 6.3.3 Considerations in Performing Concrete Building Façade Inspection

Structural engineers with various experiences in the areas of design, water and damp proofing, and construction are assumed to be the best qualified professionals to perform façade inspections [63]. They have knowledge behaviour of materials when subjected to applied loads and movements. Defining the main cause of a deficiency can be very challenging; however though not impossible if the construction process of façades and building superstructures is understood, along with the deformation and the movements resulting from the various applied mechanical and environmental loads, and the resulting failure mechanisms. A building façade performs three roles:

- **Structural resistance to mechanical and environmental loads.**
- **Protection of the building from aggressive environmental elements, including moisture and temperature.**
- Appearance and aesthetics of building.

Façades can have various types of load-bearing or curtain wall type and also can be consist of a solid or cavity wall. A solid wall can be expected to be load-bearing and has only one moisture barrier. A cavity wall has the additional advantage of two moisture barriers separated by an air space. As time passes by, façades are exposed to the various degradations as a result of normal wear and tear and chemical exposure. Moisture can penetrate from the exterior of the building or it can escapes from its interior of a building and can cause corrosion and deteriorate the panel’s supports. Freeze-thaw cycles, can result in cracks and spalling of a veneer that has trapped water vapor under pressure within it. Creep and shrinkage of the concrete manifest, in the form of shortening, and foundation settlement can cause cracks, spalling, and buckling of the façade. Temperature and moisture changes cause differential expansion and contraction that can also lead to similar problems. As expected, more severe façade degradation has occurred mostly in northern climate as compared with the southern climates due to relatively larger seasonal temperature changes, colder temperatures, significant snowfall portion, and long periods of below freezing temperatures.

Figure 6-1 Engineer conducting façade inspection via industrial rope access [63]
6.3.3.1 Movement of Materials

Façades can get deteriorated, because of local environmental exposure to chemicals, moisture and freeze-thaw cycles. In most cases differential movements within the façade and the supporting structure can cause deteriorations when using multiple materials in combination [63]. Internal stresses can develop if the system is not provided with regularly spaced horizontal and vertical expansion joints and flexible interconnections which are placed parallel to the plane of the façade; these can result in façade cracks and deformations, which can be are categorized as follows.

6.3.3.2 Thermal Movements

Expansion and contraction typically occur in almost all materials due to changes in temperature. The thermal expansion coefficients for fired clay products, such as brick, and some stone products, such as granite and limestone, are quite similar to that of concrete masonry (CMU) [63]. Marble and steel have relatively larger expansion coefficients than that of CMU. The thermal expansion coefficient for aluminum, which is often used in window and curtain wall framings, is almost three times that of the concrete masonry. Exterior cavity walls are insulated by the air space and thus a larger temperature differential between the interior side, which is exposed to residential unit’s conditioned air, and the exterior side, which is exposed to the atmosphere, can be measured than of a solid un-insulated wall. This can be larger on a dark-colored walls which are facing south. In that case surface temperatures can be as much as 4.4°C above the ambient temperature. The average temperature for an insulated 4-inch veneer will be seldom equal to the exterior surface temperature. The value of the mean temperature on a solid and un-insulated wall will be smaller than the exterior surface because of the interior and exterior temperatures.

6.3.3.3 Moisture Movements

Most materials, excepting metals, are subject to expansion and contraction with changes in moisture [63]. However, the contraction does not occur in fired clay products due to drying; they are at their smallest size when they
cool after leaving the kiln, from that point, they commence absorbing moisture at a high rate and this will continue for several years but with a relatively smaller rate than the first few weeks. This expansion is partially compensated by drying shrinkage in the mortar joints. Concrete masonry moisture absorption capacity is the largest after casting. Concrete materials are subject to shrinkage as they cure, but they expand when exposed to moisture. The combined movements usually cause an additional shrinkage.

6.3.3.4 Elastic Deformations
Building materials have elastic deformation caused by stress changes. This deformation is reversible and is a function of the stress level within the material [63]. All forces applied to a building, such as gravity and lateral loads should be included in these considerations. The exterior veneer in curtain wall construction is exposed primarily to lateral actions such as wind and seismic loads; the only applied gravity load should be the weight of the façade material above. It can be reduced by horizontal relief angles with integral expansion joints, which are usually installed at each floor level. The supporting building structure will be subjected to all of the above gravity and lateral loads, and will deform consequently. Therefore, it is quite essential to use expansion joints and flexible connections to compensate these movements and to ensure that structural loads are not shared by the veneer. Most of the solid composite exterior walls are load-bearing, and the component materials deform together. The component materials of a solid wall should either have similar details or properties to offset the difference in material properties or minimize the corresponding impact.

6.3.3.5 Creep Effects
Creep is defined as a long term deformation of materials caused by sustained loads or the resulting stresses. A large part of creep in cast-in-place concrete, concrete masonry, and mortar is not reversible, and starts shortly after the loads are applied, and decreases gradually [63]. In High-
Rise Buildings, combination of reversible and irreversible creep, and shrinkage will cause the columns and walls to shorten with a shortening deformation value measured to have an average of 25 mm in a height of 24 meters of height.

6.3.3.6 Corrosion
The embedded steel in masonry and concrete is reinforced by bars, joint reinforcing, ties, anchor bolts, shelf angles, and lintels. Generally, corroded steel embeds which have lost 25% or more of their cross sectional area cannot be assumed to be structurally effective [63]. Additionally, corrosion requires 2 to 10 times more volume than that of the iron from which it was formed. This increase in iron volume can cause cracking and spalling of the concrete or masonry in which it is embedded by imposing additional internal pressures. It is important that steel embedment be covered by a material coating to prevent corrosion, the use of corrosion-accelerating chlorides in concrete and mortar should be prohibited, and water should be discharged from the concrete and masonry surfaces.

6.3.3.7 Unstable Soils
One of the causes of differential settlement of foundations that support building façades and their superstructure backup is unstable or expansive soil [63]. Consequently, designing foundations for uniform settlement is essential to avoid the consequences of differential movement.

6.3.4 Procedures for Performing Concrete Building Façade Inspection
6.3.4.1 Inspection Process
The inspection procedure is usually initialized by a meeting that includes building users representative and maintenance personnel to obtain historical information about the building maintenance and renovation, including re-roofing, previous repairs, and known deficient conditions [63]. A quick guided tour of the facility should be performed with the inspectors to familiarize them with the layout of the building, and to let
building representatives and inspectors to determine the areas with known disorders and problems. Building security personnel should be informed about the inspection process consequently to insure safety of the personnel and equipment. Inspectors should have the authority to review any available construction documents, e.g. plans and specifications. Drawings are reproduced to help inspection and reporting processes. It is important to study the wall sections to determine the makeup of the exterior walls. Knowledge of the construction process of the façade systems is also important in determining the cause of any deficiencies that may be discovered during the inspection. As the inspection reports are prepared, they can possibly identify areas with potential visible and concealed damage, and assist in identifying high priority inspection areas.

The process of inspection usually involves two stages of general and detailed inspection. General inspection is composed of visual observation procedures at a distance greater than 2 meters from the façade, both with and without magnification. Detailed inspection generally aims at identifying and examining the original cause of the deterioration and involves some tasks such as hands-on inspection, including pushing, pulling, probing, and sounding, as well as the loose, unsound, or fractured material that presents a risk of detaching or spalling from the facade. Initial general and detailed inspections basically focus on areas with recognized and identified deficiencies, starting from both the interior and exterior of the building, as these may reveal the tendencies to the façade deterioration. The next important stage is detailed inspection of roofing and parapets.

Degraded roofing and parapets can cause corrosion and deterioration of reinforcing steel and supports, since they can be a source of moisture infiltration into the exterior walls. Furthermore, freezing of moisture trapped within the veneer can cause the material to expand and cause cracking and spalling of the veneer. Parapets host the full effect of environmental conditions and changes on both sides. Varying temperature and changes in moisture content between the parapet and the walls of the building may lead to differential expansion and contraction.
In most buildings older than 30 or 40 years, different types of expansion joints are missing in the façade structure, which is a serious occurrence that can be aggravated further by concrete frames or concrete masonry units (CMU) which can be subject to shrinkage, and steel frames that are subject to expansion and contraction due to temperature changes. All of these relative movements and corresponding stresses will cause diagonal and horizontal cracks, especially at the building corners.

