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Corrosion Prevention in Historic Concrete – Monitoring the Richards Medical Laboratories

Abstract
This thesis proposes to analyze current non-destructive techniques for the early detection of factors leading to reinforcement corrosion as part of a preventive conservation strategy for reinforced concrete. These techniques were theoretically evaluated for their efficiency and compatibility of use on concrete surfaces that require a minimum intervention approach, such as found on historic Modernist buildings where exposed concrete is considered an integral part of their significance. This study considered a real case scenario; the Alfred Newton Richards Medical Research Laboratories (Louis I. Kahn, 1960). The corrosion mechanism occurring on this building was assessed to assert its probable causes and the most appropriate method of investigation.

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CORROSION PREVENTION IN HISTORIC CONCRETE – MONITORING THE RICHARDS MEDICAL LABORATORIES

Ana Paula Arato Gonçalves

A THESIS
In
Historic Preservation

Presented to the Faculties of the University of Pennsylvania in
Partial Fulfillment of the Requirements of the Degree of

MASTER OF SCIENCE IN HISTORIC PRESERVATION
2011

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____
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To my mother (in memoriam) who always supported my love of art,

and to my father who has always supported me no matter what.

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Special thanks are due to my wonderful classmates, especially the conservation science group. Thank you for keeping me company in many sleepless nights during finals, and for sharing my worries and anxieties. But, above all, thank you for your friendship. I could never have done this without it.

I thank my father for all his counsels and for taking interest in a diagnostic process that does not involve an ailing human being. I also thank my sister for being an example of hard working professional and dedication. I would also like to thank my grandparents for their support and example.

Finally, I would like to thank God for blessing me with the opportunity of working in the conservation of historic buildings.

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Chapter 1 - Introduction

This thesis proposes to analyze current non-destructive techniques for the early detection of factors leading to reinforcement corrosion as part of a preventive conservation strategy for reinforced concrete. These techniques were theoretically evaluated for their efficiency and compatibility of use on concrete surfaces that require a minimum intervention approach, such as found on historic Modernist buildings where exposed concrete is considered an integral part of their significance. This study considered a real case scenario; the Alfred Newton Richards Medical Research Laboratories (Louis I. Kahn, 1960). The corrosion mechanism occurring on this building was assessed to assert its probable causes and the most appropriate method of investigation.

Research for this thesis involved gathering background information that provided a sound base of knowledge for its development. The literature review in Chapter 2 summarizes what has been done in terms of preservation of modern architecture, preventive conservation and developing of non-destructive techniques for evaluating corrosion in reinforced concrete.

This thesis is set on the movement toward the preservation of monuments from the recent past that has taken place in the past twenty years. The architecture produced between the 1920s and 1970s had the Modern Movement as its backbone and included all of its regional manifestations. The initiative to preserve buildings and structures that represent this historic period sprung from the architecture community's realization that some of the masterpieces of the period were under threat. Buildings from this period were (and still are) suffering from the threat of neglect or demolition, because the ever accelerating rate of change in society's needs, especially regarding new comfort and technological standards, rendered them obsolete. However, unlike previous historic periods, the mid-20th century lacks the rarity and nostalgic values that often engage people's support in heritage preservation. Furthermore, the preservation community suddenly found itself faced with the challenge of conserving materials they had never dealt with and projects that seemed to defy the current preservation principles. In this respect there has been a long discussion by preservation professionals on the challenges of preserving both fabric and design intent, which is further explored in Chapter 2.

This thesis also recognizes that it is impossible to dissociate the development of the Modern Movement from the technological advancements in the construction industry of its time. The importance of preserving original materials in Modern Movement heritage is based on this interrelationship. Each branch of the Modern Movement had its own meaning, local significance and spectrum of influence, but they all shared the characteristic of expressing the final embrace of industrialization. This was evident in the collaboration between architects and the construction industry to create new building techniques and materials. Architects and engineers of the period also recognized the new plastic and aesthetic opportunities generated by these innovative building methods.[1] This resulted in buildings and structures that broke away from the traditional building morphology to explore the aesthetic use of structural elements. These elements assumed new forms and their constituent materials were left exposed. Therefore, not only is the image of the Modern Movement associated with the color and texture of these construction materials but also most of these buildings would not have been possible without these new developments.

[1] Addis and Bussell, In: Macdonald, 2003, p.43.

From all construction techniques, reinforced concrete was the most used in this period. The focus of this thesis derives from corrosion being the most common damage mechanism in reinforced concrete. Corrosion's necessary factors (iron, oxygen and water) are ordinarily present in a concrete structure. However, this electrochemical reaction becomes passive in alkaline environments such as fresh concrete. Depassivation occurs when concrete carbonates or if there is chloride contamination around the reinforcement. On the first stage, there are no signs of damage on the surface, but, once there is enough accumulation of oxidation products, the volumetric increase will exert sufficient pressure to rupture the concrete. At this point, damage is finally observable on the surface and will quickly develop into a spall, which can only be remediated by removing the affected areas and by patching. It is important to acknowledge that other damage mechanisms present in the structure can contribute to the factors leading to the initiation of reinforcement corrosion. This deterioration process and its phases are described in detail on Chapter 3, where the data from an investigation aimed at providing comprehensive understanding of concrete characteristics and the corrosion process that takes place in the reinforcement was gathered.

This thesis was developed on the premise that the current state of technological development presents no alternatives to the traditional repair methodology. Traditional patching repair is still necessary when action is taken only after damage is detected on the surface. This results in further loss of the original concrete compromising the historical and aesthetical values inherent in it. This is why a preventive conservation approach is the most adequate for exposed architectural reinforced concrete. It relies on the early detection of the problem and monitoring of its development, so that intervention can take place while the process is still in its initial steps. The goal is to slow the deterioration rate by focusing action on the causes of the problem. If damage is already present, this approach can make repairs more effective by identifying the damaged areas more precisely and acting on the factors that could lead to re-initiation of the deterioration process. A preventive strategy must be based on a comprehensive understanding of the deterioration, its causes and the risk factors present in the building. Therefore surveying historic reinforced concrete buildings to locate and identify these factors is an essential step in implementing a preventive strategy.

However, the present conservation literature contains little on the subject of survey techniques for early detection of corrosion in reinforced concrete. This thesis was developed as an attempt to bridge this gap. Research involved recent articles that analyzed techniques that could be useful in answering the questions raised by hypothesis developed in the diagnosis of corrosion damage mechanisms in reinforced concrete structures. This research was conducted in professional and scientific publications on material science, non-destructive evaluation techniques, concrete and electrochemistry. Preference was given, when possible, to techniques classified as non-destructive and that can be performed in situ. Emphasis was given to providing information on the type of data acquired from each technique, their limitations, and possible adverse effects to the concrete surface. The intention was to inform conservators on the possibilities of these techniques so that when faced with a reinforced concrete structure they will know the appropriate course of action and which specialists to consult. The data gathered in this phase along with an analysis of how these techniques can be combined in order to provide a complete picture of the damage mechanism can be found in Chapter 4.

A preliminary assessment of the conditions found on post-tensioned precast reinforced concrete elements on the façade of the Richards Medical Research Laboratories at the University of Pennsylvania provided a practical case study for this thesis. This case study was selected in order to keep this thesis close to the requirements of practice, while still keeping it broad enough to be applied in other cases. This particular building was chosen because of its well established historical significance and relationship to its concrete structure. In addition, the building has been showing clear signs of reinforcement corrosion on its façades, which had not been diagnosed yet. An analysis of the post-tensioning tendons in the structural elements at the Richards Medical Laboratories was not part of the scope of this thesis due to the specificity of the evaluation techniques that such an analysis would require. Another factor for the election of the Richards Medical Laboratories as a case study was the availability of original documentation at the Architectural Archives and the Facilities and Real Estate Department Archives, both at the University of Pennsylvania.

This methodology was based on the scientific approach to diagnosis proposed by Watt.[2] Therefore, it started with data gathering on the building, which included retrieval of historic and archival data on the building's construction, and in situ observations. Based on this, hypotheses were developed to explain the cause of the damages observed. This analysis revealed a complex relationship between different conditions found in the structure. These new factors prompted a broader investigation of the deterioration mechanisms that affect reinforced concrete. The goal was to determine how they altered the characteristics of the material that resulted in higher susceptibility to reinforcement corrosion. These hypotheses generated questions that need to be answered in order to validate the hypotheses. The knowledge gathered in this thesis' first phase of investigation informed the proposal of an evaluation plan for the Richards Medical Laboratories that intends to confirm the hypothesis formulated. This

[2] Watt, 2007, p.166.

was included in Chapter 5 along with a compilation of all data found on the state of the Richards Medical Laboratories, a description of the conditions observed there and the hypothesis formulated to explain them.

This thesis demonstrates that prevention is the best approach for the preservation of historic reinforced concrete structures, especially when exposed architectural reinforced concrete is involved. A preventive strategy must be based on sound knowledge of the building and diagnosis of the damage mechanisms afflicting it. In the case of buildings with reinforced concrete this requires the use of techniques that are capable of detecting reinforcement corrosion before it has affected the concrete. Therefore, the preservation of monuments from the mid-20th century will depend on conservators getting acquainted with the possibilities and limitations of concrete survey techniques. This thesis is an introduction to this field and an invitation to further research on this subject.

The conservation of reinforced concrete is still in its infancy, if compared to the conservation of other building materials such as stone and brick masonry. However, the quantity of potentially historic buildings that use reinforced concrete and their rapid decay rate urges further investigation in this field.

Chapter 2 - Literature Review

This chapter provides a context for the development of this thesis. The current state of discussions on the subject of Modern Movement preservation provides the theoretical background that supports the need for the development of preventive conservation strategies for reinforced concrete. Preventive conservation has mainly been discussed in relation to the Modern Movement preservation in terms of the importance of implementing cyclic maintenance programs and the need for further development of appropriate techniques for in-depth investigation of deterioration causes. The concept of preventive conservation is presented in order to establish the differences between what is currently considered a preventive conservation approach and what would be necessary to implement this same philosophy in a reinforced concrete building. This chapter also includes an overview of the current state of technological development in non-destructive techniques for reinforced concrete.

2.1. Modern Movement Preservation

During the last decade of the 20th century and into the 21st, there has been an upsurge in publications concerning the preservation of recent heritage including principles, methodology and techniques. The two most prolific organizations represented in this body of publications are English Heritage (the agency that counsels the English government on heritage preservation issues) and DOCOMOMO (an international non-profit organization that advocates the preservation of Modern Movement architecture). Both organizations have responded to the recognition that the legacy of the most recent historic period is threatened by a lack of knowledge among experts on how to deal with the new challenges imposed by mid-20th century architecture.[1,2]

Authors such as Susan Macdonald,[3,4] John Allan,[5] Peter Burman[6] and Theodore Prudon[7] are in agreement that the main challenge that distinguishes the preservation of 20th century architecture from the preservation of more traditional buildings is the difficulty in reaching a balance between design intent and material authenticity. The difficulty lies on the multiple factors that influence this negotiation.

The first factor is the historic proximity to the moment of the conceptualization of the design, which does not grant the time needed for the accumulation of other significant historic layers. Therefore, there is a natural tendency to place more value on the original design and appearance of the building than on the patina of age or later modifications. This argument is often used to justify large scale replacement of original material that has failed to perform as expected, with similar materials that perform better, but maintain the design intent intact.

The second factor is the scale of material failure encountered in 20th century architecture. Buildings of this period often use materials and details that had not passed the test of time and durability that has benefitted traditional building techniques such as carpentry, where current practices have been developed over many centuries of trial and error. As a result, buildings of the recent past frequently present early failures, where preservation or "in-kind"

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1 Guillet, In: Macdonald, Normadin and Kindred, 2007, p.151-156.
2 Macdonald, In: Stratton, 1997, p.207-224.
3 *Ibid*.
4 Macdonald, 2001, p.32-40.
5 Allan, In: Macdonald, Normadin and Kindred, 2007, p.13-46.
6 Burman, In: Stratton, 1997, p.15-33.
7 Prudon, 2008, p.25.

replacement of the original fabric might lead to continuing decay of the building. Standardization being a goal of the construction industry throughout the 20th century, an unsuccessful design or construction detail might compose a large portion of the building, resulting in compromise of material authenticity if replaced. An aggravating factor to be considered: the innovative use of building material, even if unsuccessful, is sometimes an important aspect of the building's significance.[8] Large scale material failure in 20th century buildings is also related to the mid-century optimism in the indestructibility of new building materials. This optimism was used to justify the general lack of maintenance in these buildings, but it also gave basis for the use of building materials in exposed locations as the aesthetic of choice.[9] The lack of protective cladding makes these structures more vulnerable to weathering and decay, since there is no sacrificial layer to protect them. In addition, the modern aesthetic advocated for the elimination of all façade details which were decorative, but also served as protection from weathering by shedding water away from the building.[10] In the case of reinforced architectural concrete, the monolithic nature of the material adds to the difficulty of incremental or spot repairs.[11] As a result, the overall material homogeneity of the surface is easily ruined by a poorly executed patch.

According to Peter Ross, the early failure of concrete in post-war buildings is related to the false belief that concrete was a durable material, combined with a change in concrete manufacture in the 50s.[12] The spike on the building industry, thanks to post-war rebuilding efforts, caused a competition among cement manufacturers for the production of a

[8] An interesting example of this paradox is the replacement of original prefabricated reinforced concrete panels at Auguste Perret's Notre Dame du Raincy, 1923. (Macdonald, 1996, p. 91)
[9] Starting with Le Corbusier in the 20s and culminating with Brutalism on the post-war era.
[10] Matthews, et al., In: Macdonald, 2003, p.196.
[11] Ross, In: Stratton, 1997, p.143.
[12] *Ibid*., p.155.

product that would gain strength more quickly in the curing process. The result was cement with finer grains and concrete mixes with lower cement content, resulting in cured concrete of increased porosity and lower durability (this relationship shall be further explained on the subsequent chapter).

The third contributing factor identified by the authors was the lack of appropriate repair techniques for 20th century materials. The current practices in concrete repair, for instance, are contrary to the conventional preservation principles of minimum loss of material fabric and maximum addition to the lifespan of the structure.[13] The current repair methods can be divided in two categories, patches and coatings. Patch repair requires the removal of original damaged fabric, which is difficult to match in both color and texture, and weathers at a different rate, and it does not solve the origin of the damage. On the other hand, coatings offer protection from external factors that might trigger deterioration but they often alter the original appearance of the building and introduce extra maintenance costs.

The surveyed publications presented the challenge but also proposed solutions. On the matter of principles there was a reaffirmation of the validity of the methodology presented by the Burra Charter.[14] This charter advocates that all intervention should respect the values that contribute to the cultural significance of the structure and that these values change over time.[15] As time passes, a reassessment of the building's significance will allow the addition

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[13] *"With traditional buildings such as stone or timber we have established, over the past 100 years or more, repair methods which enable the maximum amount of building fabric to be retained, whilst extending the life of that building. When we are dealing with twentieth century architecture built of materials such as concrete we have not yet established methods which fulfill such aims (…)"* Macdonald, In: Stratton, 1997, p.210.

[14] Burman, In: Stratton, 1997, p.31-32

[15] Australia ICOMOS, 1999.

of new layers of history.[16] This methodology allows design intent and original appearance of Modern monuments to be granted a higher degree of importance, but recognizes that the hierarchy of values should be reviewed in the future as the building continues to be a part of history. The publications on the preservation of Modern architecture also recognized that, like the heritage of any other period, the material fabric, as the vehicle through which significance is conveyed, should be preserved as much as possible. Therefore, new conservation techniques needed to be developed. There was also an appeal for the development of more accurate diagnostics of damage mechanisms and the incorporation of maintenance programs as a preventive measure following a repair campaign.[17] The publications focused on the study of non-destructive repair techniques, such as electrochemical methods to arrest further development of reinforcement corrosion. However, few of them mention any survey techniques and none of them offers a critical analysis of the techniques for early detection for preventive conservation, presumably because the publications were a response to historic buildings where immediate action was needed.

Terry S. Kreilick's master thesis in Historic Preservation at the University of Pennsylvania was one of the few works in the field of architectural conservation that presented a general description of different survey methodologies. Although the focus of the thesis was electrochemical repair methods, a chapter was dedicated to a very brief description of techniques that could be used to assess the reinforcement corrosion at Frank Lloyd Wright's Freeman House. It included corrosion potential measurement, corrosion rate measurement,

[16] Prudon, 2008, p.21.
[17] Macdonald, 2001, p.32-40.

concrete cover measurement, electrical continuity of reinforcement, chloride concentration, carbonation depth and petrographic analysis. [18]

The only publication directed at conservation professionals and completely dedicated to concrete deterioration was edited by Susan Macdonald in 2003. This book compiles papers developed by different authors covering all aspects of concrete conservation. John Broomfield, a renowned British corrosion specialist, contributed to this publication with a chapter on the identification of deterioration mechanisms in concrete, which includes a section on condition survey techniques. He briefly describes each one of them and stresses that a survey will most likely require multiple techniques. He also wrote the chapter on repair techniques with Susan Macdonald.

2.2. Preventive Conservation

According to Alice Finke, preventive conservation is a philosophy that has the goal of maximizing the life span of a historic resource by taking action to minimize probable deterioration risk factors.[19] In other words, it directs action toward the causes and not the consequences of the deterioration mechanism. Finke's research revealed that this is still a new and relatively unknown concept in architectural conservation, although it is well established in object conservation. Her case studies showed that preventive architectural conservation is usually done through regular examinations that include monitoring for risk factors and frequent visual inspections.

[18] Kreilick, 2000, p.55.
[19] Finke, 2008, p.10-11.

The preventive conservation approach starts with a comprehensive study of the structure at hand in order to understand all possible threats and which factors might trigger damage mechanisms.[20] Documentary research of all prior repair and alteration campaigns is essential, as well as a scientific characterization of the materials that compose the building. In addition, an initial visual assessment of the entire building should be conducted to locate possible ongoing problems and risks. With some training a surveyor will be able to identify most decay mechanisms early enough for the intervention to be minimal, therefore preserving more of the original fabric.

However, the limitations of visual detection are where preventive conservation of reinforced concrete diverges from that of other building materials. The most common damage mechanism found in reinforced concrete is reinforcement corrosion. The damage caused by corrosion initiates inside the concrete element and usually remains hidden until it has developed enough to cause damage to the surface of the concrete in the form of cracks and spalls (this mechanism will be explained in detail on the subsequent chapter). The problem is that when reinforcement corrosion affects the concrete surrounding it, the only possible remedy is traditional repair, which involves further loss of original fabric. Although current patching techniques are not much different than what was done twenty years ago, matching color and texture has become more common. The question that remains is whether these patches will age similarly to the original material. As mentioned before this kind of repair also triggers discussions on authenticity. In conclusion, visual inspections and material characterization are important tools for preventive conservation, but they are not enough when the material surveyed is reinforced concrete. In such cases, the inspection should be

[20] *Ibid*., p.8.

complemented with non-destructive techniques that can provide some insight on the reinforcement condition under an apparently healthy concrete cover.

2.3. Early Detection of Reinforcement Corrosion

Non-destructive testing for concrete structures began to be developed in the 1970s, but gained momentum in the subsequent decades.[21] This upsurge of interest is connected to the need to lower maintenance costs in reinforced concrete infrastructure, especially bridges, and the recent concern with environmental sustainability which encourages decreasing the amount of raw material consumption by repair instead of replacement.[22] Corrosion being the principal cause of deterioration of reinforced concrete bridges, many techniques have recently been developed to detect insipient corrosion or its consequences such as delaminations. Most of these techniques involve electrochemical, electromagnetic or acoustic wave methods. It is important to remember that these techniques have been classified as "non-destructive" by engineering and materials professionals concerned with minimizing repair costs in civil infrastructure. Therefore, "non-destructive" is associated with techniques that cause minimal damage, but these techniques are not necessarily harmless to the surface of the building from the perspective of the architectural conservator.