After completing a visual survey, the facade inspector is able to distinguish the required close-up access to perform a detailed inspection that may include touching the facade surface, and use further probing procedures. Access for close-up inspection can be achieved by utilizing several methods using an existing permanent platform for example balconies or fire escapes, a short-term platform such as a contractor’s scaffold, or using industrial rope access. The façade system should be inspected thoroughly and systematically by scanning the exterior in both horizontal and vertical directions using tripod-mounted binoculars. Cameras with telephoto lenses are used to document any deficiencies. The main purpose of this operation is to identify, quantify, and visually determine deficiencies within the façade such as missing components, stains, cracks, spalling, bulges, previous repairs, deteriorated sealants, and any other unidentified physical damage. These observations can be documented along with a unique deficiency and photograph number for each photograph or sketch to aid development of the report.

In addition to the general inspection which includes previously identified deficiencies and repair history, suspicious areas are identified for further detailed inspection. Based on the building dimensions and access provisions, detailed inspection is usually performed from the adjacent roofs or with the help of a ladder, swing stage, telescoping boom lift, and an industrial rope access. For the cases with large holes in the façade, one can use mirrors or a remote camera, to observe and register the substrate condition. If a remote camera or mirror cannot be utilized in the hole, with the permission of the building owner, it is possible to drill other holes in mortar and sealant joints, and use a bore scope, again to observe and
record the substrate. These holes should be filled with sealant at the end of inspection procedures.

In the case of probing of the facade, several methods can be used such as insertion of a fiber optic bore scope, disassembly of facade components, or selectively cutting materials. In historic buildings, extreme caution should be practiced to protect the building façade from any damages.

Figure 6-2 Detailed façade inspection including sounding for delamination being conducted from a telescoping boom lift [63].

6.3.4.2 Precast Concrete Façade Investigation

Methods of sealing and supporting precast concrete façade panels are important considerations for any examination procedures [69]. In most cases, precast concrete panels are sealed with a proper sealant and backer rods at the joints. If the panel and the joints at the caulk bond line are exposed aggregate, the procedure of sealing the aggregate should be performed in an effective and careful way. If there are gaps in the aggregates, adequate attention should be devoted to grinding of the joints to produce an effective water-proofing with the caulk. Additionally, water testing of the joint should be performed effectively in a sequential manner as follows:

- Step 1: Water testing to find whether the joint leaks
- Step 2: Replacing the caulk, leaving the joint in its present condition and perform the water test
- Step 3: Grinding and sealing the joint, and water testing

Grinding of the joints is not needed if it does not leak during the second step. If leakage is noted during Step 2, grinding will certainly be needed. Such water testing can help the building owners to recognize the necessity of joint grinding and to effectively seal the precast façade panel joints against water and moisture ingress. Typically, precast concrete panels are mounted on the building structures by two load bearing points; one supporting the panel to resist the gravity loads and the second preventing its rotation and tilt. Examination of the connections may include invasive procedures. In most cases the deficiencies of the precast concrete façade panel connections are result of water intrusion into the steel connections, or delaminated concrete surrounding the connections which have corroded. A temporary support of the precast panel is usually needed during the repair activities, which may include a simple angle bolted to the slab, steel frame support, or other more elaborate temporary supports. Precast connections are typically installed to provide some space for thermal expansion and contraction of the precast concrete panel, wind loading on the panels, and service loading of the slab which produces differential movement between the slab and the precast concrete. To investigate whether the precast concrete is cracked at the connections, an examination of the precast elements should be conducted. When the panels are long laterally and have intermediate supports to the structure besides the supports at the ends of the panel, the precast concrete may be cracked at the connections. It is quite difficult to construct a slotted connection that does not need maintenance. Due to the existence of leakage through cracks, embedded steel in the precast concrete is likely to suffer from corrosion due to water intrusion. Therefore, structural repair and water tightness of the repair as well as the aesthetic appearance of the repair should be considered explicitly in repair design. The investigation operations for precast concrete panels should include the following stages:
  - Examination of joint seals
- Invasive examination of the connections
- Investigation for cracks in precast concrete at connection points.

### 6.3.4.3 Reporting

The professional analyzers will study all of the noted deficiencies noted in the documents such as reports, etc. and recognize the main cause of the phenomena and their level of severity [63]. This analysis should be undertaken concurrently with the inspection and should be documented later. The severity for the identified deficiencies can be classified at the following levels:

- **The term “unsafe condition”** is used when the identified deficiency poses a serious threat to individuals or property and should be immediately pointed out to the owner, and local authorities, providing potential repair and corrective options.
- **“Requires repair/stabilization”** is used for a case that may become unsafe if it is not scheduled for the next inspection program.
- **“Ordinary maintenance”** identifies the cases when something is needed to be addressed for the next scheduled maintenance.

A detailed budget estimate with the severity classification is included in the final report to assist the owner with the budgeting of future maintenance of the building façade. The budget estimate should include all costs of contractor’s labor, materials, equipment, overhead, and general conditions, as well as the fees for architecture and engineering services, owner’s administration, and unpredicted events.

To assist the building owner/manager in planning for necessary repairs and future inspections, the report should include a survey of the history and condition of the façade in terms which can be understood by an amateur. The original building construction, alterations, renovations, and repairs should be included as well. Primary structural system, roofing, parapet construction, façade system and support, waterproofing, and foundations are needs, to be conveyed to the owner/manager. Methods of inspection, classification of deficiencies and the probable root causes
should be presented as along with illustrative documents and proposed remedial alternatives and repairs and the related cost estimates.

### 6.3.5 Facade Cleaning - Preparation

A very basic and important factor for preparing a cleaning procedure for building façades is to decide whether to perform it before or after the repairs and restoration work [64]. As previously mentioned, when a surface is heavily coated in dirt, stains, paint or other coatings, it can be difficult to detect what may need to be repaired. Although the best alternative may be patch or repair a clean sound surface, it may be preferable to clean the façade before any repairs.

In a few cases, patching and repairing cannot be a proper solution. When a building has extensive water leakage problems, the patching and sealant work should be performed under supervision of design professionals. It would be a serious mistake to add water during cleaning to already “precarious” areas. The design professional may choose to patch and seal areas of water intrusion before the start of cleaning procedures.

To protect the building structure and exterior against damages during façade cleaning, a detailed description of the design including drawings and diagrams of the proposed materials and methods of protection should be prepared and presented to the owner/manager by the design professional. To protect all glass, metal, wood or painted surfaces which should remain without cleaning, the design professional should specify proper protection materials and methods, such as masking products that are occasionally part of a manufacturer’s chemical cleaning system. Through the entire procedure of cleaning all windows and doors and other existing openings should be temporarily sealed to prevent permeation of liquid and particulate matter. As the conclusion of the work, window and door hardware should be checked for operability.

A critical element of the façade cleaning process is test-cleaning of a patch of the façade. It can be used to ensure that the cleaning effort has the desired results and also to ensure that the chosen method would not damage the façade. Before performing a full masonry cleaning project, a
test cleaning should be conducted as a pilot operation for a 100 square feet surface area for each substrate for the selected cleaning method. Full cleaning procedure should not start until the design professional and the building owner have reviewed and confirmed the results from the patch test cleaning.

Before the stage of Test-cleaning, it must be verified that the work of other sections that might affect the cleaning work is finalized. Cleaning should not be performed until all other work has been completed. Uniform coverage of all surfaces must be achieved during the cleaning process, to cover all corners and moldings, and to produce an even effect without damaging the surface.

Knowledge of the prevailing climate is essential in protecting against damage to the building during façade cleaning. The weather can cause the façade cleaning project to be aborted. Low temperatures will cause the liquid cleaning products and water to freeze and transform to sheets of ice. On the other hand, if it is too warm, a chemical product could dry faster, and it may not perform as it should and cannot clean the façade system properly. Wind may also cause extra problems with vapor and overspray. The design professional should prepare instructions on how to work around the weather prior to performing the façade cleaning project. As an example, it can be pointed out that a cleaning specification may require that masonry cleaning work not be performed when temperatures drops below 10 degrees, or soar above 32 degrees-Celsius within 24 hours of working time.

All façade cleaning projects can be categorized as follows: chemical, non-chemical, abrasive and a hybrid approach using combination of these techniques. For example, a masonry façade cleaning mission may partially succeed with a non-chemical water soaking procedure to wash the dirt away, an appropriate cleaning agent (chemical) to treat areas of heavy stains may be necessary.

The building owner or manager should check with the design professional to come to an agreement on choosing the best façade cleaning method that is suitable for their building.
6.3.5.1 Water Cleaning Methods

The first method of water cleaning to be described is “water soaking”. This method involves a slow and steady stream of water to loosen the dirt and wash it away. Water soaking is a very effective method as the dirt becomes distended and soft [64]. Many piping and nozzles are constructed and considered for this purpose. After water soaking, a hand scrubbing procedure with brushes or a rinsing operation with 400 psi pressure water spray can be used. For each façade cleaning project with water-soaking, the design professional should determine the following appropriate considerations:

- Duration of soaking (in hours);
- Number of gallons of water per minute per nozzle
- Nozzle spacing

The maximum effectiveness by this method is achieved principally on stone and glazed brick wall. However, the water soaking procedure has number of possible limitations that must be considered:

- Long exposure causes oxidation of natural components of masonry and inserts harmful salts deep through the masonry.
- Drying of saturated masonry usually takes several weeks.
- The procedure of cleaning of the masonry façade should not be scheduled for times when the possibility of freezing is high.
- Continuous pouring of water causes surface erosion.
- The possibility of damaging interior surfaces, furnishings and equipment may exists.
- Controlling water run-off is equally important.

The second water cleaning method is “pressure washing” in which pressurized water washes the stains and contaminants away from the façade. This procedure has a relatively high efficiency on stone, masonry and concrete to remove moderate atmospheric and organic rust and stains. This method utilizes high temperature water, with temperature below 70°C, which effectively removes grease and oil stains. Occasionally termed
as “power washing”, pressure washing is specified by the design professional according to four parameters:

- Pressure ratings (psi);
- Water flow rate;
- Type and size of spray tip
- Distance from the substrate

Limitations related to this method are:

- Using pressure washing alone cannot perform the removal of hard and large loads of stains.
- High pressures can partially remove mortar and etch stone.
- The possibility of oxidation of masonry may exist.
- The procedure of drying saturated masonry may takes up to several weeks.
- This method of cleaning should not be scheduled when there is a possibility of freezing.
- Water may penetrates through small openings and cause premature deterioration.
- Water run-off must be controlled.
- This method cannot be assumed as an alternative to hand labor in cleaning procedures.
- Using this method for applying chemical cleaners may be dangerous as the chemicals will permeate deep into the masonry and cause damage to the structure

### 6.3.5.2 Chemical Cleaning Methods

Dissolvent chemical cleaning products are often used to overcome “tough” façade stains by fully washing them away [64]. Generally, chemical cleaners are categorized as: acidic and alkaline cleaners, organic solvents, and special non-sudsing detergents. Many commercial chemical cleaners which are useful for cleaning different types of façade surfaces are available. Some are specifically designed to remove efflorescence and salt staining. Some other types are used mainly to remove excess mortar, grout stains and dirt. Others chemical cleaners are available for use on brick that
may have a high metallic content. Typically in large cities or high pollution areas, extremely dirty and heavily carbonated masonry parts exist for which, the various effective restoration and related cleaning operations are designed. There also exist commercial plasters, designed for areas in which the contaminant has penetrated into the substrate. Strippable masking materials can be also useful to protect glass, metal and polished stone parts from the acidic effect of some brick cleaners.

6.3.5.3 Abrasive Cleaning Methods

Abrasive cleaning is as a unique method to clean stone, masonry and concrete, because it is designed to completely remove the outer stained portion of the substrate, rather than just dissolving and cleaning the stain [64]. Thus, abrasive cleaning is not necessarily useful for restorative façade cleaning projects. Abrasive cleaning involves different methods such as grit blasting, grinding wheels, sanding disks, sanding belts and wet sandblasting (grit blasting combined with high pressure washing). New non-intrusive methods, such as using very small (20- to 100- micron) grit and containment of the cleaning area, are available as well. Despite the fact that the abrasive cleaning methods are efficient and functional in removing various surface stains, there exist a number of boundaries associated with various related techniques which need to be considered:

- The monitoring of progress is difficult because of the significant amount of dust created by abrasive techniques.
- A more rapid deterioration occurs in a softer substrate due to removal of the masonry surface.
- Abrasive cleaning techniques cannot be used to remove the subsurface stains and covers.
- Airborne silica dust is quite hazardous. Sandblasting is forbidden in many metropolitan areas and cities.
- Abrasive cleaning makes the surface area of the treated substrate to be vulnerable to atmospheric corrosion, moisture absorption and other deterioration processes.
- Grit blasting may require a repainting work.
6.4 Corrective Maintenance

Any needed corrective maintenance must be defined as a result of the observations from the different inspections performed on the structure. In this stage of the maintenance strategies, it is essential to define a framework of decision based on the results of the evaluation of the quality of the different construction materials and the performance of the various structural elements [31].

Corrective maintenance involves repair, rehabilitation, and strengthening. The rehabilitation process engages all necessary repairs that must be performed with the aim of restoring the service levels, safety and serviceability of the facade as close as possible to the original conditions. Strengthening also involves the improvement of the load bearing capacity of the facade at a certain time, by increasing the strength and the stiffness of the relevant components of the structural system, as closely as possible to the original capacity of the facade.

Typical exterior wall components should theoretically last over 20 years [70]. Although one is quick to blame building age for façade instability, the fact is that age alone is hardly the cause of façade failures. Rather, façade instability is caused by a combination of factors, which include: poor design, improper connection and installation, corrosion from moisture and water intrusion, water penetration into the cavity between façade and the backup, damage due to freeze/thaw, and poor exterior wall maintenance. The loss of support or weakening of anchoring systems can result in falling debris, a hazard to the property and in the worst of cases, to pedestrians and others in the proximity of the building. When exterior wall components are not maintained properly; the repair cost can be exceptionally greater than the expected maintenance budget.

Capital rope access can help you avoid these escalating costs by performing the following services:

- “Flashing and moisture barrier installation
- Expansion joint installation and repair
- Window sealant reconstruction brick and concrete
- Wet sealing, caulking, and building coatings” [70].
Maintenance of building façades should be an on-going process [71]. However, maintenance prioritization issues are often neglected due to the lack of available tools to assess susceptibility to deterioration. Key components of the façade system most in need of maintenance interventions ought to be identified to prevent premature failure of façade components, to sustain the health and safety of the occupants, and to maintain the serviceability of the system over its service life.

The effects of moisture and other climate effects on the deterioration of façade components are normally known. Likewise, water penetration of the façade from wind-driven rain to the interior causes damage, mould growth and degradation of thermal performance. Knowledge of the combined effects of wind, moisture and thermal loads permits determining the response of the wall, that in turn allows evaluating the hydrothermal performance, dilation at panel joints, susceptibility to water penetration, or the development of combined responses that act to deteriorate the façade system. The most severe combinations most likely to deteriorate the facade can then be determined; these provide a basis for prioritizing maintenance programs for buildings. The process can be used to establish the risk of deterioration from climatic effects among different types of walls for a given building façade, between the level of risk among different buildings in a given climate, or for comparing the relative effects on similar facades located in different climate zones. Kami Farahmandpour [72] has proposed some appropriate techniques and approaches to repair pre-cast concrete facades that is be briefly described in the following section.

6.4.1 Repair Considerations

6.4.1.1 Cause and Extent of Deterioration

A proper investigation of deterioration mechanism and its extent should be performed [72]. Although under most circumstances the repair methods for spalled and delaminated concrete will be the same regardless of the cause, the deterioration mechanism and its extent may dictate a different repair approach in some cases. For example, if high levels of chloride ions
are present in the concrete, a more aggressive repair approach, such as the use of corrosion inhibiting materials or cathodic protection measures may be needed. Also, in most cases, the extent of deterioration will have a significant impact on the decision to repair or replace a component. The most common type of deterioration encountered in exposed concrete facades is that associated with corrosion of embedded metals. The second most common cause of deterioration in cold climates is due to freeze-thaw cycles which cause damage to the concrete elements. Coating failures and leakage through concrete cracks are also common problems.

6.4.1.2 Repair Objectives

Once the cause and extent of deterioration are determined, repair objectives should be defined [72]. Typically, these would be one or more of the following:

- Improving the aesthetics of the building: In some cases, the concrete deterioration may not impact the structural integrity, water tightness, or the durability of the facade. In this case, the only objective would be to improve the aesthetics of the building.