It usually takes a long time for a new testing technique to emerge from of Non-Destructive Testing research and become accepted as a standard of care in the practice of civil engineering.[23] It is only after this process of acceptance that architectural conservators start to get in contact with non-destructive techniques by the engineers who specialize in structural

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[21] Song and Saraswathy, 2007.
[22] Mancio, Zhang and Monteiro, 2004.
[23] McCann and Forde, 2001, p.71.

assessment of historic buildings. Techniques that have become common practice in the building industry are easily recognized by the existence of consensus standards compiled by industry associations such as ASTM (American Society for Testing and Materials), ACI (American Concrete Institute) and RILEM (Reunion Internationale des Laboratoires et Experts des Materiaux, Systèmes de Construction et Ouvrages).

The most recent scientific developments have been directed at improving the accuracy of well accepted techniques such as potential mapping, corrosion rate measurement and ground penetrating radar. These new developments concentrate on the improvement of data collection and processing, and imaging for interpretation, while still using the same technology for the data acquisition. Their goal is to increase accuracy in order to minimize the repair area, which would reduce the project's costs, but also preserve more original fabric.

Chapter 3 – Corrosion Damage Mechanism in Reinforced Concrete

In order to prevent reinforcement corrosion, or at least slowing its process, it is essential to have a comprehensive knowledge of how the corrosion mechanism develops and the factors that initiate and affect its progression. In order to facilitate comprehension, these factors have been broken down in four categories according to their relationship to the corrosion mechanism. Harris defines necessary factors as the ones that must be present in order for the mechanism to exist, in other words, the subtraction of any of them would render the mechanism impossible.[1] The same author also defines sufficient factors as those capable of initiating the mechanism. Influencing factors are those that indirectly result in reinforcement corrosion, because they determine the development of one or more necessary and sufficient factors. Possible causes are the primary conditions that can lead to influencing or even necessary factors (ill. 3.1). Recognizing the different factors that can contribute to corrosion, directly or indirectly, is important in order to understand how the corrosion mechanism relates to different environmental and material characteristics.

In addition to understanding its initiation process, it is also important to understand how the corrosion process progresses. This process is marked by key thresholds that divide the process into distinct phases (ill. 3.1). When considering intervention, the chosen approach should be tailored to the specific corrosion phase, since each phase presents different types of damage. This will dictate the scale of the intervention as well as the extent to which an intervention would be invasive to the existing material, an important consideration with historic buildings. Based on this comprehensive understanding of the damage process, it is possible to

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[1] Harris, 2001, p.22.

define strategies for the early detection of corrosion as part of a preventive conservation approach (Chapter 4).

3.1. Necessary and Sufficient Factors

Corrosion of steel is a naturally occurring electrochemical process where the unstable metal iron (Fe) reacts in the presence of oxygen (O_2) and water (H_2O) to produce a more stable molecule, hydrated ferric oxide ($Fe_2O_3.H_2O$), also known as rust. This process is initiated when an iron atom releases electrons in order to become an ion (Fe^{2+}) – an anodic reaction. These electrons are consumed in a reaction with water and oxygen generating hydroxyl ions (OH^-) – a cathodic reaction. This cycle of releasing and consuming electrons form an electric current, similar to what happens in a battery. The presence of an aqueous solution is important, since an electrolyte will generate an environment with low electric resistivity, allowing an easy circulation of electrons. The ions generated on both reactions will form ferrous hydroxide ($Fe(OH)_2$), which will further react with water and oxygen becoming ferric oxide ($Fe(OH)_3$). Finally, the ferric oxide, being an unstable molecule, becomes hydrated ferric oxide.[2]

Corrosion's Chemical Reactions:
(Broomfield, 2007, p.7-8)

$$Fe \longrightarrow Fe^{2+} + 2e^-$$

$$\tfrac{1}{2} O_2 + H_2O + 2e^- \longrightarrow 2OH^-$$

$$Fe^{2+} + 2OH^- \longrightarrow Fe(OH)_2$$

$$4\,Fe(OH)_2 + O_2 + 2H_2O \longrightarrow 4\,Fe(OH)_3$$

$$2\,Fe(OH)_3 \longrightarrow Fe_2O_3.H_2O + 2H_2O$$

[2] According to Broomfield (2007, p.7-8) the formation of rust can also be expressed in other ways.

Any reinforced concrete structure exposed to the atmosphere, without protective coating or cladding, presents the necessary elements for these reactions to occur. Iron from the reinforcement steel[3] can be exposed to oxygen and water entrapped during the mix and later, water penetrating from the atmosphere via interconnecting pores in the concrete. However, the highly alkaline environment provided by concrete (pH 12-13) renders iron oxides (corrosion products) thermodynamically stable due to the creation of an anodic polarization[4] on the steel surface.[5] These stable molecules are less prone to chemical dissolution, thereby creating a densely packed protective layer of iron oxides that isolates the sound steel core from the corrosive environment.[6,7] This layer is known as the passive layer. The nature, composition and structure of passive layers in metals have been studied for the past 150 years, but a consensus has not yet been reached.[8]

The origin of concrete alkalinity lies on the calcium hydroxide ($Ca(OH)_2$) that comprises 20-25 percent of the volume of solids in the hydrated cement paste.[9] As long as the pH of the concrete surrounding the reinforcement is maintained above 11.5, the passive layer will remain stable.[10,11] Breaking the passivity of the corrosion reaction in the reinforcement steel is a sufficient factor for corrosion. This passivity can be broken in two cases: carbonation or chloride contamination of the concrete. Carbonation is the reaction between calcium hydroxide

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[3] Unless the rebar is epoxy coated or made of stainless steel. These are very recent technological advancements that will only appear in mid-century buildings if used in a recent repair campaign.
[4] Anodic polarization refers to a situation where a material looses electrons to its environment, creating a positive potential. (Schennach, 2006/2007, p.2)
[5] Schennach, 2006/2007, p.12.
[6] Glass and Buenfeld, In: Macdonald, 1996, p.105.
[7] MacDougall and Graham, In: Marcus, 2002, p.190.
[8] *Ibid.,*p.189.
[9] Mehta and Monteiro, 2006, p.29.
[10] *Ibid.*, 2006, p.179.
[11] Broomfield, 2007, p.17.

and carbon dioxide (CO_2) that results in the formation of calcium carbonate ($CaCO_3$) in the concrete mass. This causes the pH to drop to 8.[12] This process occurs as carbon dioxide from the atmosphere progresses towards the reinforcement through the surrounding concrete. Carbonation initiates as soon as the structure is built, but it is usually a slow process that depends on the permeability of the concrete and the atmospheric concentration of carbon dioxide. In order to keep the carbonation front from reaching the reinforcement during the structure's design service life, the reinforcement should be provided with an appropriate concrete cover thickness.[13]

Carbonation's Chemical Reactions:
(Broomfield, 2007, p.16)

$$CO_2 + H_2O \rightarrow H_2CO_3$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O$$

Chloride contamination initiates reinforcement corrosion differently from carbonation. Chloride ions are capable of breaking the passive layer without lowering the pH of the concrete and without being consumed in the process. The exact process, whereby chloride breaks the passive layer, is not known.[14] Passivity is broken when the chloride concentration surpasses 0.6 of the hydroxyl concentration in the concrete.[15] Chloride ions can result from contact with de-icing salts[16] or from the atmosphere if the building is located in a salt water environment. Until the mid-1970s, it was common to use calcium chloride as an additive to

[12] Broomfield, 2007, p.18.
[13] Cover thickness is kept to the minimum necessary, because minimizing the amount of material is usually prioritized in order to lower construction costs.
[14] McDougall and Graham, In: Marcus, 2002, p.204.
[15] According to Broomfield (2007, p.23), this ratio is approximately 0.4% chloride by weight of cement if chlorides are cast into concrete and 0.2% if they diffuse in.
[16] Both of the most common types contain chloride: sodium chloride (NaCl) and calcium chloride ($CaCl_2$).

accelerate concrete curing,[17] therefore the concrete mix of buildings from this period can also be an inherent source of chloride.

In short, corrosion will happen when the reinforcement is in contact with oxygen and water. Most important, it will become a damage mechanism in reinforced concrete if the pH of the concrete encasing the reinforcement drops below 11.5 or if the concrete presents enough chloride concentration to break the passive layer.

3.2. Influencing Factors and Possible Causes

Concrete permeability and the thickness of the concrete cover on the reinforcement are the most important factors influencing the corrosion process and its rate. Concrete permeability controls the access of corrosion inducing factors to the reinforcement, such as oxygen, water, chlorides, and carbon dioxide that causes carbonation. Permeability also determines the electric resistivity of concrete, because the electric currents will be subjected to the tortuosity of the paths provided by water in the pore network. Concrete cover thickness is also important in creating a barrier for corrosion agents, but its main role is to provide enough distance between the reinforcement and the carbonation front. Both of these influencing factors can be affected by multiple conditions.

Concrete cover thickness is determined by the engineer's specifications before construction. Even when the specifications are correct, there is still the possibility of error during construction. The occurrence of errors such as misplacement- when a worker places the reinforcement in the wrong position-, or displacement- when an initially correct placement is disturbed- of the reinforcement on the formwork happen more often in environments with low

[17] Broomfield, 2007, p.20.

quality control and oversight, such as found on construction sites in the case of a cast-in-place structure, but it can also happen in precast plants. This kind of error might also be caused by the incompatibility between a complex design and the available level of skill and experience of the workers, this situation affects both precast and cast-in-place reinforced concrete structures. These two causes for lack of concrete covering, design and construction, are easily distinguishable on buildings, since construction errors would show as random areas with less covering than others, and an inadequate design would result in uniform lack of cover.

Permeability refers to the capacity of a material to allow liquid or gas to pass through it. This characteristic is determined by the amount of voids, their size and connectivity that form a network throughout the material. The volume of capillary voids in concrete depends mainly on the water/cement ratio of the mix.[18] Voids are formed during hydration when space that was initially occupied by water is not filled with solid hydration products. Consequently, the more water in the mix, the more space is left unfilled. However, not all pores contribute to permeability, in concrete, only pores larger than 100 nm form interconnected voids, the smaller ones tend to remain isolated.[19] The key factor in defining the permeability of concrete is the microstructure of the interface zone between the hydrated cement paste and large aggregates. The existence of the interfacial transition zone, usually 10 to 50 μm thick around large aggregates,[20] is the reason why concrete has a higher permeability than cement paste with the same water/cement ratio (fig.3.1). This happens because larger aggregates attract water during curing increasing the water/cement ratio on its surroundings. The result is the formation of larger crystals and a greater quantity of calcium hydroxide (needlelike crystals oriented toward

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[18] Mehta and Monteiro, 2006, p.36.
[19] *Ibid.*, p.41.
[20] *Ibid.,* p.24.

the aggregate) composing a porous framework.[21] Although this condition might improve with age due to the late formation of hydration products, the microstructure of the interfacial transition zone remains more porous than the hydrated cement paste. This poor microstructure and higher porosity negatively affects the strength of the concrete in general. Moreover, it creates zones of weakness that are more prone to microcracking, which increases the permeability even more. Pores present in aggregates also influence the total permeability of concrete, this will depend on the physical characteristics of the stone used.

Both micro and macro cracks play an important role in the penetration of liquid and gases in concrete by providing continuous and easier paths through it. Cracks also increase the surface area exposed to the atmosphere, thereby expanding the carbonation front and the area contributing to moisture absorption (fig.3.2). Therefore, even when shallow cracks are restricted to the concrete surface they contribute to concrete deterioration. Cracks can be caused by many different mechanisms that damage the concrete by exerting internal pressures higher than the concrete's tensile strength. Most of these mechanisms relate to how the concrete reacts to its environment which is mainly determined by its composition, microstructure that results from it, and form.

Mechanisms that cause concrete cracking:

a) Drying shrinkage: strain caused by the loss of adsorbed water from calcium silicate hydrate (C-S-H) due to exposure of concrete to an unsaturated environment. The use of good quality aggregate that, in the drying process, shrinks less than the concrete paste restrains concrete shrinkage and avoids cracks. The effect of aggregates depends on the volume used in

[21] Mehta and Monteiro, 2006, p.43.

the concrete mix, as well as the aggregates' modulus of elasticity. Curing conditions influence this phenomenon. Environmental conditions during curing, such as the ambient temperature, relative humidity and wind speed, can increase the drying rate and cause cracks due to drying shrinkage. Other factors that increase drying rate include the precipitate removal of formwork and geometry of element (a high perimeter/section ratio increase the rate of moisture loss).[22]

b) Crazing: a form of drying shrinkage that shows as discontinuous hairline cracks that occur on the surface of freshly hardened concrete and are caused by a higher water concentration on the element's surface due to improper curing and finishing. Common in exposed concrete with a smooth finish (low concentration of aggregates close to the surface).[23]

c) Creep: strain that is also caused by the loss of adsorbed water from calcium silicate hydrate (C-S-H), but for a different reason than drying shrinkage. In this case, cracking is caused by the long term action of stress that causes water loss. Influenced by the same factors as drying shrinkage.[24]

d) Stress in compression: a loaded structure can develop cracks even if the ultimate strength has not been reached. According to Mehta and Monteiro, a stable microcrack system develops in the interfacial transition zone under 50% of the ultimate stress, some of which were initiated before loading due to thermal and drying shrinkage. When a concrete structure is subjected to 50-75% of the ultimate stress the crack system becomes unstable and proliferates through the cement matrix. Any stress above that will cause a rapid propagation of cracks and eventually result in failure.[25] This situation can be aggravated if a structure is loaded before it has reached the required initial strength. For example, a structural member that is

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[22]Mehta and Monteiro, 2006, p.95.
[23] *Ibid.,* p.380.
[24] *Ibid.,* p.95.
[25] *Ibid.,* p.89.

post-tensioned before it reaches the minimal strength for this procedure, or a precast piece that, prior to attaining sufficient strength, is loaded during shipping, handling or erection procedures.

e) Stress in tension: concrete is not usually used in tension due to its brittle nature, which is why concrete elements subjected to any kind of tension are reinforced with steel. Structural elements in tension, such as beams, have a higher concentration of microcracking on the tensioned zones. Poupard, et al., described a case where corrosion rate was higher on the bottom of a beam (the tensile zone), which was attributed to the higher permeability caused by microcracking.[26] However, concrete can also be exposed to this kind of stress in unique situations such as improper handling and transportation of pre-cast elements, failure of reinforcement or earthquakes.

f) Thermal expansion/contraction: caused by the concrete's response to the changes in temperature and aggravated by the poor distribution or lack of expansion joints.

g) Freeze/thaw: formation of ice lenses inside the concrete pores during curing under freezing temperatures, if the structure is not properly protected. The volume increase caused by freezing water can exert enough pressure on the surrounding material to rupture it. The level of damage depends on the amount of cycles of freeze and thaw that the pore water goes through, therefore the local climate must be characterized by temperature fluctuations that repeatedly go above and below freezing. The microstructure of the material is the determining factor for the damage caused by this mechanism, because having voids that can accommodate the ice growth can prevent the pressures it causes.

[26] Poupard, et al., 2006, p.518.

h) Alkali-silica reaction: chemical reaction between the alkali content of concrete and unstable silica minerals[27] that results in the formation of gels that expand in the presence of water. Depends on the mineral composition of aggregates and exposure to water.

i) Sulfate attack: chemical reaction between the alumina-containing hydration products, calcium hydroxide (also a hydration product) and sulfate ions resulting in the formation of ettringite, which causes expansion. Sulfate can be found in aggregates that contain gypsum, atmospheric pollution, industrial and natural water.

j) Reinforcement corrosion: the corrosion products have a much bigger volume than the original steel, this causes internal pressures in the concrete (this phenomenon will be further explained on the next section).

It is interesting to observe that all mechanisms that depend on the ingress of water or a contaminant are influenced by the concrete permeability. Once they cause enough pressure to crack the concrete, they end up increasing their own rate of damage due to the creation of more efficient pathways for moisture transport via the crack network, essentially bypassing the low permeable mass of concrete. This makes the reinforced concrete more susceptible to the initial deterioration mechanism, but also to the initiation of other mechanisms that are governed by the penetration of water and other atmospheric components, such as reinforcement corrosion.

3.3. The Three Phases of the Corrosion Damage Process

As previously mentioned, the corrosion process in concrete reinforcement can be divided in three distinct phases that take place once concrete is no longer a passivity inducing

[27]Alkali-reactive minerals: opal, obsidian, cristobalite, tridymite, chalcedony, chert, andesite, rhyolite and metamorphic quartz (Mehta and Monteiro, 2006, p.170).

environment (ill.3.1). The first phase is characterized by the accumulation of corrosion products on the interface between the reinforcement and the concrete. Hydrated iron oxides have a volume six to ten times bigger than that of the original iron.[28] This expansion will at first be accommodated by voids in the concrete mass surrounding the reinforcement.[29] However, once these spaces are occupied, the volume increase, constrained by the lack of available space, builds up pressure and causes tensile stress on the surrounding concrete (fig.3.3). Once this pressure surpasses the tensile strength of concrete, cracks start to appear. This marks the transition of the process to another phase where corrosion is not only attacking the reinforcement, but is also damaging the concrete mass by creating new fractures or enlarging existing cracks.

This phase is characterized by an acceleration of the damage rate due to an increase in water and oxygen penetration resulting from the new or enlarged cracks.[30] Not only does the volume of water penetrating the concrete mass increases, but the rate of wetting and drying cycles increases as well. The increased frequency of wetting phases supply more water to the corrosion process, while the increased frequency of drying phases allow more space for oxygen penetration. Further accumulation of corrosion products widens and multiplies the cracks. These appear as parallel cracks on the concrete surface aligned with the longitudinal direction of the corroding reinforcement bar. In a cross section, these cracks clearly radiate from the reinforcement bar. As time passes, the progressive enlargement of the cracks and the weathering of the internal surfaces of the cracks can lead to loss of key in the fracture face and

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[28] Broomfield, 2007, p.9.
[29] Yuan, Jiang and Peng, Nov-Dec 2010, p.565.
[30] *Ibid.*, p.564.

develop into a spall. This phenomenon characterizes the transition to the final phase in the corrosion process.

This last phase is marked by loss of concrete surface mass due to spalls, which result in direct exposure of the corroding reinforcement to the atmosphere and reduction of the concrete cover over adjacent reinforcement. Once exposed to the atmosphere, the reinforcement has no protection against the necessary factors for corrosion. Consequently, the process will progress until all iron has oxidized. Since iron oxides are not structurally sound, the progressive loss of steel section will eventually threaten the stability of the structure due to the transfer of tensile strain from the steel to the surrounding concrete, which is by then compromised by fracturing and weathering.