- Restoring durability of building components: In most cases, the main objective of the facade repair program will be to restore the durability characteristics of the concrete elements and to significantly reduce the rate of deterioration. It should be noted that, in most cases where corrosion of embedded metals is the cause of deterioration, completely preventing future deterioration is not practical.

- Restoring structural integrity: If the extent of deterioration is such that the structure of the building has been compromised, the main objective of the repair program should be to restore the structural integrity of the affected components or the framing system. It should be noted that most conventional concrete patch repairs are cosmetic in nature and will not produce composite action with the structural members. If a structural repair of the concrete is needed, special provisions for shoring and temporary removal of all loads from the members should be considered.
Leakage control: In some cases, deterioration of concrete will result in unacceptable water intrusion through the building envelope components. In such cases, repair objectives will include controlling water leakage. It must be noted that due to the nature of the building envelopes with exposed concrete framing members, complete prevention of water intrusion is not practical.

6.4.1.3 Environmental and Logistical Limitations

Repair design for exposed concrete (especially for High-Rise Buildings) should consider the unique environmental and logistical challenges associated with such work [72]. The following are the most typical environmental and logistical factors that can influence specifications for exposed concrete framing elements:

- **Wind**: High wind on tall buildings can accelerate the drying of concrete patch materials and pose curing problems.

- **Time limitation**: On tall buildings, lifting of concrete patch materials to the repair location with a swing stage scaffold can take up to 30 minutes. This will shorten the pot life of many materials that have to be mixed on the ground.

- **Lifting repair materials and lowering debris**: Deteriorated concrete that is removed will have to be lowered to the ground. Meanwhile, repair materials must be lifted to the repair location, all by scaffolding equipment that has its weight and size limitations. These factors can significantly limit repair options and methods. For example, the use of shotcrete for repairs on tall buildings is usually not practical due to these factors.

- **Worker fatigue**: Working on high-rise facades from a swing stage scaffold while wearing safety equipment, is very difficult. In some circumstances, workers have to remove concrete from soffits of balconies and slab overhangs while standing on a suspended scaffold. These conditions can cause worker fatigue and adversely impact the quality of work. In some cases, repairs that heavily rely on good workmanship are not possible on a consistent basis.
- Overhead protection: Performing repairs on a high-rise building facade will require overhead protection on the ground. Depending on the height and location of the building, the overhead protection may have to extend onto the adjacent streets.

- Temporary weather protection: In most cases, removal and patching of concrete are not practical in the same day. Therefore, at areas adjacent to windows and other diffusions, concrete removal and surface preparation will reduce the building envelope vulnerability to water intrusion. Consideration should be given to temporary waterproofing.

- Inconvenience to building owners: Concrete repair techniques involve the use of chipping hammers and sandblasting equipment. The use of chipping hammers will typically cause excessive noise and vibration to be transmitted through the building frame. These vibrations can result in damage to other building components, such as interior plaster and adjacent windows. Sandblasting can also create dust and can cause considerable damage on the ground, if not contained properly. These factors should be considered during the design process and should be communicated to the building owners.

6.4.1.4 Temporary Support and Shoring

It is common that the exposed concrete elements being repaired are structural framing members [72]. Therefore, concrete removal around the reinforcing steel will reduce the structural capacity of the member. In High-Rise Buildings, significant removal of concrete from columns without due consideration to the structural integrity of those columns can have catastrophic results. Removing portions of balcony slabs and removing concrete from slab overhangs adjacent to columns where significant shear transfer occurs, must be dealt carefully Therefore, it is important that the anticipated location and extent of concrete removal be reviewed by a qualified structural engineer prior to specifying repairs. Of course, concrete removal should also be carefully monitored during repairs to avoid the same issues.
6.4.1.5 Cost Versus Service Life
Like most things in life, longer lasting repairs can cost more. Features that enhance concrete repairs, such as protective coatings, sealers, corrosion-inhibitors, and cathodic protection can add significant cost to the repairs. However, due to the high access costs for building facades, the additional service life realized will typically offset the initial cost [72].

6.4.1.6 Selection of Repair Materials
Proper selection of repair materials is a critical step towards successful repair of concrete [72]. Experience has shown that materials that are not compatible with concrete can fail prematurely, even if the repair material characteristics are superior.

One of the most important materials used in the repair of concrete is the patch material itself. Experiences with epoxy and other resin-based materials have not yielded favorable results. Currently, the state of the art in repair materials is more conventional proprietary cementitious repair mortar that contains various additives to improve performance. Among the advantages of the proprietary repair mortars are the exact proportioning provided by the bagged materials and better quality control. In addition, such bagged materials are more suitable for use on high-rise facade repairs where, typically, small quantities of repair mortar are used at one time.

The most common additives found in repair mortars are corrosion-inhibiting admixtures (to reduce the potential for future corrosion of reinforcing steel), shrinkage-compensating materials (to reduce the potential for shrinkage cracking), polymer modifiers (to reduce permeability and increase bond strength to the substrate), and accelerators or retarders (to control material set time).

Although sophisticated proprietary repair mortars have been used successfully in the past, conventional concrete materials have also yielded excellent performance for the past several years. Conventional concrete mixes propose lower cost and better suitability for high-volume applications.
When selecting a repair mortar for a specific application, one should consider the following attributes of the material:

- **Compressive strength and modulus of elasticity**: It is desirable to specify repair materials with compressive strength and modulus of elasticity similar to those of the substrate material. This is more critical when performing structural repairs where the patch material will act compositely with the remaining section of the member.

- **Bond characteristics**: Durability of concrete patches greatly depends on their bond to the substrate material. Therefore, careful consideration should be given to the ability of the repair mortar to bond to the substrate material.

- **Shrinkage**: Another important factor in the durability and performance of a patch is the shrinkage potential of the materials. When placed in the confines of a concrete member that has undergone most of its drying shrinkage, any shrinkage of the repair mortar will result in cracks that can adversely impact its durability.

- **Permeability**: If the repaired areas of concrete are susceptible to airborne chlorides (such as on buildings along coastal areas), repair materials with lower permeability, will be desirable to reduce the rate of chloride migration to the reinforcing steel. Lower permeability of the repair materials is also desirable to slow the rate of water penetration into the repaired area and the reinforcing steel.

- **Corrosion protection**: The selected repair materials should provide adequate protection against future corrosion of the embedded reinforcing steel and adjacent areas. Some of the proprietary repair mortars available on the market today incorporate corrosion-inhibiting admixtures for this purpose.

- **Coefficient of thermal expansion**: The coefficient of thermal expansion of the repair material should be similar to that of substrate material. Lack of compatibility of the coefficients of thermal expansion can lead to the development of high stresses along the bond line between the patch and the substrate and may ultimately result in failure of the patch.
Resistence to deterioration due to freeze-thaw cycles: In colder climates, exterior building elements can undergo several freeze-thaw cycles each winter. Exposed balcony slab edges and overhangs are particularly susceptible to such degradation. As a result, the selected repair materials should have good resistance to freeze-thaw degradation.

Aggregate size: The aggregate size used in the repair mortar should be compatible with the patch geometry. Most proprietary patch materials are formulated with fine aggregate only (sand). The use of such materials in large patches will result in excessive shrinkage, which in turn can lead to cracking of the patch. For this reason, most repair mortar manufacturers will indicate a maximum recommended application thickness for their products. Conversely, large, coarse aggregate particles are not suitable for small repairs where patch thickness is small or the clearance between the reinforcing steel and the substrate concrete is small.

Workability and set time: The workability of the repair mortar should be consistent with the placement methods used. For example, if the dry patching method is used for placement, a stiff material is required. On the other hand, when the form-and-pour method is used, a more flowable material should be used to facilitate consolidation. Setting time can also be an important consideration, since the repair materials are typically lifted to the patch location via scaffolding after they have been mixed on the ground.

Appearance: Although most patched areas are ultimately covered with a decorative coating, some concrete patches will be left uncoated. In such cases, the texture and color of the patch should resemble the adjacent materials. Some patch-repair mortar manufacturers offer custom blending of their products with color pigments.