3.4. Intervention and Prevention

The degree and kind of damage caused by each phase will guide the appropriate intervention approach. It is important to highlight that while there is little accumulation of iron oxides on the steel-concrete interface, deterioration develops under the concrete surface, hidden from sight. In addition, damage to the concrete progresses rapidly once cracks become evident on the surface. From that moment on, intervention is likely to include patching, and the resultant fabric loss is inevitable in this repair process.[31] Grouting is not recommended when cracks have been caused by reinforcement corrosion, unless grouting is used as a temporary stabilization until the appropriate repair can be made. Grouting should only be regarded as provisional, since it might diminish the rate of corrosion by blocking the by-pass access to water and oxygen provided by the cracks, but it does not address the cause of damage which is

[31]Broomfield and Macdonald, In: Macdonald, 2003, p.165.

reinforcement corrosion. Corrosion will continue to occur, consequently, soon causing further cracks in the concrete. There is also the question of proper adhesion, since the presence of loose corrosion products might compromise the contact between grout and concrete.

Traditional patching is used because it has the capacity of reestablishing passivity locally and arresting the corrosion mechanism. This process consist of removing the affected areas of concrete with enough depth to completely expose the reinforcement (fig.3.4), which is then cleaned or replaced as appropriate and the area is refilled with new concrete, thereby re-passivating the corrosion reaction. This new concrete will have to be matched both in color and texture to the original surface, which can be challenging and is rarely done satisfactorily. One of the reasons is that the concrete used for patching has to reach a determined strength and be able to bond to the substrate, these characteristics usually determine the proportion of the mix, the additives, and the type of binder used. However, the proportion and type of materials used in the mix can significantly affect the final color, which is likely to be different from the original concrete. Pigments can be used to help reaching the appropriate color, but they tend to age differently from the original fabric, mainly due to pigment fading. According to Broomfield and Macdonald, the patch can be matched to the original appearance of the concrete and look different from the rest of the structure until it acquires a similar patina. A common practice is to apply an opaque coating on the whole surface to hide the patches, this not only erases the patina but also softens the surface texture. In cases where the patch was matched to the aged concrete, it started to become distinct from the rest of the surface with further weathering.[32] Another point to be considered is that patches will not necessarily work structurally. Consequently, patching can affect structural stability if performed

[32] Broomfield and Macdonald, In: Macdonald, 2003, p.165.

in a large scale without the appropriate structural appraisal by an experienced engineer. The patch has to extend beyond the location of observable damage and substitute the entire carbonated or chloride contaminated area in order to be effective. Alternatively, the patch can be restricted to the damaged area if combined with other techniques that address the cause of the corrosion, such as impressed current cathodic protection, electrochemical chloride extraction and realkalisation.

These electrochemical techniques depend on a current source that is connected both to the reinforcement and an external anode. Among electrochemical approaches, the impressed current cathodic protection technique is the only permanent installation. Impressed current cathodic protection uses a low current to invert the electrochemical reaction so that the reinforcement that has been acting as an anode becomes a cathode. As long as the system is properly functioning the reinforcement will no longer corrode, instead, this oxidizing reaction will take place in the external anode, which will need replacing after 10-40 years depending on its composition.[33] The anodes have to be uniformly distributed across the surface, so proper planning is essential in order to minimize impact to a historic building's appearance.

Electrochemical chloride extraction is a temporary installation. Treatment can take about eight weeks to be completed. Differently from cathodic protection, this technique uses high current to drive chloride ions outside of the concrete. Electrochemical chloride extraction is capable of removing between 50-90% of the chloride content.[34]

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[33] Broomfield and Macdonald, In: Macdonald, 2003, p.173.
[34] *Ibid.,* p.176.

Realkalization is also a temporary installation, but the process is faster than chloride removal. Realkalization uses a low current and a carbonate electrolyte to increase alkalinity in carbonated concrete.

These electrochemical repair techniques share the same restrictions. According to Broomfield and Macdonald, they are difficult to apply in prestressed concrete members and, since they require electrical connection to the reinforcement, they can be expensive in structures where the reinforcement is not continuous, such as precast structures. Although they generally require a higher initial investment than traditional repairs, they tend to be cost effective on the long term, because of the savings with future repairs.

It should be remembered that the loss of original fabric is an undesirable outcome when the building or structure in question has historical value. Loss of original fabric poses a threat to the aesthetic quality of the exposed concrete, as well as to the historic integrity of the building. However, the options of noninvasive treatments are still quite limited for reinforced concrete. Therefore the most appropriate approach would be to act preventively, before the concrete is irreversibly affected by the corrosion process.

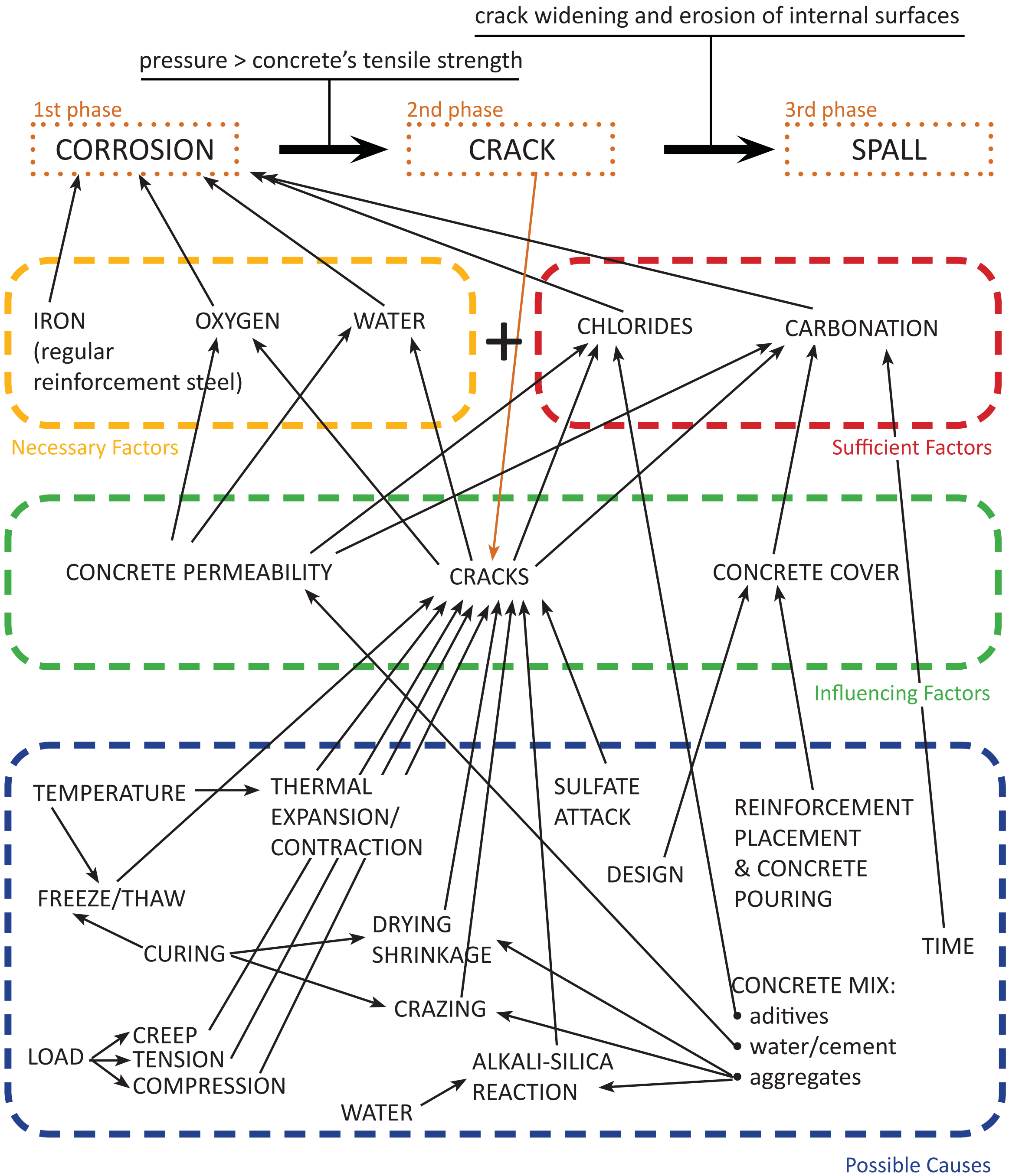

Illustration 3.1- Diagram of the three phases of the corrosion mechanism in reinforced concrete and a holistic view of factors that can affect corrosion.

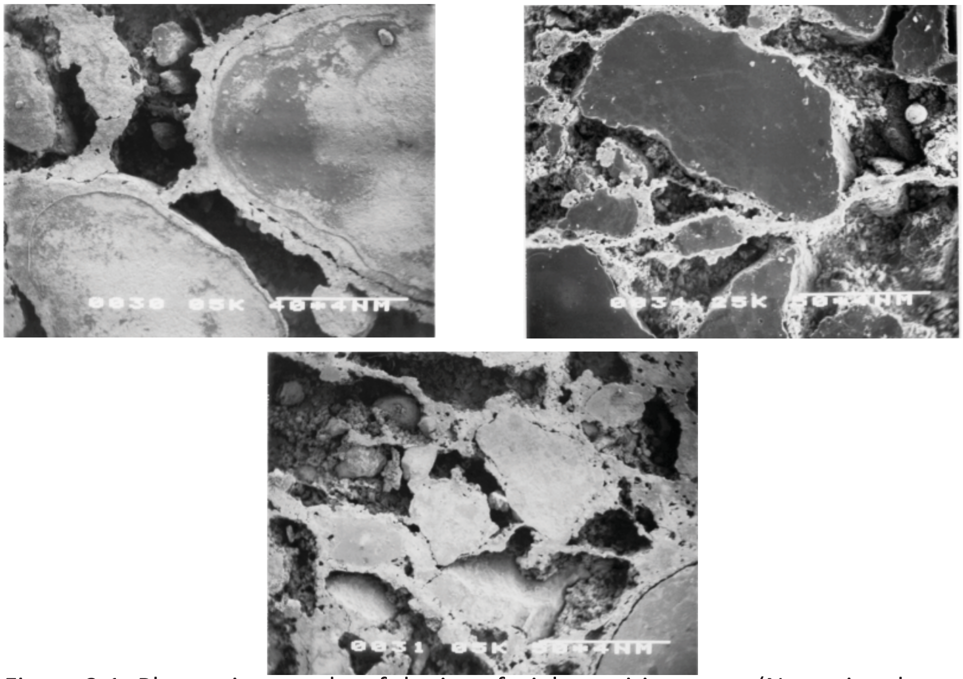

Figure 3.1- Photomicrographs of the interfacial transition zone. (Nemati and Monteiro, 1997)

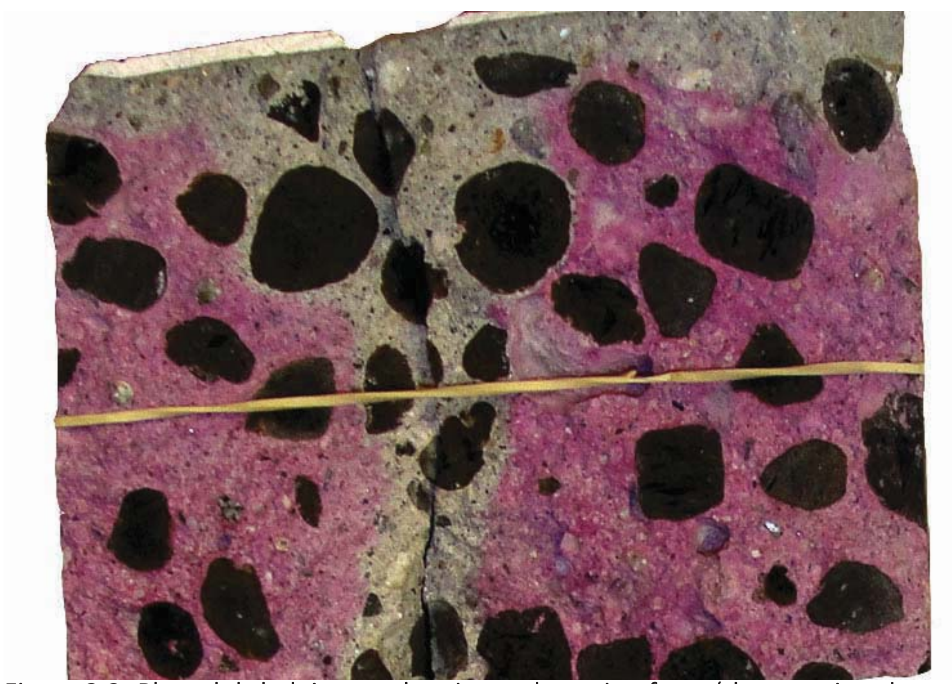

Figure 3.2- Phenolphthalein test showing carbonation front (the non-tinted area) advancing from the fracture face of a crack.

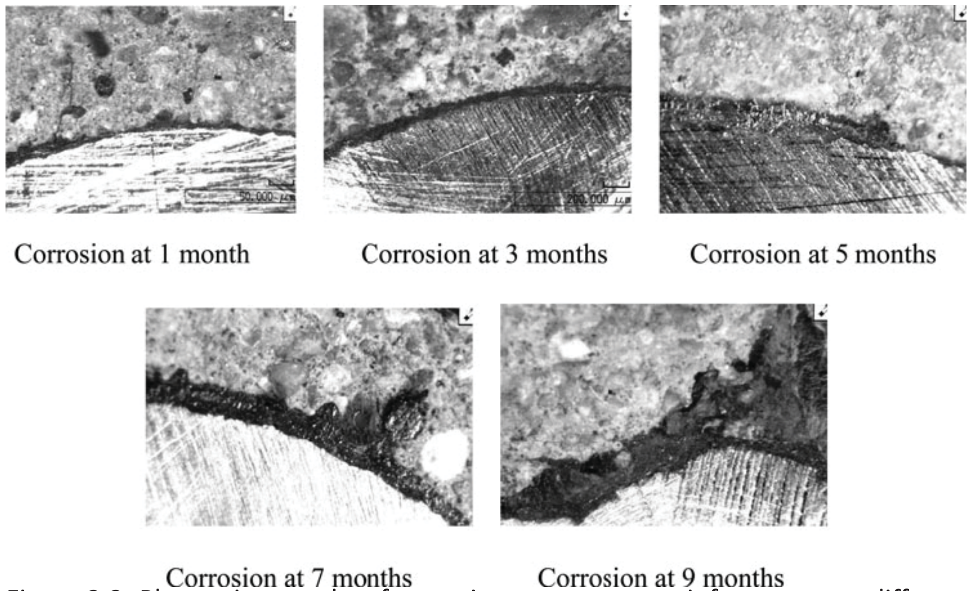

Figure 3.3- Photomicrographs of corrosion on concrete reinforcement at different stages of development. (Yuan, Jiang and Peng, 2010)

Figure 3.4- Preparation of damaged area to be repaired by patching. (Macdonald, 2003)

Chapter 4 –Techniques for Early Detection of Reinforcement Corrosion for a Preventive Conservation Strategy

Preventive conservation, in the case of reinforcement corrosion, refers to any actions targeting factors that contribute to the corrosion process with the goal of delaying its initiation or slowing the rate of damage that it might cause. Therefore it is appropriate to say that the preventive approach should be employed before corrosion has caused cracks in the concrete. The preventive opportunity occurs before the corrosion products have reached a volume sufficient to rupture the concrete, and after a repair campaign, when the corrosion process is returned to its incipient stage. The preventive approach is based on the acknowledgement that all exposed concrete structures in contact with the atmosphere and built with common steel reinforcement have the necessary factors for corrosion to occur.

Preventive strategies have to be founded on a sound knowledge of the building. Therefore the first measure is to gather detailed and comprehensive information on the building's history, previous repair campaigns and material characteristics. This should be followed by an investigation on the possible presence of sufficient factors, such as carbonation and chloride contamination. Whether or not they are present, an assessment of which risk factors might lead to the development of sufficient factors is also necessary. Two kinds of actions are possible, either conducted individually or in combination: monitoring the progress of sufficient and risk factors, and taking measures to stop their development by acting on the primary conditions described on the previous chapter.

The present chapter first describes the risk factors that can be assessed, and in which phase of the process this should be done as part of a preventive strategy for reinforcement corrosion. Later, this chapter describes and evaluates the techniques that are currently employed in the early detection of risk factors and corrosion in reinforced concrete. The chapter concludes with general strategies on how to compose a survey plan that can serve as a base for the development of a preventive approach to conservation, and according to each structure's specificities.

4.1. Measurable Risk Factors for a Preventive Strategy

The previous chapter identified the necessary factors for corrosion - water, oxygen, and iron - and the sufficient factors for corrosion initiation in reinforced concrete – carbonation of concrete surrounding the reinforcement or enough concentration of chloride ions to cause depassivation. Based on this, a list of risk factors can be compiled as part of an assessment of their presence and evolution in the building as the first step in a preventive strategy. Since preventive strategies are only appropriate when implemented before the corrosion mechanism has caused mechanical damage to the concrete, the time frame of action is restricted to before initiation of corrosion, and to the first phase of the damage process once corrosion has started.

Factors acting in this time frame can be divided between constant and progressive. The first term refers to factors that are inherent characteristics to the structure and do not evolve with time. The second term refers to factors, inherent or not, that pose no initial threat, but that can evolve into one due to aggravating mechanisms. The assessment method for these factors should reflect their nature, because while constant factors may be measured only once during the life time of the building, progressive factors should be measured every time a new assessment is conducted. Moreover, in the case of progressive factors, the rate of their evolution will have a bigger impact on the building's life span than their immediate measured value.

Two factors can be classified as constant:

a) Depth of cover - mostly a function of design and workmanship, therefore unlikely to change over time. The measurement of cover depth and reinforcement location can produce drawings equivalent to architectural as-built plans. Depth of cover could be considered a progressive risk factor if the structure is exposed to a highly abrasive environment, such as water tides.

b) Chlorides in the concrete mix – calcium chloride used to be added to the concrete mix in order to accelerate the curing process until the mid-1970s. In this case, the residual chloride concentration could be sufficient to break corrosion passivity right after concrete curing.

The progressive factors category holds the remaining risk factors:

a) Liquid and gas penetration – considered the most influential risk factor, because it controls the access of external agents that constitute necessary and sufficient factors, such as water and oxygen, or that inflict depassivation, like carbonation and chloride contamination. Liquid and gas penetration through concrete is a consequence of concrete permeability and crack formation that provides easier paths to liquid and gas transport. Permeability decreases in time due to carbonation, but the quantity of cracks tends to increase in time with the progress of deterioration mechanisms causing them. Though initial permeability can be sufficient to allow the ingress of a deleterious amount of external agents, as in the case of a low strength concrete (high water/cement ratio), liquid and gas penetration can be progressively aggravated due to the bypass effect of cracks.

b) Carbonation – as previously explained, the progressive transformation of calcium oxide into calcium carbonate in the presence of carbon dioxide takes place in every exposed concrete structure, however the concrete characteristics (low permeability and high cement content) can maintain a slow rate in the carbonation front progress, so that carbonation will not reach the reinforcement during the projected life span of the structure. The challenge with structures that have become historic or architecturally significant is that they are expected to last much longer than expected when they were initially designed. Therefore an estimation of the carbonation front's rate of progress is important in predicting when the protective highly alkaline environment surrounding the reinforcement will be lost.

c) Chloride ingress – the availability of chloride sources where the structure is located will determine if this is a risk factor to be considered. The most common external sources are sea water spray that is carried by the wind in marine environments and de-icing salts in climates susceptible to freezing temperatures. Chloride ions are not consumed in a chemical reaction, so their concentration is always increasing as long as the source remains. Since the presence of chlorides can break the passive layer once chloride concentration reaches a certain threshold, monitoring chloride concentration and its rate of change is useful in estimating the time remaining before depassivation.

Once corrosion has started, measuring the parameters mentioned above will be useful in determining causality. In addition, identification of the areas where reinforcement is corroding along with an estimation of corrosion rate is important in guiding the planning phase of an intervention. Together, these measurements can produce information that can be used to minimize the area of intervention through increased accuracy in defining damage location, maximize the durability of the intervention by guiding it to act on the primary causes of the damage, and prevent the development of mechanical damage to the concrete by indicating the presence of active corrosion underneath the surface of sound concrete.

4.2. Techniques for Early Detection of Reinforcement Corrosion: Description and Evaluation

The techniques described herein are well known in the concrete industry. However, some, especially non-destructive techniques (NDT) for corrosion detection, have not yet found their way into common building conservation practice. This section describes techniques that can be used in the early detection of reinforcement corrosion and risk factors, and evaluates these methods in the context of historic preservation and building conservation. Therefore they will be analyzed according to their effectiveness and compatibility with sound historic preservation principles, such as minimum intervention (see table 4.4 in the end of the chapter).

In the case of tests that require sampling of the concrete, this should be done according to ASTM C823 "Standard Practice for Examination and Sampling of Hardened Concrete in Constructions". This standard recommends that a sampling plan should be made according to the type of data that needs to be extracted from the material. For example, if the goal is to identify the origin of an observable problem, samples should be taken from both deteriorated and sound areas made of the same concrete mix. Results will be derived from the comparison between these samples. On the other hand, when the goal of the test is to determine average and distribution of properties, samples should be taken from randomly chosen areas if the concrete is consistent throughout the building. However, if it is clear that different areas present different concrete mixes, sampling of each concrete type should be proportional to its occurrence.[1]

The number of samples should be determined statistically according to ASTM E122 "Practice for Calculating Sample Size to Estimate with a Specified Tolerable Error the Average for Characteristic of a Lot or Process".[2] However, this is not usually possible since the number of samples can be high enough that the cost of the sampling process could be prohibitive. In historic buildings, the number of samples is further restricted by the significance of the material. The appropriate number of samples depends on the mean and standard deviation values calculated from the results gathered from each sample. Therefore, the appropriate sample size can only be calculated after a preliminary sampling is done. This often results in extra sampling being needed. Friedman proposes alternatives to minimize the possibility of errors without sampling more. A conservative intervention plan could be used to counteract the possibility of false negatives by accepting a large number of false positives. Asking for a second opinion from an experienced professional and comparing the case at hand to other similar cases can orient the decision making process. This kind of practice can force a positive result despite of a negative result. Another option proposed by Friedman is to complement the results of a destructive test with data obtained by less invasive or non-

[1] Poole, 2006, p.20.
[2] Steele, 2006, p.22.

destructive tests. However, he alerts that accurate sampling size is still the most reliable method of obtaining results, especially when dealing with an unusual case.[3]

a) Context and historic research

Any survey technique must be informed by documentary research into the history and context of the building, especially when the building is historically significant.[4,5] It can reveal some of the risk factors that can lead to reinforcement corrosion and give focus to subsequent investigations. A study of the building's context should include a characterization of the local climate and air pollutants. This will give an idea of what types of deterioration agents, such as sulfates, might be penetrating the concrete. In addition, context research will inform whether winter temperatures justify the use of de-icing salts, if the atmosphere can contribute to increase the concrete's moisture content, or if warm temperatures might accelerate corrosion. This study should also include a description of the structure's location and surroundings. For example, the building's closeness to a salt water source could implicate in increasing chloride content over time. In addition, different deterioration levels between façades could be explained by the surrounding buildings that could influence the degree of exposure of the building's façades to rain and wind. It is also important to understand the state of knowledge available at the time and place of construction on the material and construction technique employed.

Historic research should be conducted using both primary and secondary sources. Construction drawings, specification documents and photographs taken during

[3] Friedman, 2000, p.44.
[4] ASCE-SEI, 2000, p.3.
[5] Venice Charter, article 9.

construction can aid in understanding how the building was constructed, as well as the composition of the materials. It should be noted that information derived from design documents should be regarded as guidelines for further investigation, since later modifications to the design, materials and construction might not be documented. Other important sources of information are accounts of previous repairs and old conditions assessment reports. They can determine if a deterioration mechanism reoccurs throughout the structure's life, or whether a mechanism that is no longer present could have influenced the current condition.

b) Visual inspection

Visual inspection is the second step of the survey phase. Combined with the background research mentioned before, it will guide the detailed investigation that will follow. Although this can be considered the most simple of all survey techniques, visual inspection relies on the surveyor's skills of observation, training and experience.[6] The safety and comfort of the surveyor also play an important role in the accuracy of the results when the access to the structure is challenging. The level of access by the surveyor to the deteriorated areas determines different degrees of accuracy and detail.[7] Therefore the method of access should be compatible to the purpose of the survey. In the case of large structures, the complexity and costs of vertical access restricts initial inspection to what can be seen from the ground, sometimes aided by binoculars or camera lenses. Alternatively, a representative area of the building could be surveyed. As a consequence, if an intervention is programmed, time should be reserved to re-inspect the structure once scaffolding has been installed, and budget should be set aside for the likely readjustments that will follow.

[6] Watt, 2007, p.151.
[7] Prudon, 2008, p.176.

Any visual assessment requires the compilation of a glossary with the types of conditions to be noted and recorded, preparation of a set of drawings and rectified photographs that can be used to map conditions. An annotation system that meets the needs of the survey project should be developed on a case by case basis, since the number and nature of conditions can vary. This information can be directly plotted on digital format with the use of portable digital tablets, or later transferred to a computer. Recently, software has been developed to facilitate field data collections. Mapping systems such as GIS (Geographic Information System) have become the most popular. Advantages include the quantification and spatial identification of damage areas, and tools that aid in the correlation analysis of various conditions and their possible sufficient factors and risks.

c) Petrographic analysis

Petrographic analysis is not a single test, but a whole area of expertise that is based on the field of geology. This technique obtains data through macroscopic and microscopic observations of samples. Depending on what is being investigated and the method of observation, samples can be cut in cross section and polished, or in thin sections that allow the use of transmitted light (fig.4.1). Specific characteristics can be enhanced with dyes, acid etching and spot testing. The results are highly dependent on the experience of the petrographer.

Sampling for petrographic analysis of hardened concrete requires extraction by core drilling. This sampling technique uses a diamond core drill to extract a cylindrical sample from the structure, usually 100 mm in diameter and, preferably, 203 mm in depth (fig.4.2). A minimum of three cores per tested area should be taken. Fragments broken due to deterioration or extracted with a sledge hammer can be used for a preliminary evaluation, but core samples would still be needed for obtaining a definitive result. When the objective of the petrographic analysis is to identify cause of deterioration, two separate areas should be sampled for comparison, an area affected by the deterioration and another area that is not deteriorated, but that share the same concrete mix.[8]

Although core sampling can be considered destructive for a historic structure, the amount and range of information that it can provide through petrography is still unmatched by any other technique. For example, petrographic examination can provide the proportion of the different concrete phases, such as coarse aggregate, fine aggregate, voids and cement paste. The area occupied by macroscopic features can be measured by grid counting on core halves, while microscopic features can be measured by point counting in thin sections.[9] Acid etching is commonly used to enhance the difference between cement paste and aggregates, because the cement paste is left on a second plane after being etched away. In a thin section, voids can be enhanced with dyes and incident fluorescent light under a petrographic microscope. The same thin section can also be observed with transmitted cross polarized light to identify carbonation products and alkali-silica gel. In addition, petrographic analysis can provide the water/cement ratio based on paste texture, distribution of non-hydrated cement grains, speed of water absorption and reaction upon scratching. A more specific ratio can be provided by chemical analysis.[10]

Petrographic analysis should be done according to the ASTM C457-98 "Standard Test Method for Microscopical Determination of Parameters of the Air-void System in Hardened

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[8] Walker, Lane and Stutzman, 2006, p.247.
[9] Broekmans, 2009, p.645.
[10] Walker, Lane and Stutzman, 2006.

Concrete" and ASTM C856-95e1 "Standard Practice for Petrographic Examination of Hardened Concrete".

d) Liquid and Gas Penetration test

Liquid and gas penetration tests the volumetric transport of a liquid or a gas through a material. Transport depends on the volume of pores, their shape and size, and on the connection between them. There are three types of transport occurring in the material, and each can be tested separately. Absorption is transport of liquid in a solid by capillary suction, permeability is the inherent capacity of the material to transport liquid or gas through the material under pressure, and diffusion is the transport of ions and molecules from an area with higher concentration to an area with lower concentration.

Based on the fact that moisture is a necessary factor in most damage mechanisms that attack reinforced concrete, many researchers identify permeability as a reliable indicator of concrete durability.[11] As explained in the previous chapter, the penetration of liquid and gas can increase due to cracks caused by different types of damage mechanisms, which increase the rate of deterioration because cracks provide a path of lower resistance to the ingress of deterioration agents. Therefore, this is a condition that should be monitored over time. Monitoring requires that a test be performed several times, consequently, minimizing the damage caused by the test is essential. However, most liquid and gas penetration tests have to be performed in a laboratory using samples. Thus in-situ techniques for measuring this characteristic will be given priority in this study. The advantage of in-situ techniques is that they

[11] Long, Henderson and Montgomery, 2001, p.66.

have a smaller impact on the original material because they do not require sampling. However, the results of in-situ techniques can be affected by the presence of moisture in the pores.

It is important to notice that both laboratory and in-situ tests are referred to as “permeability” tests in the professional literature, but for the purpose of this thesis the term “permeability” only refers to the capacity of the concrete to transmit fluid as determined by the pores in the concrete’s microstructure without transport through micro- and macro- cracks. Since so-called “permeability” tests actually measure transport without distinction of void type, these techniques will be referred to as liquid/gas penetration tests in this thesis.

Determining absorption demonstrates how much moisture will penetrate the concrete when water comes in contact with the surface. It can be tested in a number of ways, the most simple of which is a standpipe test. This test consists of measuring the volume of water absorbed through a given surface area over a certain period of time using a graduated vertical pipe. This device is standardized by RILEM Commission 25-PEM Test n°11.4[12] and it has to be tightly attached to the concrete surface with removable putty. Although this test has the advantage of being harmless to the surface and easy to perform, it is not sensitive enough to distinguish between different absorption levels in concrete.[13] Long, Henderson and Montgomery describe three other tests that are more sensitive. The Initial Surface Absorption Test (ISAT) uses a watertight cap connected to a water reservoir and a calibrated capillary tube (fig.4.3). It measures the time taken by the water level at the capillary tube to change, once a water head of 200 mm is applied. The main difficulty is to ensure a watertight seal that will not damage or leave residues on the surface. The AUTOCLAM sorptivity test (fig.4.4) is similar to the ISAT, but it

[12] RILEM, 1980, p.175-253.
[13] *Ibid*, p.71.

is easier to secure watertightness, because it uses a smaller base against the concrete. The equipment used is controlled automatically and is capable of acquiring digital data. Another advantage is that the same equipment can be used to measure air and water penetration. The Figg water-absorption test (fig.4.5) is also capable of measuring absorption, air and water penetration, but it uses a hypodermic needle inserted in a hole (40 mm deep, 10 mm in diameter) drilled in the concrete and sealed. The main disadvantage is that the drilling process can increase the liquid/gas penetration of the surrounding concrete due to the formation of microcracks.[14]

Liquid/gas penetration test gives insight into the configuration of the pore network. Although the same equipments mentioned before to test absorption are used in the liquid/gas penetration test by the AUTOCLAM and Figg methods, the liquid/gas penetration test does not use water. It measures the time it takes to change the pressure applied inside a hole or chamber. The applied pressure will tend to reach a balance with the surrounding material by either attracting air from the concrete voids, if pressure is too low (Figg), or releasing air into the pores, if pressure is too high (AUTOCLAM). How long it takes air to go in or out of that confined space is a measure of the connectivity and tortuosity of the pore network. The Schönlin air permeability test (fig.4.6) uses a vacuum chamber and the same principles as the Figg test. It has the advantage of not needing any form of attachment device, because the vacuum created is enough to hold it in place.

Knowing the diffusion coefficient is important when the structure is exposed to chlorides from the surrounding environment, because the rate of chloride ion penetration will

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[14] Long, Henderson and Montgomery, 2001, p.73.

determine when depassivation will occur. There are different tests that can be done, most of which are performed in a laboratory using core samples. They basically consist of exposing each face of the sample to a solution with a different concentration of chlorides and applying an electrical potential difference to stimulate transport (fig.4.7). ASTM C1202-10 “Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration” should be used as guidance.

Recently, there have been some successful attempts at developing an in-situ chloride diffusion test.[15] The principles of this test are exactly the same as the process described above, the difference is in the equipment set-up. The in-situ ion migration test, known as PERMIT, uses two cylinders concentrically placed on the concrete surface (fig.4.8). The inner surface contains a cathode submerged in a chloride solution, and the outer cylinder contains an anode submerged in distilled water. When the potential difference is applied, chloride ions flow from the inner ring, through the concrete and into the outer ring. A selective electrode is used to measure chloride concentration in both solutions until stabilization. The slope, formed before stabilization is reached, is used to calculate the coefficient of ion migration. Basheer, et al., informs that the test area should be pre-wetted before measurement. The location of the test area should take in consideration that reinforcement located within 25 mm of the surface can affect test results by falsely increasing the concrete resistance to ion migration. Even though chloride ions inserted in the process can be effectively removed after testing, nitrate ions could

[15] Long, Henderson and Montgomery, 2001,p.75.

be used alternatively. In addition, the authors conclude that further development is required to decrease the testing time of ten hours, so that it can be practical for field use.[16]

e) Phenolphthalein test (carbonation depth)

Phenolphthalein is an organic compound, $C_{20}H_{14}O_4$, which is regularly used to classify substances as basic or acidic. It has the property of changing color depending on the pH, colorless if the pH is less than 9 and pink if it is more than 9 (fig.4.9). Phenolphthalein is highly soluble in ethanol and insoluble in water.[17] A solution of phenolphthalein can be used as a qualitative test to indicate depth of carbonation in concrete elements, it is inexpensive, and it does not require special training to be performed. According to Broomfield,[18] maximum color contrast can be obtained with a solution of 1g of phenolphthalein in 100ml of a 50:50 alcohol-water mix. This solution should be sprayed on freshly exposed concrete, either by splitting a core sample or on a fresh fracture on the structure. Therefore, carbonation testing can be considered a destructive technique, since it inflicts mechanical damage to the built fabric in order to be performed, and the same area cannot be tested again, because once fracture exposes a new surface, carbonation will start in this new area. Care should be taken not to cross contaminate concrete layers with dust from different depths. It is also necessary to pre-wet the surface in case the concrete is very dry.

Although this test is well known and established in practice, there is no consensus standard to guide its application.[19] This might not be relevant for an immediate evaluation of carbonation depth, but if previous tests have been made, a reliable comparison

[16] Basheer, et al., 2005, p.228.
[17] http://en.wikipedia.org/wiki/Phenolphthalein
[18] Broomfield, 2007, p.55.
[19] Yu, Lee and Chung, 2010, p.1.

might not be possible if the same procedure is not followed. This can seriously compromise an estimation of carbonation rate. The reliability of this test is undermined by a variation in solution concentration utilized, amount sprayed, moisture content of the concrete, surface condition and time of measurement.[20] Sometimes this test can also be affected by aggregate's composition and the concrete color can provide poor contrast with the phenolphthalein, making it difficult to read.

However, the most important consideration regards the pH level at which any changes can be observed, known as the "end point". Phenolphthalein stains areas with pH above 9, but a pH below 11 is sufficient to break corrosion passivity.[21] Therefore, if carbonation is still in an initial stage around the reinforcement this test will not indicate the passivity loss. Yu, Lee and Chung have researched alternative chemicals that could be used instead of phenolphthalein or in combination with it. Their goal was to find an indicator whose end point was equal to or higher than pH 11, with a good hiding power to provide more contrast with the concrete, low toxicity and market availability. Their results indicate that tropaeolin O and a mixture of thymolphthalein and phenolphthalein meet these requirements, with end point of 12.1 and 11.2 respectively (fig.4.10). These alternatives also proved to have better color stability than pure phenolphthalein.[22]

Once the sample is stained and the carbonation depth is measured, the results should be plotted against depth of concrete cover. This comparison can indicate areas where the reinforcement is no longer protected by high alkalinity. An estimation of carbonation rate can be made by considering that the process has started right after hydration was complete.

[20] *Ibid.*, p.2.
[21] Broomfield, 2007, p.56.
[22] Yu, Lee and Chung, 2010, 6-7.

This should only be considered an estimation, because as carbonation progresses it decreases the permeability of the concrete cover. The permeability decrease causes the carbonation rate to drop. A more accurate result could be obtained by comparing carbonation depth values taken at different times in the structure's life, but, as stated before, the lack of standardization can compromise this comparison.

f) Chloride concentration measurement

Chloride ions can damage reinforced concrete if they are present in the pore solution of the concrete surrounding the reinforcement and once they reach critical concentration. Broomfield identifies two critical concentration values: 0.4% of Cl^- by weight of cement if chlorides are cast into concrete and 0.2% if they diffuse into concrete after it has cured.[23] However, Angst alerts that even after fifty years of research on this subject, no agreement has been reached among professionals on a value for the critical chloride concentration threshold.[24] Not all chloride ions result in reinforcement corrosion. Inherent chloride ions that are bound to molecules, either from aggregates or cement paste, are less important than the free ions diffused in from the atmosphere and found in solution inside pores.

Current techniques for measuring chloride concentration in concrete have to be performed in a laboratory with samples extracted from the building. These techniques either measure total chloride content or free chloride content, depending on the sample preparation required by each technique. These measurements should be performed on multiple samples,

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[23] Broomfield, 2007, p.23.

[24] These authors published a literature review on the subject. They identified the cause of disagreement as being the multitude of factors that influence the chloride threshold and the different techniques used to measure chloride content in each research. (Angst, et al., 2009, p.1123)

extracted from different areas of the structure, to ensure a result that is statistically correct. Material collected at different depths can also provide a profile of chloride concentration, which can be analyzed along with the material's diffusion constant in order to estimate the penetration rate.[25]

Total chloride content measurement techniques are performed in samples that have been powdered and dissolved in nitric acid solution. The amount of dissolution time and the strength of the solution can affect the quantity of bound chlorides released. The concentration of Cl^- ions in the resulting solution can be measured with a variety of techniques such as titration, ion selective electrodes or spectrometric methods. Angst considers X-Ray Fluorescence Spectrometry the most accurate technique, albeit more expensive. As a consequence of these techniques being well accepted by professionals, standards were developed: ASTM C-1152 "Standard Test Method for Acid-soluble Chloride in Mortar and Concrete" and RILEM TC 178-TMC "Testing and Modeling Chloride Penetration in Concrete".

Free chloride content measurement techniques differ from total chloride techniques in the sample preparation. For example, high pressure can be used on a sample to extract its pore water solution. However, this procedure is inadequate for concrete specimens with low water/cement ratio, coarse aggregate, or very dry samples. Some studies also raised the concern that the pressure might be high enough to pull away weakly bound chlorides, increasing the resulting value.[26] Another way of extracting the pore water solution is through leaching. This technique requires grinding the sample and mixing it with a mild solvent, such as distilled or boiling water, that will not dissolve bound chloride.

[25] Broomfield, 2003 (http://www.jpbroomfield.co.uk/html/corrosion_topics-condition_surveys.htm#Chloride)
[26] Angst, et al., 2009, p.1134.