When selecting repair materials, consideration should also be given to the need for bonding agents. In the author's experience, the popularity of bonding agents has diminished over the years. This may be due to the marginal benefits offered by the bonding agents, the restricted number of
failures because of their misuse, and the improvement in bond value between state-of-the-art repair mortars and the substrate concrete. The purpose of a bonding agent is to improve the bond between the repair mortar and the substrate concrete. Most common types of bonding agents include cement slurry, epoxy resin, and polymers. Although these bonding agents can improve bond values between the repair mortar and the substrate, there is no substitute for proper surface preparation and application practices. The misuse of bonding agents can also lead to bond failures. For instance, if an epoxy bonding agent is used prior to the erection of the formwork and sufficient time elapses before the repair mortar is placed, the epoxy bonding agent can harden and instead become a “bond breaker”. For this reason, if a bonding agent is specified, consideration must be given to its method of use, set time, etc.

Another repair material that needs to be selected properly is the corrosion protection coating on the reinforcing steel elements. Various protective coatings include zinc-rich coatings, cementitious coatings, and epoxy coatings. All of these have shown various degrees of success. Each has advantages and disadvantages. The selection of the reinforcing steel coatings should depend on compatibility with other repair materials, ease of application from a swing stage, curing time, and the level of corrosion protection.

### 6.4.2 Patching Techniques and Materials

Over the years, several repair methods have been used by the concrete repair industry [72]. Based on the observed success of such repairs, the following repair techniques and sequence have evolved:

#### 6.4.2.1 Identifying Delaminated Areas and Extent of Required Concrete Removal

Delaminated concrete on building facades is typically identified using a hammer tapping method. Although a trained worker can easily identify delaminated or unsound concrete with the hammer tapping method in a
majority of cases, identifying deep delamination or voids in concrete may require more sophisticated methods [72].

Once the delaminated areas are identified, they should be marked immediately so that they can be verified by an engineer, architect, or qualified inspector.

6.4.2.2 Concrete Removal/Rough Demolition

Once the delaminated or unsound areas of concrete are identified, the concrete in the affected areas should be removed [72]. On high-rise facade repair projects, concrete removal is typically performed using pneumatic chipping hammers. The use of chipping hammers in excess of 15 pounds is typically avoided to prevent excessive substrate bruising, which can occur when chipping hammers cause micro-cracking of the sound concrete. Excessive micro-cracking results in a weakened concrete zone along the bond line, where bond strength is crucial.

Concrete removal should always extend into sound concrete without excessive removal of sound areas. In most cases, the extent of concrete removal can be determined only during the rough demolition process. An experienced worker should be able to adjust the patch geometry depending on what is found during concrete removal. Sometimes, lightly corroded reinforcing bars can be encountered several inches past the perimeter of the delaminated area. Here, the affected areas should be removed until clean reinforcing steel is encountered. Current industry standard practices dictate that concrete be removed around the entire perimeter of corroded reinforcing steel so that the affected rebars can be completely encapsulated in repair mortar.

Concrete removal should be performed so that large variations in patch depth are avoided. Also, the overall geometry of the patch should be simple (i.e., square, rectangular, etc.) with no re-entrant corners. The patch geometry has a significant influence on cracking of the repair mortar and its durability.
6.4.2.3 Saw Cutting Patch Perimeter and Surface Preparation

After the rough demolition process, the perimeter of the patch should be well defined by saw cutting around the entire perimeter of the patch [72]. The saw cut will provide a straight edge for the repair mortar to bond to the substrate concrete and will prevent feather-edging the repair mortar. The depth of the saw-cut is typically 1/2 inch; however, the depth of saw cut should be reduced where reinforcing steel is encountered. On small patch repair areas where mechanical anchoring of the patch with reinforcing steel is not used, the saw cuts should be made at a slight angle to form a dovetail shape for the patch. This will mechanically lock the repair mortar in place and prevent spalling if a loss of bond occurs. Surface preparation of the substrate concrete should include removing all damaged and unsound concrete that is left by the rough demolition process.

6.4.2.4 Reinforcing Steel Repairs

Since most concrete repairs on high-rise facades are necessitated by reinforcing steel corrosion, repairs to the reinforcing steel are typically needed [72]. At a minimum, reinforcing steel repairs should consist of removing all corrosion products around the entire perimeter of the affected bars. This is performed using sand blasting or water blasting methods. However, in some areas where sandblasting or water blasting causes containment problems on the ground, wire brushing using power tools may also be used. Regardless of the method used, cleaning of the reinforcing steel bars should render them completely free of corrosion products.

If reinforcing steel corrosion has resulted in significant loss of bar diameter, a qualified structural engineer should review the patch area and determine if there is a need for supplemental reinforcing. Where supplemental reinforcing is required, it can be coupled to the existing bars using mechanical couplers or simply lapped adjacent to the affected bar.
In some cases where re-bar congestion in the patch will prevent proper placement and consolidation of the repair mortar, some bars should be removed. Once again, a qualified structural engineer should determine whether selective removal of reinforcing steel will have an impact on the structural integrity of the member.

Since most concrete repairs do not act compositely with the existing member, supplemental reinforcing steel may be unnecessary in some cases. However, supplemental reinforcement is typically added to provide mechanical anchorage for the patch. This is undertaken to prevent spalling of concrete from the facade, a serious safety issue, in case of loss of bond between the patch and the substrate concrete.

Supplemental reinforcing is typically installed in substrate concrete using adhesive anchoring systems. Where supplemental reinforcing is used merely as mechanical anchorage for the patch, it can consist of 6 mm-diameter stainless steel threaded bars that can be bent and formed easily on a swing stage.

After repairing reinforcing steel and installing supplemental reinforcement, a corrosion-inhibiting coating is applied over the exposed steel bar surfaces.

The most commonly used reinforcing steel coatings consist of epoxy coatings, zinc-rich coatings, and cementitious coating. Care should be taken to avoid the application of the re-bar coating on substrate surfaces, as it can serve as a bond breaker. Care should also be taken to ensure that the entire perimeter of affected bars is coated properly. A routine check of coating application should be made with an examination mirror to inspect areas that are not visible.

Another consideration in performing reinforcing steel repairs is the possibility of galvanic corrosion. For this reason, contact between dissimilar metals should be avoided.

### 6.4.2.5 Final Preparation

The final preparation of the patch cavity, including cleaning and coarsening the concrete surface and making final modifications to the
patch cavity geometry, is usually executed along with cleaning of the embedded metals using sandblasting or water blasting approaches [72]. It is important to note that one cannot implement sandblasting or water blasting of the patch cavity after applying of corrosion resistant coatings on the reinforcing steel, and additional corrosion protection planned must be implemented at this stage.

6.4.2.6 Form and Pouring Technique

Presently, most of concrete patch repairs on High-Rise Buildings are implemented using the form-and-pour technique, which includes nearly all of the patches placed on horizontal surfaces, such as balcony and overhang top surfaces, and vertical surfaces, such as columns and walls [72]. In rare cases, cavity is formed and the repair mortar is pumped from bottom of the formwork to place the mortar. This technique offers certain advantages over straight placement methods even though it is rare due to its logistical requirements.

The repair cavity should be formed, unless the repair mortar is placed by a dry-pack or concreting technique. Forming of the repair cavity is similar to conventional concrete placement. Openings should be formed at the top of the patch when forming patches on vertical surfaces for conventional placement (pouring). Openings at the top and bottom of the patch should be made when pumping technique is used to place the form. Forms should be braced using post shores and other additional members, depending on the patch geometry.

6.4.2.7 Substrate Wetting, Patch Placement, and Finishing

Normally the surface is in SSD (saturated surface dry) condition to reach finest bond between the surface and the repair mortar[72]. This is why the patch cavities should be wetted before placing the repair mortar to saturate the surface. However, before placement of the repair mortar to attain surface dry conditions, adequate time should elapse. Afterwards, one places repair mortar in the cavity or formed areas. Placement should be
instantly followed with finishing of the patch surfaces if dry-pack technique is performed.

6.4.2.8 **Curing and Form Removal**
For ideal strength improvement and for decrease of the cracking related to drying shrinkage, all cementitious materials need appropriate curing [72]. In small concrete patches of building facades, due to the higher potential for a limited patch to develop shrinkage cracking, curing has a more significant role. Before the material gains adequate strength to withstand cracking, to reduce the shrinkage cracking, the curing process should prevent evaporation of moisture from the repair mortar surface. The curing procedure should prevent exposure of the repair materials to low temperatures, in cases materials are placed in colder temperatures. Usually, satisfactory protection is offered by well coated plywood forms, for patch surfaces that are not exposed to aggressive climates. To prevent rapid drying of concrete, after removal of the forms, plastic sheets or a suitable curing composite are applied over the patch surfaces. The application of curing compounds should be avoided, if a coating is required over the patch surfaces. Curing composites should be eliminated from the surface later by grinding or sandblasting, if applied. However, it is necessary to always abide by the curing time and techniques recommended by the patch material producer.

6.4.2.9 **Surface Grinding**
Patch surfaces should be inspected for deficiencies after curing and voids should be filled with a cementitious mortar [72]. Usually, to provide a smooth transition between the patch surface and nearby concrete, grinding of the patch is required around the edges.

6.4.2.10 **Coating Application**
Typically, repaired concrete surfaces on high-rise facades receive an application of coating to provide a uniform appearance, since redoing the painting and texturizing the existing concrete is not practical [72]. Some
coatings will also deliver resistance to carbonation and reduce surface permeability of the concrete and make it less probable to draw or suck water by capillary action, besides their aesthetic benefits. Although there are several waterproofing coating systems available for concrete façade application, one should not only rely on coatings to deliver waterproofing on concrete surfaces since these materials have shown varying degrees of success in concrete surfaces waterproofing characteristics.

When selecting coatings for concrete facade surfaces, one should consider factors such as the purpose of the coating (waterproofing, aesthetics, etc.), existence of coating systems that will remain on the surface, transport properties of new coatings and sufficiency of their vapor transmission and their limitations (temperature, curing, moisture conditions).

Acrylic coatings, elastomeric coatings, and cementitious coatings are the most popular types of coating systems for concrete facades. Except for the situations where cracks have been verified to be non-moving, usually, noticeable cracks should be sealed with an elastomeric sealant before applying the coating. However, one should be cautious in application of a coating over sealant because if the sealant and coating are not well-matched, movement of plasticizers from the sealant into the coating could cause staining of the coating.

6.4.3 Repairing Cracks in Concrete

Cracks on a barrier type concrete facade can lead to water penetration to the building interior or to the reinforcing steel, thus, typically, all visible cracks on a barrier type concrete facade should be sealed properly [72]. One can allow proper movement of the joint without applying excessive stresses on the sealant by routing of the cracks that will create a reservoir. To avoid three-sided adhesion, the bottom sides of each sealant reservoir surfaces should be treated with a bond breaker. It is essential to check the compatibility of the sealant with the concrete coating system before selecting the sealant. In several cases, silicone sealant extrusions are utilized to cover the cracks which would cause the cracks to be more visible, even after application of a coating. Injecting epoxy or chemical
grout and applying a coating system that can bridge the crack are other methods of crack treatment. Using these methods is limited for performing repair for so called “non-moving cracks”.

6.4.4 Quality Assurance
Durability of concrete patch repairs on high-rise facades is highly dependants on good workmanship and successful application of each of the techniques introduced in this chapter [72]. Therefore, at various stages of the work a quality assurance program is needed for durable repairs. There are a number of stages that need repair area inspection. These stages are as follows:

6.4.4.1 Initial Sounding and Identification of the Patch Area
An experienced and qualified structural engineer or inspector should verify the operations performed by workmen to ensure that all concrete surfaces are properly sounded and delaminated areas are identified.

6.4.4.2 Rough Demolition
After completion of the rough demolition, an inspection procedure should be carried out to guarantee that all unreliable materials have been removed, and also to check the geometry of the patch, and to guarantee that no further deterioration is present beyond the patch perimeter [72]. At this stage, it should be identify whether supplemental reinforcing steel is needed, and the contractor should be advised about the location and number of supplemental anchors.

6.4.4.3 Final Surface Preparation
Immediately, after completion of the surface preparation and before placement of any forms, an inspection should be conducted to check the quality of installation of supplemental reinforcement, cleaning and coating of the existing reinforcing steel, and surface preparation [72].
6.4.4.4 Form Removal
After removing all forms and initial curing, another inspection should be performed to check all patch surfaces for cracking or improper consolidation and also to verify whether the parts are sounded properly [72]. All defects should be highlighted or marked for corrective measures. At this stage, all remaining cracks which need to be routed and sealed and also all patch surfaces requiring grinding and filling should also be marked.

6.4.4.5 Final Inspection
After completion of crack repairs and coating application, a final inspection of the repairs should be performed to guarantee proper application of the coating and crack repairs [72].

6.5 Summary
Building facades deteriorate during their service life due to imposed mechanical and environmental loads, along with the various aggressive environmental deteriorating mechanisms. Therefore, to extend the service life of facades, planned maintenance must be executed. This maintenance strategy is mainly divided into preventive and corrective maintenance. Preventive maintenance generally involves cleaning and regular inspection of the facade. Cleaning approaches restore facade systems to their original aesthetics as well as eliminating chemical salts and impurities that can deteriorate the structure. It also allows specialists to have a better visual inspection. Periodical visual and detailed inspections must also be performed on facades to ensure the integrity and safety of the systems and in case inefficiencies are detected, corrective maintenance strategies must be applied in accordance with the type of deficiency.
Chapter 7  Facade Failure: A Case Study

7.1  The Peel Street Incident

On July 16, 2009, Léa Guilbeault was celebrating her 33rd birthday, dining with her husband at a table in north-west corner of a Downtown restaurant terrace when she was struck and instantly killed by a 320 kg precast slab of concrete falling off the Downtown hotel façade located on Peel Street, near the corner of De Maisonneuve Boulevard [73].

A slab of decorative concrete came crashing through the atrium window of Mikasa Sushi Bar, located on the ground floor of Marriott Hotel, from 18 stories above (Figure 7.1). Montreal police said the victim's husband was transferred to hospital due to injury and severe shock. As a precaution a section of Peel Street, , was closed for several hours while the fire department inspected the building.

![Figure 7-1 The scene where a slab of concrete fell from the 18th floor of a downtown hotel killing a woman and injuring her husband in Montreal Thursday, July 16, 2009 [74]](image)

At first it was not clear what caused the 320kg slab, about 1 meter by 1½ meters in surface area, to detach from the building façade. Fire officials suspected that a weld holding the slab of concrete had become loose and had broken due to water infiltration. Police considered it to be an accident and they did not suspect any foul play. However, police and city engineers
as well as the fire department continued to investigate the scene on the following Friday morning. Also, Québec’s Régie du bâtiment, the provincial board in charge of building safety, was slated to meet the same day to determine the cause of the accident.

Structural engineer Normand Tétreault, who is a concrete specialist, said that in his 30-year career in Montreal, he has seen only one other incident similar to this one, and that was at Olympic Stadium [75].

After examining the building from a distance using binoculars. Mr. Tétreault stated that there appears to be corrosion of anchors of the concrete panels, and possibly some anchors were missing; however this can only be determined by a detailed inspection of the building (Figure 7.2).

According to Québec law owner of the buildings are held responsible for the safe upkeep and maintenance of their buildings. In this case, owner of the building, the BCF Corporation, was required to hire engineers to undertake a full inspection and proceed with any repairs and replacement of the concrete panels[76].

According to Ronald Dubeau, deputy chief of the Montreal Fire Department, the engineer representing the owner presented a schedule for inspection to the Régie du bâtiment and Montreal’s Ville Marie borough. After the schedule was accepted by both sides, they started visual and technical inspection of the panel. Spokesperson for Montreal’s Ville Marie borough, Jean-François Sonier, said the owner of the building was responsible for ensuring that entire façade of the structure is secure before the street was reopened to traffic [77]. This required inspection of hundreds of decorative concrete panels on the façade facing the street. When this task was completed, both reports from the owners and the city engineers were transferred to the Régie du bâtiment du Québec for review.
7.2 Coroner’s Report: Analysis and Cause of the Incident

7.2.1 Definition of Building Situation

The hotel in reference is located Downtown Montréal and has 24 floors and 190 rooms; it is the 87th tallest building in Montreal. Generally, these high-rise buildings are constructed with an inner structural system to carry loads from upper floors because the outer walls do not have the required load carrying capacity [79].

No rehabilitation work has been done on building façade except for minor caulking repairs between the joints and the panels, which was performed in March 2000.