According to Angst, total chloride content measurements are more frequently used because the effect of bound chloride on reinforcement corrosion is not fully understood yet, and there is also a question of reliability of the techniques that perform free chloride measurements.[27] Though corrosion risk might be overestimated with total chloride measurement, it allows for a margin of error that can be useful in the evaluation of such a complex mechanism of deterioration.

As described above, most of these techniques require extensive sampling and the consumption of the sampled material during analysis. The procedure has to be repeated every time a structure exposed to environmental sources of chloride is assessed, which would pose conflicts with the preservation of historical value of the material. The need for a laboratory and the time-consuming techniques that are currently available have to be taken into consideration when planning a survey. Some alternative techniques are being studied, such as laser-induced breakdown spectroscopy which has the capacity of quickly determining total chloride content of a sample without the need of a controlled environment. Though still in its infancy, this technique has the potential to be developed as an on-site assessment tool.[28] Another advantage is the small amount of material consumed in the process, which consists of vaporizing a small amount of surface material using a short laser pulse. Then, the chemical composition of this material can be determined by analyzing the radiation emitted by using a spectroscopic technique. Researchers have been working on improving the calibration of the technique to make chloride readings more evident in the resulting spectrum.[29]

g) Ground penetrating radar (GPR)

[27] *Ibid.*, p.1136.
[28] Wilsch, et al., 2005, p.724.
[29] *Ibid.*

This survey technique emits radio pulses and detects their reflections caused by sharp density changes in the material. At present, it is successfully used to locate voids and metal in reinforced concrete, as well as measure the concrete cover thickness over the reinforcement. The equipment is composed of an antenna to emit radio pulses, a transducer to collect reflected pulses and a portable computer to store the digital data produced. The equipment can vary in size and frequency. For example, bridge deck surveyors frequently use GPR equipment that can be attached to a vehicle, but handheld equipment is also available in the market. Data collection is very fast and it works by creating sections of the surveyed element as the transducer is dragged along a grid at regular intervals (fig.4.11). This data is entered into a computer where software creates a graphical representation of void, interface and reinforcement locations based on the data.

The accuracy of the graphic images depends on precise positioning of measured sections. Broomfield recommends the use of an electronic distance measuring wheel attached to the system.[30] Another solution, applied by Taffe, Hillemeier and Walther, and Stainbruch, is the use of an automated survey system coupled to a frame that guarantees the perfect alignment of the measurements.[31,32] Accuracy of the results also depends on the frequency of the antenna and the concrete conductivity.[33] While higher frequencies provide better resolution, highly conductive concrete decreases resolution due to its attenuation effect on the propagating waves. However, increasing the frequency has a negative effect on the maximum depth of readings. Consequently there must be a compromise between required surveyed depth

[30] Broomfield, 2007, p.86.
[31] Taffe, Hillemeier and Walther, 2010, p.6.
[32] Stainbruch, 2009, p.4.
[33] Perez-Gracia, et al., 2009, p.4.

and resolution when choosing the appropriate antenna frequency. Broomfield recommends 1.5 GHz for concrete surveys.[34]

Recent advancements in digital data processing capacity contributed significantly to the improvement of GPR data interpretation and accuracy. Stainbruch describes the advantages of 3D GPR surveys, such as the easier interpretation of results. He also mentions the possibility of using the technique to characterize the concrete with regards to its porosity, humidity and chloride content. According to Stainbruch, this was possible due to the increased sensitivity of the equipment for the detection of weak signals.[35]

h) Half-cell potential mapping

This technique is used to perform a qualitative analysis of reinforcement corrosion in reinforced concrete. It uses a high impedance digital voltmeter (around 10 megohm)[36] to measure the potential difference between a known metal embedded in a pre-fixed solution of its ions (an electrode) and an unknown (fig.4.12). In this case, the unknown is the steel reinforcement (iron alloy) embedded in a solution of corrosion products (iron oxide) of unknown concentration. It indicates the probability of corrosion, because it assesses the presence of dissolved iron ions in the concrete pores surrounding the reinforcement, but not depassivation. If corrosion is active, there will be a higher concentration of iron ions in the solution surrounding the reinforcement, thereby generating a lower potential. By convention, the positive terminal of the voltmeter is connected to the steel and the negative terminal to the reference electrode, therefore areas with active corrosion will have values that are more

[34] Broomfield, 2007, p.86.
[35] Stainbruch, 2009, p.1.
[36] Broomfield, 2007, p.46.

negative. These values depend on the nature of the metal used as the reference electrode, consequently results should be compared to threshold values according to the electrode type, such as the values identified on ASTM C-876-9 “Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete” and on RILEM TC 154-EMC “Recommendations: Half-Cell Potential Measurements- Potential Mapping on Reinforced Concrete Structures”.[37]

Copper/copper sulphate	**Silver/silver chloride/ 1.0M KCl**	**Standard hydrogen electrode**	**Calomel**	**Corrosion condition**
>-200mV	>-100mV	+120mV	>-80mV	Low (10% risk)
-200 to -350mV	-100 to -250 mV	+120mV to -30mV	-80 to -230mV	Intermediate risk
<-350mV	<-250mV	-30mV	<-230mV	High (>90% risk)
<-500mV	<-400mV	-180mV	<-380mV	Severe corrosion

Table 4.1- ASTM criteria for corrosion of steel in concrete for different standard reference electrodes. (Broomfield, 2007, p.49)

Half-cell potential measurements require a direct electric connection with the reinforcement, implying a small removal of concrete to uncover the reinforcement (fig.4.13). In order to minimize fabric loss, areas where the concrete has already spalled or where previous patch repairs have been made can be used for this connection. Once the steel is exposed, it should be cleaned and all corrosion removed in order to provide a good electric connection. Before proceeding with any measurements, the reinforcement should be checked for discontinuities, this can be done with a DC resistance meter placed between two well separated points on the reinforcement. According to Broomfield, the resistance should be less than 1 ohm.[38] Once the reinforcement and the reference electrode are connected to the voltmeter, the reference electrode is placed on the concrete’s surface taking point measurements on a pre-

[37] Elsener, et al., 2003.
[38] Broomfield, 2007, p.48.

established grid pattern. The values are stored in a digital data logger attached to the equipment, which are later plotted on a drawing of the surface to form a map of the potential measurements.

There are many factors that can affect a potential reading and influence the reliability of the results.[39,40] For example, a decrease in oxygen concentration at the reinforcement-concrete interface lowers the potential values, despite lowering the corrosion activity. In the case of carbonation, although it causes slightly more negative values, they are not proportional to the large increase in corrosion rate that carbonation causes. Previous interventions can also affect readings. Corrosion inhibitors can have either a positive or a negative effect on the potential values depending on their nature, and patch repairs can cause anomalies due to different characteristics of the concrete. The most influential concrete characteristic is resistivity, largely a function of pore saturation. Low pore saturation increases the electric resistance of concrete. This causes unreliable results, because readings from passive and active areas become very similar.[41] Therefore it is necessary to assess the structure for the presence of these factors prior to performing half-cell potential measurements. González, Miranda and Feliu recommend always measuring the concrete resistivity at the same location and time of potential measurement.[42]

It is generally recognized that potential measurements should be complemented by other techniques. This is due both to the multiple factors influencing the reliability of the results and their qualitative nature. There is a natural tendency to interpret the

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[39] Gu and Beaudoin, 1998, p.2-3.
[40] Broomfield, 2007, p.49-50.
[41] González, Miranda and Feliu, 2004, p.2473.
[42] González, Miranda and Feliu, 2004, p.2473.

results as absolute values indicating degrees of corrosion activity, however a small variation in potential can correspond to a wide range of corrosion rate values.[43] The ASTM standard C876-9 correlates degrees of corrosion activity and potential measurements, this was established based on empirical observations and developed for bridge deck assessments.[44] Since reinforcement corrosion in bridge decks are most commonly caused by chloride contamination due to the use of de-icing salts, these correlations are well suited for corrosion initiated by chloride contamination, but are less accurate in other cases where more parameters might influence the results. Poupard, et al., have studied alternative methods of interpretation for half-cell potentials. They describe the RILEM TC 154-EMC recommendations for half-cell potential measurements as a better standard, since it analyzes the results based on ranges developed for multiple scenarios, instead of absolute values based on a single influencing factor.[45]

Typical Ranges of Potentials of Normal Steel in Concrete Measured with a Copper-copper sulfate Electrode (Volts)	
Water saturated concrete without oxygen	-0.9 → -1.0 V
Wet, chloride contaminated concrete	-0.4 → -0.6 V
Humid, chloride free concrete	+0.1 → -0.2 V
Humid, carbonated concrete	+0.1 → -0.4 V
Dry, carbonated concrete	+0.2 → 0 V
Dry concrete [passive corrosion]	+0.2 → 0 V

Table 4.2- Correlation between potential range and concrete conditions, according to RILEM TC 154-EMC. (Elsener, 2003, p.464)

i) Concrete resistivity

Since corrosion is a reaction that requires an electric current to flow from anode to cathode, the electric resistivity of the environment where it occurs influences the corrosion rate. For example, a concrete structure with high resistivity is likely to have lower corrosion

43 Song and Saraswathy, 2007, p.4.
44 Broomfield, 2007, p.49.
45 Poupard, et al., 2006, p.510.

rates. The electric current flows through an electrolyte, in the case of concrete the electrolyte consists of the pore water and the dissolved ions in it. Resistivity is a measure of the ease of electron flow. Therefore it depends on the volume of electrolyte available (pore volume and saturation) and the tortuosity of the path (permeability). Given that higher porosity yields lower strength, resistivity has been increasingly used to indirectly evaluate the quality of concrete.[46] Moreover, it is an important complementary measurement for a more reliable interpretation of potential surveys. It should not be used as the sole indicator of reinforcement corrosion, because resistivity measurements are related to the capacity of the concrete to allow corrosion, but not to depassivation.

According to Broomfield, the technique used to measure concrete resistivity was developed to measure soil resistivity. Most equipments use four aligned probes, which are pushed onto the concrete's surface without causing any damage to it (fig.4.14). The center probes measure the voltage decrease of an electric current that is transmitted between the outer probes.[47] The positioning of the probes can influence the reliability of the results. It should avoid areas with reinforcement or, at least, be perpendicular to it, so that the current only passes through the concrete and not the reinforcement. The operator should also be aware of areas that are more prone to water accumulation, such as edges or depressions, since these measurements will be more affected by exposure to water than concrete characteristics. A standard for this technique can be found at RILEM TC 154-EMC "Test Methods for On-Site Measurement of Concrete Resistivity".[48]

j) Linear polarization resistance

[46] Song and Saraswathy, 2007, p.5.
[47] Broomfield, 2007, p.63.
[48] Polder, et al., 2000.

The linear polarization technique determines the corrosion rate at the time of measurement. It works by measuring the current being produced by the corrosion reaction, which is proportional to the amount of iron being oxidized. The equipment used is very similar to the one used to measure potential. However it has an extra electrode, referred to as the auxiliary electrode (fig.4.15). This technique works by monitoring the change in potential between the reference electrode and the reinforcement before and after the application of an electric current to the reinforcement. This electric current is applied through the auxiliary electrode. The current required to cause a change in potential determines the polarization resistance. Polarization resistance can be determined in two ways, depending on which factor is known and which one is measured. In the galvanostatic method the applied current is known and the potential change is measured, and in the potentiostatic method the necessary current applied to achieve a predetermined potential change is measured.[49]

In most equipment set-ups there is a third electrode that forms a ring around the other electrodes in order to confine the electric signal to the area immediately beneath it, otherwise the signal tends to form a cone and affect an unknown area of reinforcement. This would compromise the reliability of the results, because the equations utilized to obtain the corrosion rate from the change in potential depend on the affected surface area of reinforcement. The relationship between polarization resistance and corrosion current was determined by Stern and Geary in the equation:

[49] Broomfield, 2007, p.71.

Stern-Geary Equation:
(Broomfield, 2007, p.71)

$$I_{corr} = \frac{B}{Rp}$$

Where:

I_{corr}= corrosion current
B= constant
R_p= polarization resistance

Corrosion Rate Equation (µm/year):
(Broomfield, 2007, p.71)

$$X = \frac{11 \times 10^6}{A} \times \frac{B}{Rp}$$

Where:
A= surface area of steel in cm^2

Polarization Resistance Equation:
(Broomfield, 2007, p.71)

$$R_p = \frac{\text{(change in potential)}}{\text{(applied current)}}$$

A possible source of error in calculating the corrosion rate is the constant B. It can be either 26mV, if the steel is actively corroding, or 52mV, if the steel is passive. Therefore it is important to perform a qualitative assessment to distinguish between areas of active and passive corrosion before measuring linear polarization resistance.[50] Other factors that can affect the reliability of the results include: temperature, pore water content and area of steel being polarized. Temperature affects readings, because corrosion's chemical reaction is affected by the amount of heat energy available. Higher temperature also reduces concrete resistivity due to an increase in salt solubility and ion mobility.[51] As mentioned before in this chapter, concrete resistivity is controlled by the pore saturation. Although corrosion rate readings can be doubled depending on pore saturation, this is not enough to approximate passive and active corrosion readings, since active areas can have values 50-100 times higher than passive areas.[52]

Even though the use of a guard-ring helps to confine the signal, determining the exact surface area of steel affected by it is still challenging. According to Feliu, et al., it is not

[50] Mehta and Monteiro, 2006, p.422.
[51] Broomfield, 2007, p.76.
[52] González, Miranda and Feliu, 2004, p.2481.

possible to guarantee that the equipment is affecting the exact area underneath it. Their studies show that maximum current confinement can be achieved by maintaining an optimal ratio between the current densities that flow from the guard-ring to the working electrode (reinforcement) and from the reference electrode to the working electrode.[53] Other researchers propose to use another parameter, the time constant, to measure corrosion rate.[54,55] The time constant is determined by measuring the time interval necessary for the total change in potential to fall to 37% of the initial value and is independent of surface area.[56]

These are examples of the steady debate that has been developing recently on how to improve the accuracy of this technique. Scientific research is targeting improvements on the interpretation of the results, while using the same equipment set-up. Some consensus can be found at RILEM TC 154-EMC "Recommendations: Test Methods for On-Site Corrosion Rate Measurement of Steel Reinforcement in Concrete by means of the Polarization Resistance Method".[57]

Corrosion Current	**Interpretation**
I_{corr}<0.1 μA.cm^{-2}	Passive condition
I_{corr}0.1-0.5 μA.cm^{-2}	Low to moderate corrosion
I_{corr}0.5-1 μA.cm^{-2}	Moderate to high corrosion
I_{corr}>1 μA.cm^{-2}	High corrosion rate

Table 4.3- Correlation between corrosion current measured with devices that use a sensor controlled guard ring and corrosion rate. (Broomfield, 2007, p.75)

53 Feliu, et al., 2005, p.232.
54 González, et al., 2001.
55 Birbilis and Holloway, 2007.
56 González, et al., 2001, p.615.
57 Andrade, et al.,2004.

4.3. Survey Strategies for Preventive Conservation of Reinforcement Corrosion

After analyzing the literature regarding survey techniques, it is possible to conclude that there are very few techniques that are completely non-destructive. Even some of the techniques that are classified as “non-destructive” by the concrete industry, such as liquid/gas penetration, half-cell potential and linear polarization, still cause small damage, mostly during preparation for data acquisition. Furthermore, the current technology is still unable to provide non-destructive techniques to assess all aspects of concrete characterization. In the case of chloride, carbonation, composition and microstructure analysis, destructive techniques still provide the best results. Instead of dismissing techniques that cause any degree of damage to the historic concrete structure, the conservator should attempt to reach a balance between damage caused by surveying, amount and quality of information gathered, and preservation of site values. Having a clear view of what are the values that should be preserved and which elements of the building help to convey them is essential to plan an effective survey, because it provides criteria for choosing a survey technique.

The current state of technological development still does not permit a continuous monitoring of existing reinforced concrete structures without using embedded sensors. Because embedded sensors have to be installed prior to concrete placement, they have to be planned for during the structure’s design phase. This excludes the use of this technology in existing structures. Consequently, preventive conservation can only rely on intermittent monitoring in the case of reinforced concrete.[58]

[58] Long, Henderson and Montgomery, 2001, p.66.

The conservator should also be aware of the limitations and purpose of each technique in order to recommend the appropriate one. For example, visual inspection might be enough to survey deterioration that initiates on the surface, but it is not enough for a preventive approach to reinforced concrete. In this case, incipient deterioration (the target of preventive conservation) can only be detected under the concrete's surface by specialized techniques. Each of these techniques has limitations, but they can be used together to obtain more reliable and comprehensive results. For example, resistivity and potential measurements should be performed together in order to assess reinforcement corrosion, and carbonation depth should be plotted against concrete cover thickness values obtained with GPR survey to assess depassivation.

Combining techniques with different resolutions can work to the advantage of the survey plan. For example, Gowers and Millard mention the advantages of performing a preliminary assessment using resistivity and potential measurements followed by a detailed assessment using linear polarization.[59] This is based on the inherent characteristics of each technique. Resistivity and potential measurements should be performed together, as explained before, to improve the reliability of the results. These measurements are faster and cheaper to perform than linear polarization, but the resolution is much lower. According to Song and Saraswathy, areas that present a small difference in potential can have very different corrosion rate values.[60] Therefore, the preliminary survey with resistivity and potential measurements can indicate the critical areas where a detailed survey with the linear polarization technique will be necessary. Minimizing the survey area for corrosion rate is not only more economical, but

[59] Gowers and Millard, 1993, p.7.
[60] Song and Saraswathy, 2007, p.2.

increases the possibility of performing all measurements under similar environmental conditions. This measure will allow the comparison of values obtained at different points. Identification of areas of active corrosion, prior to corrosion rate survey, is also useful in choosing the appropriate value for the constant B.

Once the appropriate techniques have been chosen, locations to be sampled and where reinforcement connections can be made have to be determined. If a structure's size and budget restrain survey to a small portion of the total area, this area should be chosen from the ones most impacted by risk factors. In this respect the background information compiled from context, historic research and local observations will indicate the most likely critic areas. This will add a safety factor to the monitoring of the structure, because this area will probably have a higher rate of deterioration than the rest of the structure. Sampling areas should be representative of different risk scenarios found on the structure. Any necessary fabric removal, such as sampling and connections to the reinforcement, should be done taking into account the statement of significance of the structure.

According to McCann and Forde, the most influential factors in the success of a survey are:[61]

a) Depth of penetration
b) Vertical and lateral resolution
c) Contrast in physical properties
d) Signal to noise ratio
e) Existing information about the structure

[61] McCann and Forde, 2001, p.71.

Other points to be considered when planning a survey:

a) Level of professional training required

b) Access to the structure

c) Availability of techniques

d) Cost

e) Qualitative X quantitative

f) Adverse effects on the fabric.

When planning a survey, the decision on which techniques to use must take these points into consideration in addition to what has been said previously.