The façade is composed of diverse concrete panels with different geometries that are joined together, and give the building a unique architectural appearance. The most remarkable element of the façade is the well-made exterior of the panels that underline the windows. These panels are connected to the frame of the building by welded joints. One Caulking joint was used in between the panels to prevent the rain and humidity from penetrating the façade (Figure 7.3). Normally caulking exposed to aggressive environment must be refurbished periodically, otherwise
rainwater and moisture can infiltrate and accelerate the corrosion of embedded steel rebars and/or the welded connections.

7.2.2 Partial Details of the Incident

The panel in question had fallen as a single block from the western part of the 18th floor façade on July 16, 2009 (Figure 7.4). Despite a corroded reinforcing steel, the concrete had not been crumbled or detached from the connection [79]. Small cracks were observed on the panel that did not impair the integrity of the block. In fact, the majority of the damage observed from panel were probably secondary due to the fall. Also, it was confirmed that the concrete quality was not the reason of this accident.

After performing a detailed inspection on the panel, it was determined that the main reason for this tragic accident was the use of insufficient number of connections to attach the panel to building frame. According to expert
observations, four connections were needed for proper attachment of the precast panel to the building frame. However, although the panel was known to have four attachments, its installation was done in a way that only two of these plates were contributing in carrying the imposed loads. In fact, absence of welding or traces of trauma in two plates situated in corner side of the building, strongly suggest that these two attachments never contributed to the load resistance. Only the attachments on the south corner of the window were engaged (Figure 7.5).

Figure 7-5 At left: Upper south corner of the panel. A rebar can be distinguished that was formerly welded to a plate which is now detached from the panel. Corrosion traces indicate the place where once the plate stood. At right: plate remained attached near the window of 18 floor. The arrow points to a deposit of slag at welds [79].

Since the cause of this accident was not the quality of concrete, but the way the panel was attached to the wall frame, the cause must be attributed to the installation work that did not respect the specifications of either the designer, or the manufacturer.

Why half of the attachments, specified by the designer were never implemented? In fact, all the panels on building façade were installed similarly with the same two connections. It seems that the installation of panels could not be simply done in accordance to what was predicted in the original facade design. Although these side plates were attached to the panel, the brick coating of lateral wall framing did not allow the welding of two attachments. The reason is the panel was placed against the wall and
these plates were too close to the edge and came to rest on the lateral framing, which could not serve as an anchor (Figure 7.6).

Figure 7-6 The lateral coating did not allow the welding of the two attachments on this side. The picture shows the brick was used as a coating material [79].

Instead of finding an alternative, they simply neglected connecting these fasteners, as was required by design. Installers relied too much on an anchor pin placed on top of the panel and one piece of rebar at the bottom of panel which were placed respectively by a rebar from the lower part of the panel above, and an anchor pin from upper part of the panel below. In the experts’ opinion, this mechanism of holding is nothing but a temporary way of easily maintaining panels in place until the final welding can be implemented.

At the interior corner (near the window), there were two attachments and the procedure of installation appears to be somewhat unusual. Only the upper attachment was welded to the frame wall; the lower attachment was welded to a steel angle linked to top of the panel below. Though this mode of attaching is not without precedence, it certainly does not represent the best way of doing it (Figure 7.7).

In the lower and upper corners, the welding implemented had a doubtful quality, containing impurities, imperfections and porosities. This resulted in water accumulation, and with time, development of advanced corrosion. In this case, mostly, there was presence of slag, a crust that forms on the welding bath. Not removing this slag suggests negligent work since it illustrates that the person performing the welding operation had not
visually inspected the quality of his work. In addition, after years, the slag contributes in maintaining humidity in the welded zone.

![Figure 7-7 Panel at issue](image)

The failure that caused this tragedy did not develop at the attachment between the plate and weld. The observations showed that it was the weld, performed at the factory between the steel rebar and the welding plate, which had become loose. This explains why after the falling of concrete panel, the plate that was welded to the panel was still fixed to the frame near the window and was detached from the fallen panel. At the failure point, slag was found over welding faults (such as lack of fusion between the rebar and the plate) and also lack of weld penetration was apparent. Only a few points attached the filler metal plaque to the rebar.

It is opinion of the experts that at a given time, the upper corner fastener that was already weakened by the poor quality welding, had become exposed and was severely corroded. As a result of the loss of material due to corrosion, it was no longer able to resist the panel weight. The panel could be dislodged at the same time the attachment failed, but it is also possible that the panel movement has occurred after a period of time. In any case, by displacing and switching, the panel pivoted around the bottom corner near the window and twisted the lower anchor before tearing off
completely (Figure 7.8). With the forces present, this tear would have probably occurred anyway, but it could have been accelerated because a portion of the rebar at this level was already broken. In fact, in the factory, before pouring the concrete, the rebar had been heated and bent to allow the plate to weld. This operation seems to have caused a crack along the outer wall of the fold (the side in tension) leading subsequently to corrosion at this location. Moreover, the rebar had appropriate composition and quality for welding.

![Figure 7-8 Anchoring of the south bottom corner of panel is intact although it is twisted](image)

**7.2.3 Summary of the Case**

Normally, the panel should be fixed to the building frame wall in four places. Two of these attachments were never implemented, since the plates were located just above the brick that decorated the lateral wall of the building. In the south corner, an attachment was broken when an internal panel weld (coated with concrete) yielded leaving only one attachment for holding the panel in place. The applied forces were more than what this one attachment could support which caused the connection to twist before finally detaching at the time of falling. Corrosion was noticed in the attachments. This was probably a contributing factor but according to experts’ judgment, the accident would not have occurred if the panel was attached as it was designed to be attached [79]. Facing this observation, it
is normal to wonder how come this accident did not happen sooner and it took forty years to occur!

According to Jacques Ramsay, the coroner who was responsible for reporting the cause of the incident to Régie du bâtiment du Québec, the July 2009 death of Lea Guilbeault was preventable and recommendations can be made to prevent similar tragedies. According to the coroner, the blame for the death of Lea Guilbeault, lies with the shoddy construction and a complete lack of building maintenance. Jacques Ramsay noted in his report that the hotel was built in 1969, before the building codes were widely adopted, and that the building facade was last inspected on March 2000 for minor caulking issues. He also claimed that the Régie du bâtiment, Quebec’s building inspection board, inspects buildings after receiving complaints, which are usually only made when a part of a building fails [74].

A positive aspect of the coroner report was proposal of Bill 122, because of the design flaws and poor quality of workmanship, including insufficiently welded elements that will eventually yield under combined effects of mechanical forces and corrosion. He suggested to inspect the high-rise building construction site for immediately correction of all the differences between the design specifications, the materials and the method of construction used and also to perform periodic inspection and maintenance of facades more than 10 years old to be inspected every five years.

### 7.3 Lessons Learnt

Besides examining the issues related to the Lea Guilbeault tragedy, the October 20, 2010 coroner’s report indirectly questioned the way of life in the society and how the organizations responsible for citizens’ security regulate and operate to ensure their safety and security. The violent tragedy is not just about corrosion and failing of anchors and falling of a slab of concrete, it is more about the many failings that led to this tremendous loss to the family in particular and the society in general. There is normally a delay in learning from the experiences of other similar cities who have suffered similar tragedies and have adopted
adequate rules and regulations to protect the citizens from such tragedies. The Greater Montreal Area municipalities should have learned from the experience of similar cities and should have adopted new by-laws and strong measures to mitigate risks before the occurrence of another such tragedy.

Based on the experience in major U.S. cities, Dr. Saeed Mirza, Professor Emeritus of Civil Engineering at McGill University, recommended the following guidelines to the City of Montreal for buildings with precast concrete or other type of façades [80]:

- Building owners should undertake inspection of facades at regular two-year intervals and undertake routine maintenance and repairs with more detailed examinations performed at regular intervals.

- The owner of a building, that finds any unsafe condition in the façade which endangers the public, should inform the city and should take immediate action to have an experienced professional inspect it and report to the city, while undertaking the repairs suggested by the professional. Depending on façade construction type, Professor Mirza recommended critical, close-up or detailed inspection on the building with scaffolding and other necessary means:

  I. Façades reinforced, or in contact with non-corrodible materials, such as stainless steel and aluminum, or with corrosion-resistant materials, such as galvanized and epoxy-coated steel, should be inspected every eight years.

  II. Façades reinforced or in contact with corrodible materials, such as carbon steel, uncoated reinforcing steel bars and uncoated steel connections) must be checked every four years.

  III. Façades primarily secured to the substrate by adhesive bond or with masonry headers are recommended to be inspected every eight years.