TECHNIQUE	PURPOSE	LEVEL OF EXPERTISE	LIMITATIONS	COMPLEMENT TECHNIQUE	LEVEL OF INVASIVENESS	STANDARDS
Context and Historic Research	Reveal risk factors inherited from the design, materials used, and location.	Low	Original documentation produced during the design phase might not include changes made during the construction phase	Visual inspection and testing	Non-destructive	No standards
Visual Inspection	Confirm background data, identify areas where damage is affecting concrete.	Low	Accuracy and level of detail determined by access to the structure and surveyor's comfort	Testing	Non-destructive	No standards
Petrographic Analysis	Identify mix proportions, carbonation depth, alkali-silica reaction among other damage mechanisms.	High	Amount of samples required for a statistically accurate result can be harmful to property's cultural values, and also cost prohibitive.	Non-destructive testing can confirm	Destructive Multiple core samples required	ASTM C457-98 ASTM C856-95e1
Standpipe Test	Determines absorption coefficient.	Low	Low sensitivity.	ISAT, AUTOCLAM, Figg	Non-destructive	RILEM Commission 25-PEM Test n.11.4
Initial Surface Absorption Test (ISAT)	Determine absorption coefficient.	Moderate	Difficult to ensure watertight seal. Affected by pore moisture content.	No complement technique	Some surface damage, depending on method used to attach equipment to the surface	No standards
AUTOCLAM	Determine absorption, air and water penetration coefficients.	Moderate	Affected by pore moisture content.	No complement technique	Some surface damage, depending on method used to attach equipment to the surface	No standards

Table 4.4- Comparison of evaluation techniques.

Figg	Determine absorption, air and water penetration coefficients.	Moderate	Drilling can increase local fluid penetrability due to formation of microcracks. Affected by pore moisture content.	No complement technique	Requires drilling in each area to be tested.	No standards
Schölin	Determine air penetration coefficient.	Moderate	Affected by pore moisture content.	No complement technique	Non-destructive	No standards
Rapid Chloride Diffusion Test	Determine chloride ion diffusivity coefficient.	High	Performed in a laboratory.	No complement technique	Destructive, core samples required.	ASTM C1202-10
In-situ Chloride Diffusion Test (PERMIT)	Determine chloride ion diffusivity coefficient.	Moderate	Experimental	No complement technique	Non-destructive.	No standards
Phenolphthalein	Carbonation depth.	Low	Indicates areas with pH above 9, but passivation is lost at pH 11.	Petrographic analysis	Destructive. Needs to be performed in freshly broken concrete, same sample cannot be reused for this test.	No standards
Chloride Concentration Tests	Chloride concentration	High	Performed in a laboratory. Chloride concentration will depend on sample extraction method.	No complement technique	Destructive, samples required.	RILEM TC 178-TMC

Ground Penetrating Radar (GPR)	Location of voids and metal in concrete. Concrete cover thickness	Low	Accuracy depends on precise positioning of measured sections. Higher frequency antennas provide better resolution, but depth of reading is compromised.	No complement technique	Non-destructive	No standards
Half-Cell Potential	Indicates probability of reinforcement corrosion.	High	Qualitative analysis. Some factors influencing corrosion activity are not well represented by this reading. High concrete resistivity makes values for passive and active corrosion areas very similar.	Resistivity, linear polarization resistance	Requires direct point of connection with reinforcement	ASTM C876-9 RILEM TC 154-EMC
Resistivity	Determines electric resistivity of concrete.	High	Function of pore saturation. Positioning of the probes in relation to reinforcement can affect results.	Half-cell potential, linear polarization resistance	Non-destructive	RILEM TC 154-EMC
Linear Polarization Resistance	Measures corrosion rate.	High	Time consuming. Difficult to confine signal to a known area. Determination of constant B depends on qualitative analysis of corrosion.	Resistivity, half-cell potential	Requires direct point of connection with reinforcement	RILEM TC 154-EMC

A B C

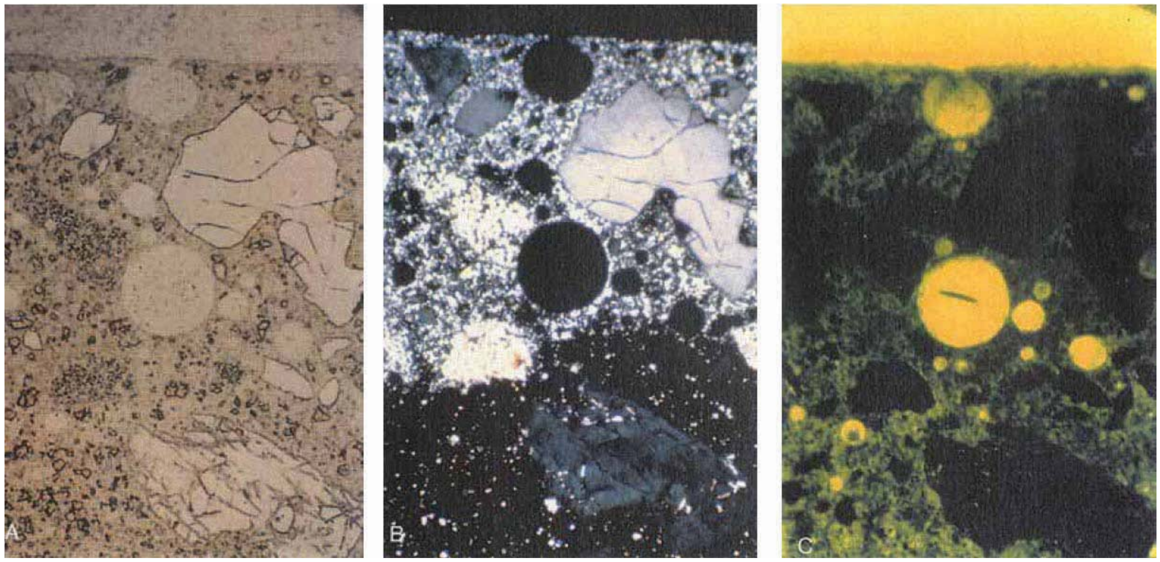

Figure 4.1- Thin section of a concrete specimen analyzed under a petrographic microscope. A) Regular light; B) Cross-polarized light: bright area shows the high birefringence of the calcite in the carbonated area; C) Ultraviolet light: fluorescence of the pore structure. (Walker, Lane and Stutzman, 2006)

Figure 4.2- Example of a core sample showing corroded reinforcement and cracks. (Walker, Lane and Stutzman, 2006)

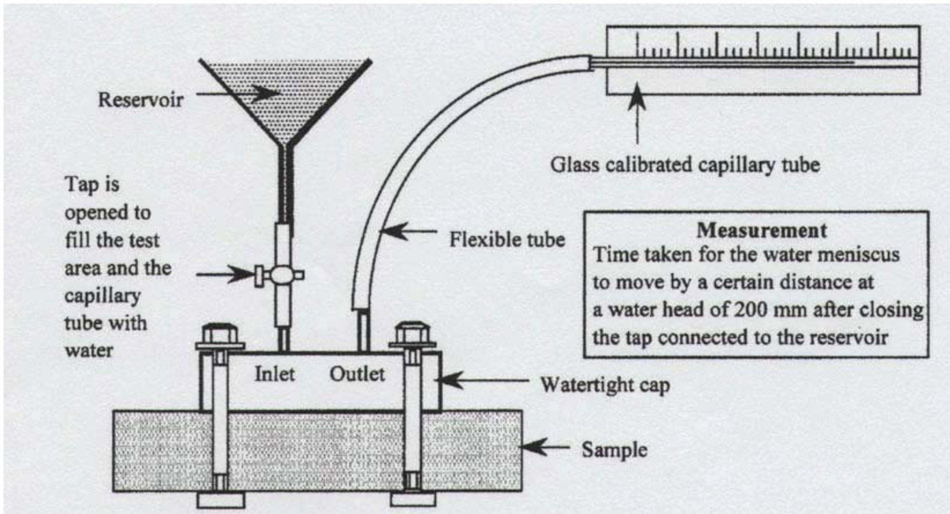

Figure 4.3- Schematic of an Initial Surface Absorption Test (ISAT). (Long, Henderson and Montgomery, 2001)

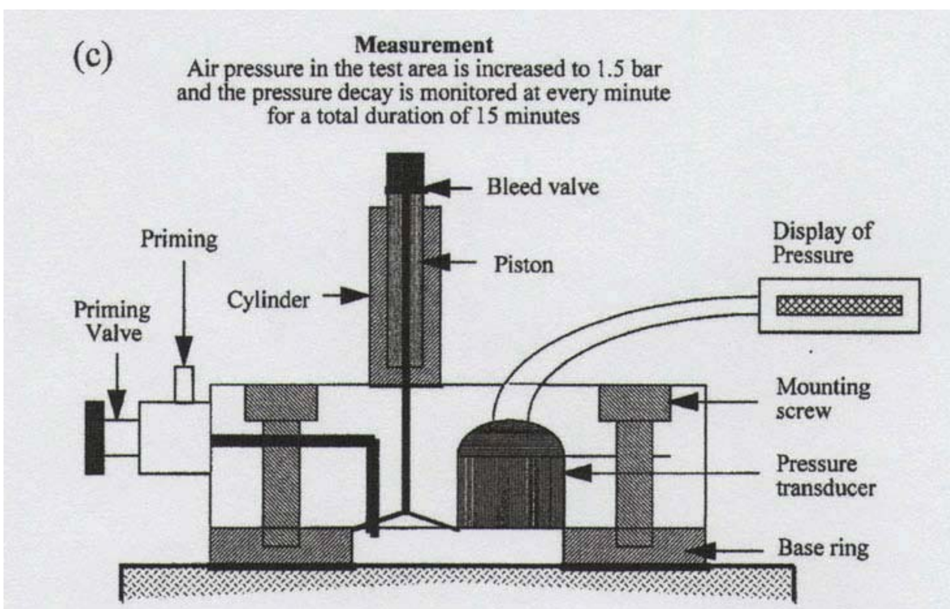

Figure 4.4- Schematic of an AUTOCLAM test. (Long, Henderson and Montgomery, 2001)

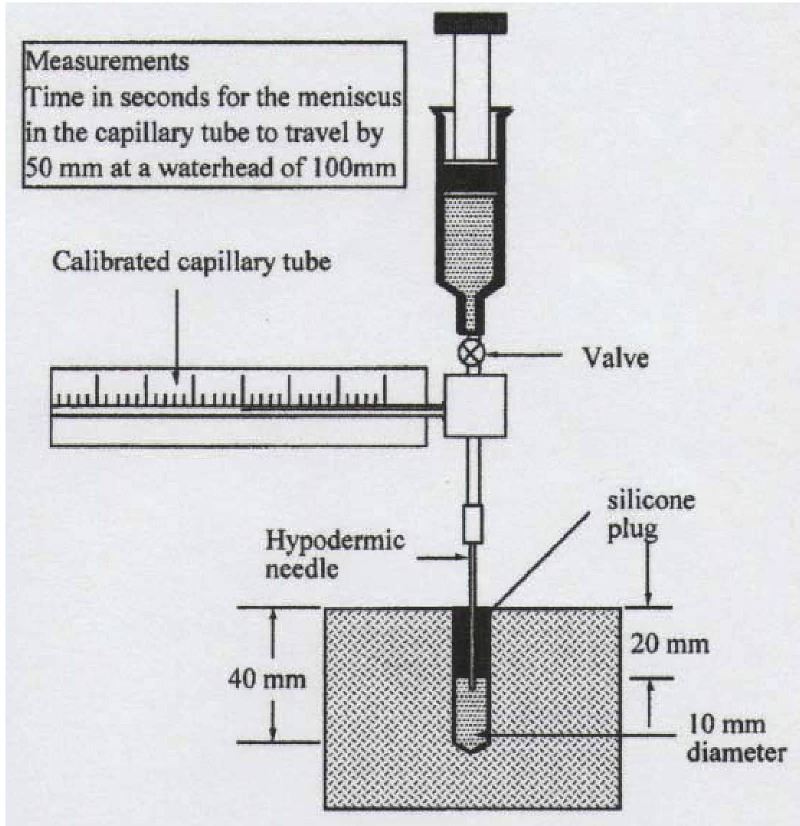

Figure 4.5- Schematic of a Figg water penetration test. (Long, Henderson and Montgomery, 2001)

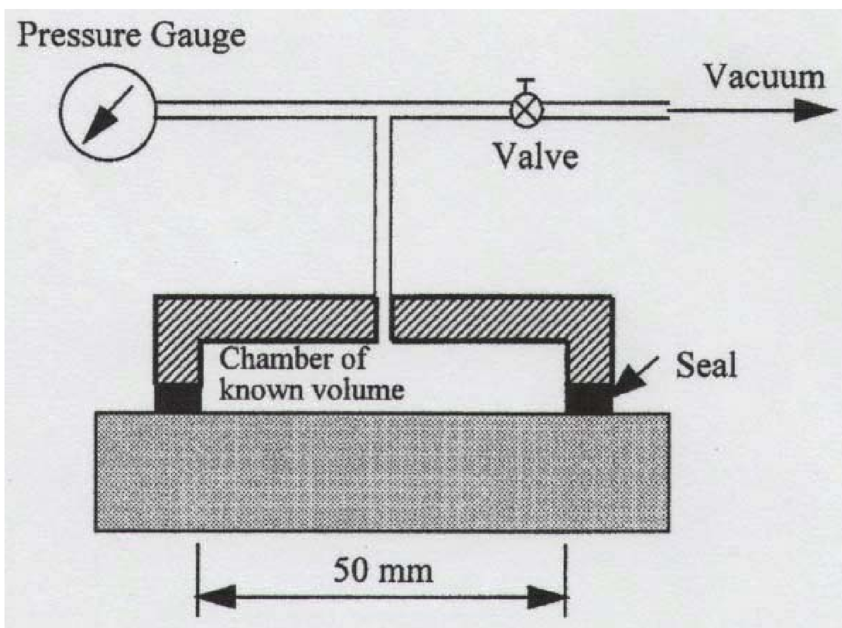

Figure 4.6- Schematic of a Schönlin air permeability test. (Long, Henderson and Montgomery, 2001)

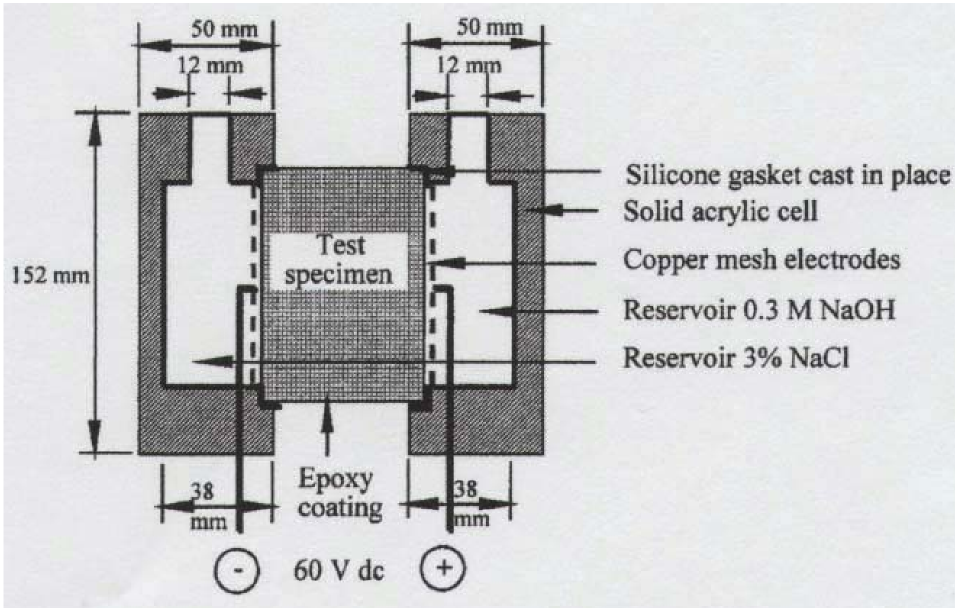

Figure 4.7- Schematic of a rapid chloride diffusion test. (Long, Henderson and Montgomery, 2001)

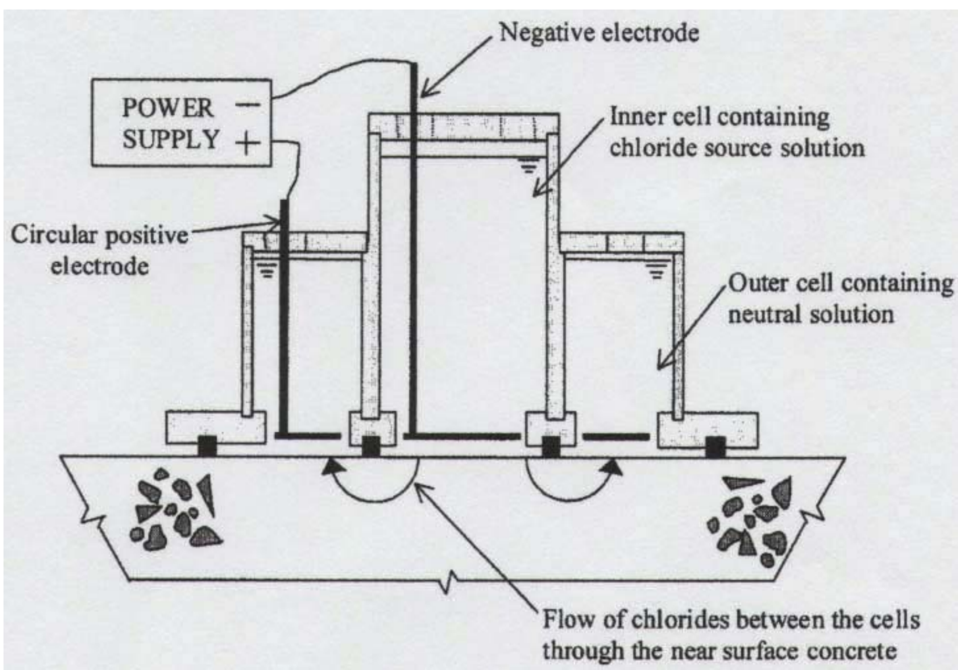

Figure 4.8- Schematic of an in-situ chloride diffusion test (PERMIT). (Long, Henderson and Montgomery, 2001)

Figure 4.9- Phenolphthalein tints areas with pH>9.