- The city should maintain record of the results of all inspections throughout the service life of the building and should assess the safety of street-level facilities and pedestrians by consulting these records.
On 18 March 2013, the Building Board of Quebec (RBQ) announced the adoption of regulations to improve security in buildings [81]. These regulations introduced new standards of maintenance and operation for buildings; the requirements for maintenance and inspection of facades and parking are presented in the Building Safety Code of the City of Montreal [82]. These new requirements meet several recommendations made by the Coroner, Mr. Jacques Ramsay, to avoid and/or eliminate fatal accidents.

The regulations to improve security in buildings with provisions for inspection and maintenance of building facades with a height of 5 floors or more above ground, as follows:

- The facades of a building shall be maintained to ensure safety and prevent the development of any hazardous conditions (any condition in which an element of a building facade may detach from the building or fall and cause personal injury).

- During its existence, the building must be recorded in a register available on Régie. This record shall contain information or documents related to the building, such as owner contact information, copies of plans designed for construction and execution work (if available), any photography, document or information on modifications that have been made; description of repair, modification or maintenance that has been done on facade elements and verification reports of facades.

- Every 5 years, the owner must hire an engineer or architect to receive a verification report indicating that the facades of the building is not in a dangerous condition, and if necessary, make appropriate recommendations to correct the faults that have contributed to the development of hazardous conditions.

- If any unsafe condition is detected during verification, or otherwise the owner must:
  I. Notify the Authority without any delay;
  II. Implement immediately the emergency measures to ensure the safety of the occupants and the public;
  III. Within 30 days, notify the Board of the description of the remedial work prepared by an engineer or architect, which needs to be
performed to eliminate the dangerous condition, for receiving an approval on the schedule of remedial work;

IV. Ensure that the work is carried out in accordance with the described plans and schedule;

V. Obtain a verification report when the repair work is completed, confirming the safety of the building façade

VI. Forward to the Board a letter signed by the engineer or architect, confirming that all remedial work are completed to his satisfaction and that there are no more hazardous conditions.

- When the engineer or architect responsible for verification detects hazardous conditions, he shall notify the owner and the Board of the emergency measures that should be implemented immediately to eliminate these unsafe conditions.

- To produce the verification report of the building façade, a review of each façade component must be carried out. The choice of verification methods and controlling tests is the responsibility of the engineer or the architect.

These Standards apply depending on the year of construction that target the health, safety or the protection of buildings against structural damage as follows:

- The owner of a building must obtain a report of verification for the façade no later than the tenth anniversary of the date of its construction. However, if the building is more than ten years of age on March 18th 2013, they must obtain a verification report according to the following schedule:
  
  I. If more than 45 years, within 24 months from this date (March 18, 2013)
  
  II. If over 25 years but less than 45 years, within 36 months from this date
  
  III. If over 15 years but less than 25 years, within 48 months from this date
IV. If over 10 years but less than 15 years, within 60 months from of this date

- Thereafter, the owner shall obtain a report verifying the safety of the building facade within 5 years of production of the last report.

The City of Montreal has adopted most of the recommendations made by Professor Mirza, excepting for some steps needed to deal with different types of connections for these precast concrete facades to the building structural frame. Now the City must implement the ordinance most stringently to ensure that such accidents that killed Lea Guilbeault do not occur due to lack of regular inspections and maintenance, and if needed, special corrective maintenance with the assistance of a specialist.

7.4 Summary

Since 1978, nine major U.S. cities including New York, Boston and Chicago, have accepted by-laws, requiring inspection of building façades [80]. The approved laws vary extensively in efficiency and the level of enforcement. Chicago and New York approved the ordinances about 30 years ago, because of some fatal accidents to pedestrians.

A façade is the non-load-bearing system on one or more sides of a building, designed to promote its aesthetic, and technical performance, such as energy efficiency. Façades can get deteriorated and damaged over time, with the rate of deterioration increasing with age. In case of extreme damage, part of façades can detach from the building and fall to the sidewalk, as was the case with the Peel Street accident which killed Léa Guilbeault who was dining in a terrace sushi bar in Downtown Montreal.

Most façade problems are related to three causes: corrosion of steel, concrete degradation and other defects caused by lack of quality control in design, construction, and maintenance. However, in Montreal incident concrete degradation was not an issue and poor construction quality and lack of inspection of the façade, along with steel corrosion caused the tragic failure.

To assess the condition of a façade, the engineer must be specialized in building structures and envelopes. Along with an inspection of the
structure, he should review the previous reports, maintenance and repairs records, and speak with building maintenance staff and engineers. The extent of this survey depends on the façade’s condition, maintenance, age and owner's needs.
Chapter 8  Summary and Conclusions

Facades are non-load bearing structural elements that are important, both structurally and architecturally. From an architectural perspective, facades are the soul of the building as they set the tone for the rest of the building and they have an important role in its aesthetics. Technically, facades are barriers that prevent the aggressive exterior environment from entering the “artificial” interior environment. They have a major role in building energy savings as well. However, like any structure they will degrade and lose their functionality over time. Although deterioration of facades is an inevitable phenomenon, one can extend their service life to an optimum point (balance between the maintenance needs and repair costs of facades), by considering durability issues in design, construction, operation, maintenance and repair of the façade, and eventually its decommissioning and replacement at the end of its service life.

Various types of materials and techniques are currently available for facades. However, since most of façade failures around the world have been related to concrete durability issues, this research has focused mainly on precast concrete façade systems.

To design a façade for durability, one must consider all deterioration mechanisms that will shorten the system service life. Most precast concrete façade deteriorations are related to three causes: steel corrosion (mostly at the connections), concrete deterioration, and structural and other deficiencies resulting from lack of quality control and supervision in design, construction, and maintenance. Consequently, the designer must focus on detailing of the system to minimize the probability of premature degradation of components and elements used. According to the National Building Code of Canada, the main functions, such as resisting structural and environmental loads, heat and air transfer, preventing water and moisture infiltration, acoustics and other related concerns, must be considered in façade design. Prefabrication of concrete panels in a pre-casting factory with a very high degree of quality control, reduces the risks
involved in poor materials and component production. A high standard of workmanship is needed to minimize the deteriorations involved in poor installation of the panels. Therefore, supervision by a specialist is quite important during all construction activities to ensure that the installation work is performed according to the original design and specifications.

During its service life, a façade is influenced by mechanical and environmental forces, and aggressive environmental deterioration mechanisms, which cause it to degrade gradually. If serious deteriorations take place before the end of the service life, and no maintenance work is performed to correct the deterioration, it may lead to detachment of façade component from the building which may causes social and economic damages as well as injury or death to the pedestrians. Therefore, planned maintenance must be performed to ensure safety and serviceability of facades. This planned maintenance consists of cleaning, inspection, and if needed, corrective maintenance. In the absence of these activities, the façade element would continue to deteriorate, and finally its repair/rehabilitation could become extensively expensive, requiring replacement of the façade. Periodical cleaning restores the façade aesthetically to its original condition, along with removal of the deteriorating salts or ions. It will also enable the inspectors to perform a better visual inspection.

To ensure safety and serviceability of facades, and to prevent any tragic accidents because of premature façade failures, some major cities in US, have adopted a set of by-laws requiring the building owners to perform planned inspection on their facades. In 2009, Professor Mirza of McGill University had made a few specific recommendations to the City of Montreal to ensure and enhance the safety of concrete building facades with different types of connectors (Chapter 7) [80]. Very recently, on 18 March 2013, the City of Montreal has adopted a detailed façade ordinance, aimed at buildings with varying heights and ages. As emphasized by Professor Mirza, the City of Montreal emphasized regular inspections and routine maintenance and repairs at regular two-year intervals, with more detailed examinations performed at specified time intervals. If the owner of a building finds any unsafe condition in the façade, and danger to the
public, he should inform the City and take immediate action to appoint an experienced professional for inspection and to report the implementation of any proposed repairs to the City. Depending on the construction type, critical, close-up or detailed inspection with scaffolding and other means should be performed on the building. Professor Mirza made some specific recommendations in this respect.

The city should keep a record of the results of all inspections throughout the service life of a building and should assess the safety of street-level facilities by consulting these records. Corrective maintenance would be needed, only if a detailed inspection reveals that rehabilitation work is needed. Then a specialist appointed, after consultation with the designer, should decide the best rehabilitation process for restoring the building façade to its original condition.
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