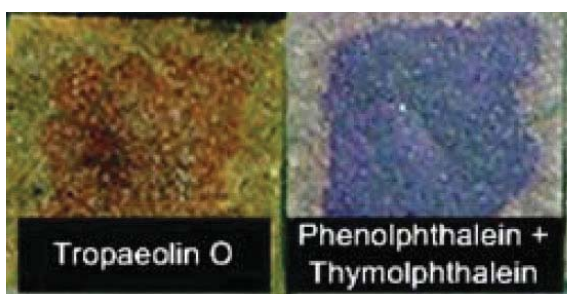

Figure 4.10- Alternative pH indicators: tropaeolin O (pH>12.1); mixture of thymolphthalein and phenolphthalein (pH>11.2). (Yu, Lee and Chung, 2010)

Figure 4.11- Data acquisition with a handheld GPR antenna. (http://www.geo-physical.com/structurescanoptical.htm)

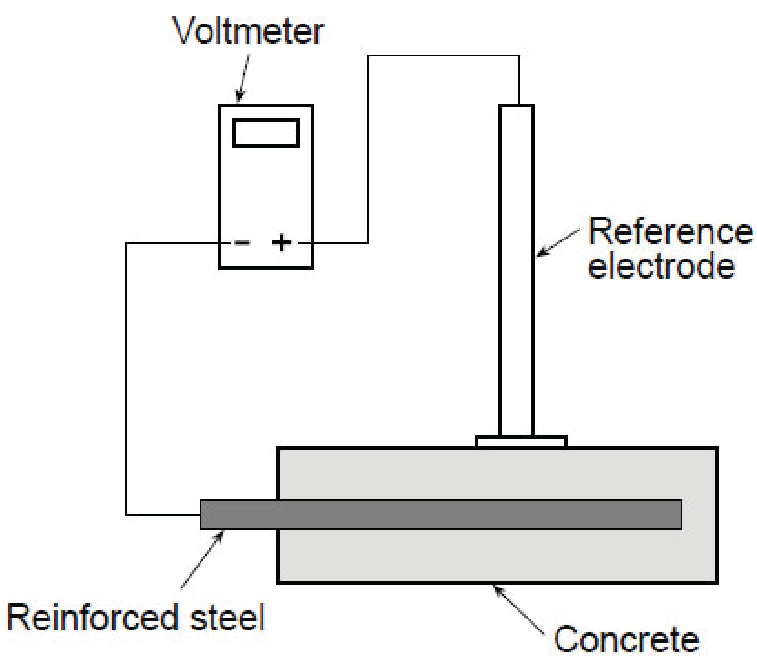

Figure 4.12- Schematic representation of a half-cell potential measurement set-up. (Gu and Beaudoin, 1998)

Figure 4.13- Example of equipment that uses a half-cell to measure corrosion potential. (http://www.ndtjames.com/Cormap-II-8482-s/100.htm)

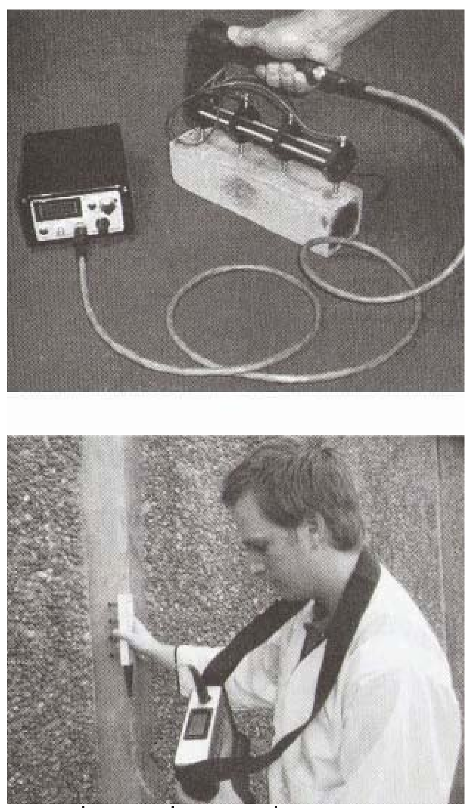

Figure 4.14- Equipment and procedure used to measure concrete resistivity. (Broomfield, 2007)

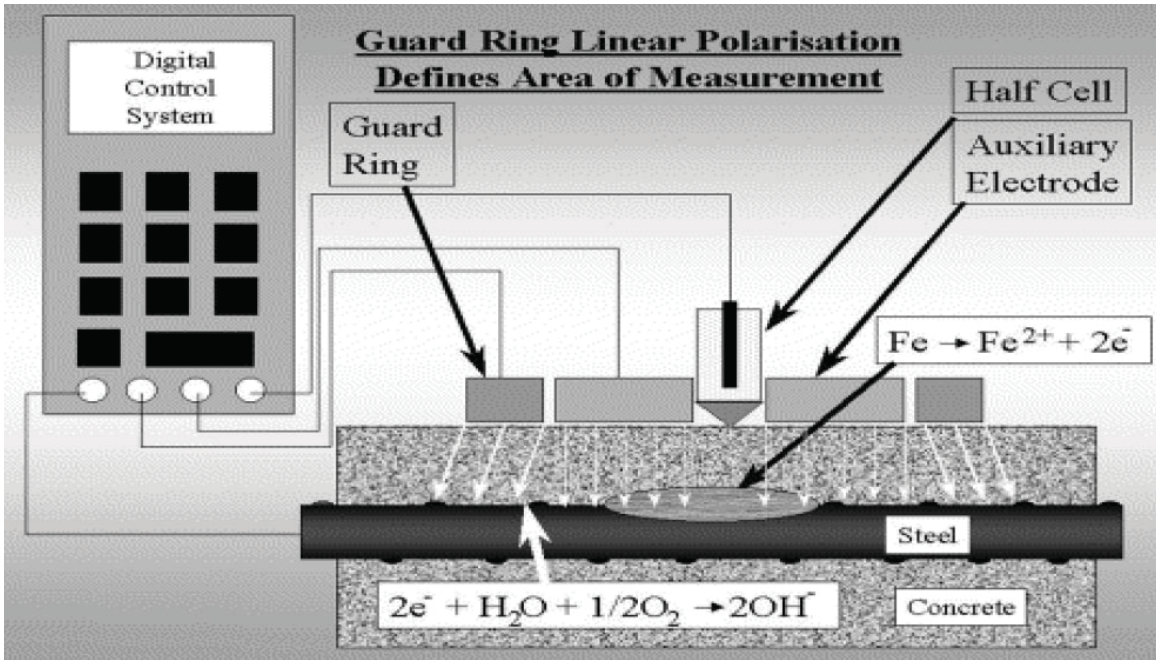

Figure 4.15- Schematic of linear polarization equipment. (Song and Saraswathy, 2007)

Chapter 5 – Case Study: Richards Medical Research Laboratories

This chapter illustrates how the survey methodology described in the previous chapter can be applied to a real case where the goal is to identify the state of concealed conditions, such as reinforcement corrosion, in order to inform interventions to prevent further damage to the building. This case is an example of how different damage mechanisms can interact by generating the necessary and sufficient factors for other mechanisms to occur, or by altering the conditions that affect their rate. In addition, this case study will show how the formulation of a hypothesis of damage mechanisms guides the subsequent survey, how the survey should be conducted and which techniques should be employed.

The Alfred Newton Richards Medical Research Laboratories, designed by Louis I. Kahn and completed in 1960, is an example of a mid-20th century building where the precast post-tensioned reinforced concrete structure has performed fairly well for the past 50 years. However, some damage is currently observable on the structural elements exposed on the façades. The current state of deterioration, though not alarming, requires action in order to prevent further unnecessary fabric loss that results from an acceleration of the deterioration rate and an increase of areas in need of invasive repair. Loss of fabric from the exposed structure at the Richards Medical Laboratories poses a threat to its architectural significance, since this characteristic is not only connected to the architect's design philosophy, but also comprises an essential feature in the building's aesthetical composition.

5.1. Statement of Significance

It is essential to have a clear understanding of why this building is considered a landmark. This status has been officially recognized in January 2009 when the Richards Medical Laboratories was designated a National Historic Landmark, forty-nine years after its dedication.[1] Understanding its significance is necessary in order to identify which architectural and structural features convey value and, consequently, to what degree they need to be preserved. The degree of preservation will impact the extent to which the building fabric can be disturbed for testing.

The recognition of the Richards Medical Laboratories' significance started even before the building was completed in 1960. The architectural community promptly identified in the building a manifesto, though unintentional, of a new design concept based on the same principles as the International Style, but interpreted and expressed in a new way. The Richards Medical Laboratories was the first project that brought Kahn the widespread appreciation of the national and international communities. The early recognition of the importance of Kahn's new project by the architectural community is illustrated by an exhibition on the Richards Medical Laboratories at the Museum of Modern Art in New York only one year after the building's dedication. Wilder Green, the curator of this exhibition, placed Louis Kahn in a different level than the rest of the generation that followed the great Modern masters of the inter-war period, Le Corbusier, Mies van der Rohe and Frank Lloyd Wright. According to Green, while the other architects restricted themselves to respectful expressions of the principles set by one of the great masters, Kahn had created his own unique interpretation of all three.[2] The significance of the Richards Medical Laboratories would only grow with time, paralleling Kahn's influence on all subsequent generations of architects.

[1] Cooperman, 2008, p.42.
[2] Green, 1961, p.5.

The Richards Medical Laboratories marks the beginning of the most influential phase in Kahn's work. In this project, for the first time the architect was able to clearly state the ideas that would guide the rest of his work. These ideas are expressed in the character defining features of the Richards Medical Laboratories.[3] The volumetric organization of the building into "servant" and "served areas" was a theme continuously explored by the architect. In this project, these functions were clearly differentiated through the use of materials and construction techniques.

While lecturing to a class of graduate students at the University of Pennsylvania in 1971, Kahn expressed his view on how an architect should approach the use of construction materials:

> *"(…) when you want to give something presence you have to consult nature. (…)And it's important, you see, that you honor the material that you use*."
> (Louis I. Kahn, My Architect: A Son's Journey, 2003)

Accordingly, Kahn explored the architectural expression of the load bearing structure at the Richards Medical Laboratories by emphasizing it throughout the building. On the façades, Kahn gave prominence to the precast structural elements. The combination of light grey colored concrete structure and dark brown colored brick masonry harmonize the building to its context, where it is surrounded by 19th century buildings characterized by the traditional use of brick masonry with accent features in light colored limestone. This is another important difference between Kahn and most architects of his generation; Kahn was able to overcome the contradictions of incorporating historical influences in his work.[4]

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[3] Cooperman, 2008, p.4.
[4] Green, 1961, p.5.

The construction of the Richards Medical Laboratories and the selection of Louis I. Kahn as its architect are related to an important transitional period in the history of the University of Pennsylvania. This period began after World War II, with the election of Harold Stassen (1948-1953), a prominent politician, as the first university president since 1755 who was not from Philadelphia. This decision was taken in an attempt to bring change to the university which had been experiencing a constant depreciation. According to Thomas and Brownlee, one of Stassen's most significant decisions was the hiring of G. Holmes Perkins as the new Dean of the School of Fine Arts with the authority to hire new faculty members.[5] The group of professionals gathered by Perkins reflected his engagement with modern architecture. This mainly young faculty body hired in during the 1950s, with members such as Romaldo Giurgola, Robert Venturi and Denise Scott Brown, was complemented by more experienced, yet modern, professionals like Louis I. Kahn, who joined the group in 1957.[6] Lead by Perkins, this group of architects would have a deep influence on the architecture curriculum, as well as on the campus of the University of Pennsylvania.

By the time Perkins had gathered a new faculty group for the School of Fine Arts, Gaylord P. Harnwell (1953-1970) had taken over the University presidency from Stassen. Harnwell was the main force behind the modernization of the university and its campus in the 50s and 60s. These changes were based on the university's shift in direction from a theory- and sports-based educational institution to a research-based program. This shift was a response to the new sources of funding and the national desire to maintain technological leadership during

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[5] Thomas and Brownlee, 2000, p.118.
[6] *Ibid.*

the Cold War period.[7] The sudden increase in demand for research space was met with the construction of new facilities that expressed this new phase of the university with an aesthetic that was a clear adoption of contemporary design (fig.5.1). One of the first buildings to follow these new trends was the David Rittenhouse Laboratories (1952-54), designed by the Office of James R. Edmund with additions (1964-67) by Carroll, Grisdale and Van Alen. The decision to adopt the language of modernism was influenced by Dean Perkins, who often took on the role of selecting architects for the new constructions, as in the case of the Richards Medical Laboratories.

From the large number of buildings under construction at the University of Pennsylvania around the same period as the Richards Medical Laboratories, Eero Saarinen's Hill Hall (1960), a women's dormitory, stands out (fig.5.2). Saarinen would often visit Kahn's construction site after inspecting his own.[8]

The David Goddard Laboratories (1961-1964) are the western part of the laboratory complex designed by Louis I. Kahn with a scheme similar to the Richards Medical Laboratories (fig.5.3). In 1960, Kahn also designed the Florence and David Kaplan Memorial Wing, a small single-floor laboratory building located on the south side of the Leidy Laboratories. Although a second floor was added in 1963-64, designed by Vreeland and Schlesinger, this building still exhibits the same architectonic language employed by Kahn at both the Richards Medical Laboratories and the Goddard Laboratories (fig.5.4).[9]

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[7] *Ibid.*, p.123.
[8] Komendant, 1974, p.19.
[9] Thomas and Brownlee, 2000, p.243.

The close relationship between design and structure employed by Louis Kahn at the Richards Medical Laboratories can be illustrated by a visit of Eero Saarinen to the construction site, as reported by August E. Komendant, structural engineer to the Richards Medical Laboratories project:

> *"One day he* [Eero Saarinen] *was accompanied by Louis Kahn, they were good friends. Eero wanted to tease Louis and asked, "Lou, do you consider this building an architectural or a structural success?" Kahn was irritated and answered, "Your question is a valid one. The elements and their shapes, like the structure they form, evolve so logically from the architectural requirements that 'structure' and 'building' cannot be separated, the one evolves the other!"."* (Komendant, 1975, p.19)

5.2. History

This section analyzes historical data gathered from secondary sources, such as books published about Louis I. Kahn and his body of work, as well as primary sources, such as drawings and reports found at the University of Pennsylvania's Facilities & Real Estate Department Archives, and at the Architectural Archives of the University of Pennsylvania, which houses the Louis I. Kahn Collection and the August E. Komendant Collection. The goal was to gain better understanding of the design and construction processes and how they might influence damage mechanisms. In addition, relevant historic information was gathered and reviewed to identify the extent and nature of damage addressed by previous repair campaigns, and to determine when the damage started to be observed.

Louis I. Kahn (1901-1974) was commissioned by the University of Pennsylvania in 1957, same year he began teaching architecture at the university's School of Fine Arts, to design a new building for the research department of the School of Medicine.[10] Kahn had

[10] Thomas and Brownlee, 2000, p.239.

graduated in architecture from the University of Pennsylvania in 1924. His office was located at 1501 Walnut Street in Philadelphia, the city where his family established themselves when they emigrated from Estonia and where Kahn would live his entire life. Before 1957, Kahn had been teaching in the architecture department at Yale for nearly ten years. Though Kahn had had a productive career, few of his works had gained attention, and only the Yale University Art Gallery (1951-1953) had reached a high level of recognition.[11]

Early in the process he decided to engage the structural engineer August E. Komendant as a consultant. Kahn had met Komendant one year earlier when they had worked together in a competition project.[12] Komendant was a New York-based structural engineer who had immigrated to the United States in 1950. Like Kahn, he was born in Estonia, but moved to Germany where he studied and received a doctorate in engineering from the Technical University of Dresden. After World War II, Komendant became a pioneer in the use of prestressed, as well as, post-tensioned reinforced concrete and made important contributions to the development of these techniques.[13] In the United States, Komendant wrote a manual "Prestressed Concrete Structures" (1952) that became an important text book on the subject. The collaborative partnership between Kahn and Komendant would help to mold the majority of Kahn's masterpieces developed after the Richards Medical Laboratories.

During the development of the design for the Richards Medical Laboratories, Komendant and Kahn worked together to create a functional building that made full use of the new possibilities offered by the use of precast prestressed concrete technology. In this design Kahn explored the aesthetics of the building material and structure, a theme that became a

[11] Leslie, 2005, p.48.
[12] Komendant, 1975, p.1.
[13] Leslie, 2005, p.96-97.

constant in his career. For the functionality, Kahn relied greatly on conversations with the researchers.[14] The design process also involved other professionals like Keast & Hood, structural engineers in Philadelphia, PA, who were the main consultants for the cast-in-place concrete.

Komendant reported that there was some difficulty in finding a contractor because of the novelty of the techniques chosen.[15] The Farrell Construction Company was engaged for the general construction and Atlantic Prestressing Company was responsible for precasting and assembling the post-tensioned elements. However, the actual erection was subcontracted to Cornell and Company, which specialized in steel frame erection, but had no experience with precast concrete. The Atlantic Prestressing Company still performed the most specialized tasks, such as grouting and post-tensioning. The structural fabrication and erection process was overseen by Keast & Hood and Komendant, who also inspected the precasting plant in Trenton.[16] Initially there was some delay on the construction process due to the unfamiliarity with the material and the complex coordination of work on a site with limited access and area.[17] However, the rhythm normalized after the construction team adapted to the job.[18]

The building was dedicated in May 1960 and was soon the subject of criticism. While the professional community praised the architects and engineers for their masterpiece, the everyday users and the university were not satisfied with the performance of the building. The main criticisms involved high heat gain, glare in the spaces and cracking of the masonry and some of the glass panes. Following these negative evaluations, in 1961, the University of Pennsylvania commissioned the United Engineers & Construction, Inc., a Philadelphia-based

[14] Komendant, 1975, p.8.
[15] Komendant, 1975, p.12.
[16] *Ibid.*, p.23.
[17] Leslie, 2005, p.114.
[18] *Ibid.,* p.115.

architecture and engineering firm, to conduct a complete condition survey and to recommend solutions.[19] Although this report could not be located, the 1964 report made by the same company recaptures some of the essential findings of the 1961 report. Regarding the precast structure, United Engineers reported, in 1964, that their biggest concern was the "rainwater leakage at precast concrete spandrel beam intersection(s) in various locations at exterior corners of Towers "A", "B" and "C"."[20] United Engineers & Construction found the cause to be the improper caulking of these joints, and the recommendation was to re-caulk them with "Silicone Construction Sealant (General Electric Company)".[21] The 1964 report also describes brown discoloration at hairline cracks on the surface of precast concrete columns that had been treated with a coat of "Rubber-Coat Liquid Hypalon"[22] following the recommendations of the 1961 report. They reported that the Hypalon-based product manufacturer (Wilbur & Williams Company, Inc) was investigating the cause of the discolorations. However, the most interesting condition reported refers to the longitudinal cracks observed on the flanges of the precast columns. The 1964 report is restricted to quoting the previous report in lesser detail and the 1964 report does not make it clear if these cracks were new or from 1961. The 1964 report indicates that the causes for these cracks were not known, it is not stated if any further investigation besides visual inspection had taken place. The 1964 report summarizes the work on the columns that followed the 1961 report:

> *"The precast columns and spandrels were rehabilitated in December of 1962 at which time <u>rust spots and exposed ends of reinforcing steel</u> were cut out, open holes were filled, the longitudinal cracks were filled and sealed, and the exposed*

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[19] "(…) a construction management firm that was then bidding on the construction contract for the second phase of the project, the Biology Building." *Ibid*., p.116.
[20] Dallas Jr, 1964, p.I-A6.
[21] Dallas Jr, 1964*,* p.I-A7.
[22] According to DuPont's website, Hypalon is a trade mark for chlorosulfonated polyethylene. (http://www.dupontelastomers.com/Products/Hypalon/hypalon.asp)

surfaces were washed and given two coats of silicone water repellent. The longitudinal cracks in the column flanges were opened at the bottoms to bleed off entrapped water, which freely ran out in many instances, and where the cracks were sufficiently open they were sealed with Hypalon putty forcefully knifed in to fill the openings. Liquid Hypalon (…) was brushed on over hairline cracks and those cracks not sufficiently wide to permit entrance of Hypalon putty as well as over cracks filled with the putty." (Dallas Jr 1964, I-A8) [highlights added]

The 1964 report identified the same type of longitudinal crack on the flanges of the precast columns that had been described and treated in 1961. The 1964 report did not make any new recommendations for this condition. However, the drawings that accompanied the report, which could have contained more information regarding treatments, were not located.

The only other report on the Richards Medical Laboratories' concrete available at the Archives of the Facilities & Real Estate Department at the University of Pennsylvania is a September 1994 report made by the Keast & Hood Company, but the drawings accompanying this report appear to be missing. The absence of drawings, a critical component of the report, compromises the full understanding of the report, since the location of the repairs was only indicated on the drawings. The 1994 Keast & Hood report was done in preparation for a bid that included "concrete restoration". The report described the recommended method to repair the exposed reinforcing bars and to patch the concrete spalls. The repair method consisted of removing the deteriorated concrete and replacing it with a patch made of a "two-component polymer modified cementitious patching compound system" that should be anchored to the substrate using stainless steel rods if the patch had to be deeper than 1-1/2". If exposed reinforcement was involved, all rust had to be removed along with the surrounding concrete with a minimum depth of ¾" behind the reinforcement and a primer should be applied to the reinforcement with a brush (the report does not mention what kind of primer).[23]

5.3. Background

This section provides the background information needed for the analysis of the current conditions of the exposed architectural concrete on the façades of the Richards Medical Research Laboratories. The location, description of the physical context of the building and environmental data are needed to identify possible external factors that might contribute to present and future deterioration of the building. A description of the building's materials and structural system provides an understanding of how this building was constructed and how that might influence its vulnerability to deterioration.

5.3.1. Location and Climate

The Richards Medical Laboratories is located along the south side of Hamilton Walk, a pedestrian walkway running on an east-west orientation on the south part of the University of Pennsylvania's campus (fig.5.5). Both sides of Hamilton Walk are lined with grass and tall trees, while the pavement consists of asphalt. The Richards Medical Laboratories is connected on the east side to the John Morgan Building, a two story building constructed in 1904, and designed by Cope & Stewardson to house the School of Medicine (fig.5.6). To the west, the Richards Medical Laboratories is connected to the Goddard Laboratories, a six story building completed in 1964 and also designed by Louis I. Kahn following a design similar to the one used for the Richards (fig.5.3). The Richards Medical Laboratories faces the Quadrangle to the north, a three story student residence, built in 1895 and designed by Cope & Stewardson

[23] Keast & Hood Co., 1994.

(fig.5.7). To the south of the Richards Medical Laboratories is the James G. Kaskey Memorial Garden characterized by tall trees and dense vegetation surrounding a pond, this area opened in 1897 as a research garden for the biology department (fig.5.8). The yard area to the north of the Richards Medical Laboratories is generally flat. However, the south yard slopes up from the ground floor level to the garden. At the southeast side of the Richards Medical Laboratories is a driveway accessing the service entrance on the basement level.

Philadelphia is in an area of warm/humid continental climate according to the Köppen-Geiger Climate Classification[24]. The ANSI/ASHRAE Standard 90.1 International Climate Zone classification is Zone 4A Mixed-Humid. The normal daily maximum temperature between 1964 and 1993 was 63.4°F and the minimum was 45.1°F. During this period the mean number of days with minimum temperatures below 32°F yearly was 95.4.[25] Philadelphia has an average of 52 freeze/thaw cycles annually.[26]

5.3.2. Structure and Materials

The Richards Medical Laboratories is composed of three seven story high towers clustered around a fourth tower, nine stories high. Each tower was designated a letter in order to aid communication during construction: tower A is located to the east, tower B to the north, tower C to the west and tower X is the core tower that connects and serves all the other ones (fig.5.9). Tower X is known as the service tower, because it houses all the animal quarters, mechanical rooms, vertical distribution of services, restrooms and elevators needed to serve the laboratory spaces. The structure and organization of tower X distinguish it from the other ones,

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[24] http://commons.wikimedia.org/wiki/File:World_Koppen_Map.png
[25] Wood, 1996, 836-839.
[26] National Climatic Data Center, 2006.

and reflect the difference in program. Towers A, B and C have the same structure and similar spatial configurations. Their internal spaces are occupied by diverse laboratories used for medical research. The laboratory spaces are organized around a central corridor and are fitted with generous corner windows. At each floor level, the central corridors in each tower connect with tower X via a small enclosed bridge (fig.5.10). Some characteristics are common to all towers. The foundation consists of deep footings of cast-in-placed reinforced concrete.[27] The towers have flat roofs and the same brick is used throughout the building. The floor-to-floor height is 12 feet in all towers.

Tower X is built of two-way cast-in-place reinforced concrete slabs supported by solid walls of cast-in-place reinforced concrete. According to Komendant, the structure of tower X did not lend itself to construction in precast reinforced concrete, so a decision was made to build it in this more traditional technique.[28] Tower X is rectangular in plan, measuring 50 feet 7 inches by 73 feet 9 inches, and its heavy appearance is related to its massive structure, necessary due to the load of all mechanical systems including cooling towers on the ninth floor (fig.5.11). The walls have an external cladding of brick masonry with few windows (fig.5.12). The limited access to natural light in Tower X hints of the architectural program that consists of circulation and short-term-occupancy spaces.

Towers A, B and C are built of columns and girders made of precast reinforced concrete with post-tensioning tendons, and cast-in-place reinforced concrete slabs. In these towers, all service uses, such as emergency staircases and exhaust systems for the fume hoods, are located in smaller subsidiary towers attached to them. The subsidiary towers are built of

[27] Leslie, 2005, p.111.
[28] Komendant, 1975, p.10.

cast-in-place concrete, similarly to tower X, and are located on the center of the façade of the laboratory tower they serve (fig.5.13). Subsidiary towers were made taller than laboratory towers in order to create a broken roof line. Towers A, B and C have a square floor plan measuring 47 feet-4 inches on each side. Each façade is divided in three bays by two columns symmetrically located leaving the end bays cantilevered 15 feet-2 inches to each side (fig.5.14). The façade columns are connected by post-tensioned pre-cast reinforced concrete Vierendeel beams and post-tensioned pre-cast reinforced concrete edge beams.

The elements of this precast reinforced concrete structure were cast and cured off-site, in a plant using metal formwork and steam curing. In the case of the Richards Medical Laboratories, most structural elements were cast in multiple sections, which were connected on site by post-tensioned tendons running in ducts cast through the section of the member. For the Richards Medical Laboratories, steel rods were used as tendons (fig.5.15). These rods were, then, subjected to a certain tension with the help of a hydraulic jack (fig.5.16), and rod ends were anchored so that the tension would be maintained through the service life of the building. Finally, the ducts were grouted in order to prevent water entry, and to protect the steel rods from corrosion. The joints between two adjacent members were grouted as well. The tensioned rods apply a compressive load on the members, which compresses the cement paste and reduces the volume of voids and microcracks. Consequently, it increases the load capacity of the member making it possible to reduce the member cross-section. All the precast concrete structural members in towers A, B and C were cast in a plant located in Trenton, NJ, by the Atlantic Prestressing Company, and were stored at the plant until needed at the site for assembly. This was necessary due to the restricted construction site area that was insufficient to store the precast concrete members.

The seven-story-high columns were cast in seven pieces, one per floor. These columns have a transversal section shaped like an "H" with asymmetrical flanges (fig.5.17); the flange closest to the building is thicker than the exterior flange. The bottom end of each column section is stepped at the thicker flange (fig.5.18). This allows the column section to seat on the beam and the column element below, like a spandrel. The inner face of the thicker flange is set flush with the main plane of the façade. The thicker flange houses five ducts for post-tensioning rods and the thinner flange houses four ducts. The columns and the edge beams are exposed on the façade, with no protective coating or cladding on the concrete.

Once the column members that composed a floor were in place, two main prestressed transverse beams were placed parallel to each other and between opposing columns, through the core of the tower. These beams were precast in one piece spanning the full length of the floor. In the perpendicular direction, the second pair of transverse beams was set. The second pair of transverse beams has the same dimensions as the first pair, but the second pair was precast in separate pieces that fit between the first pair of transverse beams, and post-tensioned. The transverse beams form a Greek cross in plan. The edge beams, also cast in one piece, were the next elements to be placed in the structure. The final pieces formed secondary beams of slender sections that subdivided the remaining spans (fig.5.19). All beams are constructed in the Vierendeel system. In order to maximize span with a minimum amount of material spent, these beams are shaped like trusses, but with the fundamental difference that, unlike a truss, a Vierendeel beam has no diagonal elements. The resulting openings allow the mechanical systems to be installed close to the floor slab, and occupying the residual space left by the height of the beams. This is useful in buildings, such as the Richards Medical Laboratories, which require numerous mechanical system zones serving the individual laboratory spaces.

After erection of the precast beams was complete, the reinforced concrete floor slab was cast. In order to allow time for the slab to cure before loading, concrete placement was sequenced among towers. In this way, the erection of precast members would proceed in the other two towers while the third had a slab cast and cured.[29] The final step was to construct the non-load bearing external walls of double width brick masonry topped by windows that extend to the underside of the floor beam above (fig.5.20).

The specifications for the project are non-specific with respect to the concrete. The mix proportioning and admixtures are not specified. Specification requirements are limited to the desired strength after 28 days (5000 psi), the recommendations of industry standards like ASTM and ACI, and that all exposed concrete surfaces be dense and uniform, with no reworking, voids or honeycombs. The specifications focus on requirements for the control of the construction quality, such as regular laboratory testing of the concrete batches and of all raw materials entering the plant, as well as designating an inspector engineer to oversee the process of manufacturing the precast elements.[30] Currently, the precast post-tensioned structural elements present a smooth, homogeneous concrete, light grey color, and only few fine aggregates are visible on the original surface.

5.4. Current Conditions

The conditions reported in this section refer to the post-tensioned precast reinforced concrete elements exposed on the façades of the Richards Medical Laboratories. These current conditions have been observed through visual inspections made from the ground

[29] Leslie, 2005, p.114.
[30] Architectural Archives of the University of Pennsylvania, Louis I. Kahn Collection, *Specifications for the Construction of New Medical Research Laboratories for the Trustees of the University of Pennsylvania*, May 19, 1958.

level using a digital camera, Sony DSC-H20, with lenses focal length 6.3-63 mm. Therefore, the surfaces of the column's flanges that are hidden from view due to their geometry, proximity to other building features, or hidden by trees, in the case of the south façade, could not be observed. Some of the conditions could be more easily observed on the elements at ground level.

The conditions observed on the post-tensioned precast reinforced concrete elements exposed on the façades of the Richards Medical Laboratories tend to affect columns more frequently than beams. Given the fact that each column is composed of individual precast sections, they were assessed unit per unit while still contextualizing these sections on their overall location in the structure. It was observed that not all column sections present damage, although a closer method of observation is needed to confirm this statement. Columns that present the highest number of deteriorated sections are the ones more exposed to rain, evidenced by the fact that columns protected by the proximity to other towers present a higher degree of soiling, but no disruption of the concrete mass (fig.5.21). The soiled surfaces are evidence of the minimal rainwater exposure, which would clean these surfaces of atmospheric deposits (fig.5.22). On the affected columns, damaged sections seem to be randomly located, i.e. they do not occur in higher concentrations at particular floor levels.

Conditions ordinarily occur in combinations of various types, suggesting a relationship among them. Therefore, the conditions that affect the same areas will be analyzed together. One condition that is, more often than not, associated to other condition types is corrosion staining. Corrosion stains are deposits of iron oxides (rust) in the surface of the concrete. These stains were found associated with cracks, spalls that reveal reinforcement (fig.5.23), and reinforcement that was originally protected with little concrete cover (fig.5.24). Although these stains can be considered minor aesthetic issues, offering no major threat to the building, they are an indication of an active corrosion process on the reinforcement beneath the surface of the concrete.

Different types of cracks were observed on the precast concrete surface. The most obvious and common are cracks that are clearly developing into spalls (fig.5.25). This is noticed because of the change of plane between the two sides of the crack, where one side is protruding from the elevation. These cracks are usually shaped as semi-ellipses. In the cases of cracks with severe face level change, cracks tend to form a complete ellipse. They often occur with corrosion stains below them. The other two types of crack were only observed in unique occurrences. A longitudinal crack was noticed on the central portion of the flange's lateral of the top floor section of the northeast column located at the north façade of tower A (fig.5.26). In this case the area also presented exposed reinforcement and concrete spalls. This crack matches the description of the 1964 report.[31] The third crack type observed forms hairline patterns on the concrete surface of the ground floor section of the northeast column of the east façade of tower B (fig.5.27). In this case, the surface of the concrete was homogenously covered with microcracks on the cement paste that were short in length and had no predominant direction. The concrete surface of this column section has a different texture than the other column sections observed at the ground floor level. It is smoother and presents no aggregates. Since these cracks can only be noticed at close inspection due to their hairline width, it is not possible to ascertain whether they occur in other column sections located above ground level.

[31] Dallas Jr, 1964, p.I-A8.

A more severe type of damage observed consists of concrete spalls. This damage is characterized by the loss of shallow sections of the concrete (fig.5.28). They mostly occur on the column flanges, usually on the face, but also observed on the side that faces the building (where they could be accessed on the ground level). On the edge beams, they are sometimes located on the window corners. In at least one instance it was possible to observe a corroded window frame anchor associated to a spall on an edge beam (fig.5.29). All concrete spalls observed revealed a corroded reinforcement bar that had once been covered by a layer of concrete.

Exposed reinforcement is observed in two situations: associated with concrete spall (fig.5.28) or originally lacking a concrete cover (fig.5.30). In all instances, the exposed reinforcement is covered with iron oxides, which sometimes percolates on the concrete surface forming the previously described corrosion stains. Even though this condition is more common on the horizontal reinforcement on the lateral of the column flanges, it can also be found on the column's edges. Additionally, exposed reinforcement was observed on the edge beams, in which case they seem to affect mostly vertical reinforcement (fig.5.31).

Previous repairs can be seen as distinct patches on the columns. They are most often found on the edges (fig.5.32), but the ground floor level section of the northwest column on the north façade of tower B has multiple patches on the flange's face (fig.5.33). The edge patches are in good conditions, but the ones mentioned in tower B present cracks and corrosion stains. The concrete used for these patches are very different, suggesting different repair campaigns. Another evidence of previous repairs is the presence of highly reflective areas (fig.5.34), usually shaped as a longitudinal crack on the main face of multiple sections located in different columns. The glossy appearance is probably related to the product used for repairing these areas.

5.5. Analyses and Hypotheses

This section provides an analysis for the current conditions found on the building. It describes the development of the most probable mechanism and the necessary and sufficient factors for its occurrence. The section also analyzes other contributing factors that might be present on the building. It concludes with a hypothesis for the probable deterioration mechanism and enabling factors (ill.5.1).

Most of the conditions observed on the exposed post-tensioned precast reinforced concrete structure of the Richards Medical Laboratories are clear consequences of corrosion occurring on the reinforcement in the precast structural members. As mentioned in Chapter 3, reinforcement corrosion can be initiated by either carbonation or chloride contamination of the concrete surrounding it. In the Richards Medical Laboratories the only possible source of chloride is the use of additives in the concrete mix to accelerate setting. This possibility has to be considered since no documents were found specifying the mix and additives used. External sources of chlorides are unlikely, because the building is not located in a maritime environment or in contact with deicing salts (there are no paved areas around the bases of columns).

Carbonation is the other possible reason for the corrosion activity. However, the concentration of corrosion in reinforcement appears to be greater in columns than in beams. This difference implies two possible causes: different depths of concrete cover on the beams and the columns; or, different concrete mixes (and hence porosity and permeability) for the beams and columns. The first scenario can be explained by errors during the placement of the reinforcement or its accidental displacement during casting. This is evidenced on the Richards Medical Laboratories by the corroded reinforcement steel that is exposed on the façade, but without any signs of spalling, and set flush to the original concrete surface. This condition is found both on edge beams and columns, but columns present more damage than beams. This could be explained by the geometry of the column pieces. Flanges are more susceptible to errors in reinforcement placement during fabrication, because the narrowness of this volume does not leave much space for the regular reinforcement and the tendon ducts.

The second scenario can be explained by an inconsistency in concrete permeability, probably caused by poor control of the concrete mixing. For example, if excess water was added to a batch of concrete this would have resulted in a more porous concrete than what was specified. Another important factor to be considered is the geometry of the column piece. A high perimeter/area ratio increases the exposed surface area creating more opportunities for carbon dioxide penetration that causes concrete carbonation.

Once the reinforcement is surrounded by an environment with an appropriate pH for corrosion reaction, passivation is broken. From then on, the rate of corrosion will control the amount of damage caused to the concrete. Corrosion rate depends on availability of water and oxygen. This explains why the columns that are in a more protected situation have more soiling, but less corrosion related damage. It also explains why flanges are more affected, since their geometry provides more surface area to absorb water and oxygen from the atmosphere. The transport of water and oxygen is regulated by the concrete permeability, but cracks can facilitate this process and increase their penetration, not only in terms of volume but also in speed. Cracks can occur for different reasons depending on the crack type. The pattern cracking observed might have been caused by crazing of the surface right after curing. The lack of coarse aggregates on the surface supports this theory. This type of crack is restricted to the concrete surface, so it does little contribution to the permeation of deterioration agents. However, it increases the surface area that can absorb water and other atmospheric elements. The longitudinal cracks that were first reported in 1961 could have been caused by a premature stressing of some precast pieces that had not reached the required strength yet, or by an uneven tensioning of the tendons. These cracks could provide a shorter and more direct route to water and oxygen to the reinforcement than through the body of the undisturbed concrete. Cracks caused by the swelling of corrosion products will also contribute to increasing the rate of corrosion by acting as an easier route to water and oxygen, this will only occur once the corrosion damage process has reached the second phase (see Chapter 3).

Each type of damage can be associated with a different stage of the corrosion mechanism. Corrosion stains can be formed on the concrete surface when water dissolves the corrosion products during the wetting process and, subsequently, carry them to the surface when drying occurs. The transport of iron oxides by dissolution can occur through the pore network and through cracks that provide direct access between the concrete surface and the corroded reinforcement. Cracks caused by the volumetric expansion associated with the production of hydrated iron oxides, provide a locus through which water can move more easily than through the concrete mass. Therefore, staining will be intensified during the second phase of the corrosion process, as a combination of increased corrosion rate and transportation speed. The transition between the second and third phases of reinforcement corrosion is marked by widening of cracks and displacement of the concrete surface, exemplified by some of the cracks observed at the Richards Medical Laboratories. The change of plane of the concrete surfaces on opposite sides of the crack indicates that the area is being displaced out and will ultimately develop into a spall. Fully developed spalls that expose corroded reinforcement characterize the third phase of the corrosion process, which is one of the current conditions observed on this building.

Summing up, the current state of the building indicates that the most likely damage mechanism is reinforcement corrosion due to carbonation, most likely facilitated by insufficient cover and high perimeter/area ratio of the columns (ill.5.2). The location of the current conditions suggests that rainwater exposure and design of the piece are important factors affecting the damage mechanism. The types of conditions observed on the building are characteristic of reinforcement corrosion mechanism at different stages of development. The lack of concrete cover, caused by errors in reinforcement placement and casting, resulted in early carbonation of the concrete surrounding the steel on these locations. This mechanism might have been accelerated by the permeability of the concrete, increased water and oxygen penetration due to cracks, and geometry of columns.

5.6. Proposed Validation Methodology

The methodology proposed in this section has the objective of providing evidence of the veracity of the hypothesis presented in the previous section. In addition, it has the goal of providing the necessary data for the formulation of a preventive plan for this building. Through the understanding of the current damage mechanism, the risks threatening the sound areas of the structure will be better assessed and preventive measures can be taken. In addition, this information will help in identifying areas where corrosion is still in phase one, The sequence and combination of techniques proposed were based on the ideas of minimizing the amount of tests and increasing their efficiency. They were selected based on the questions raised by the data that was not found in the background research and the hypothesis formulated above. These questions can be summarized as follows:

- What concrete mixes were used?
- What is the permeability of the uncracked concrete?
- What additives were used and how do the additives affect the damage mechanisms?
- What product were applied in previous repair campaigns, if any? How have these products affected corrosion mechanism?
- Where is the reinforcement located?
- How thick is the concrete cover over the reinforcement?
- How deep has the carbonation front reached?
- Are these conditions localized or widespread?
- How fast is corrosion progressing?

The preliminary evaluation of the damage could be done through surveying a representative area of the building. This restriction is necessary due to the large expanse of areas that might be affected by corrosion. In addition, vertical access is an important issue to be considered. Inspection can be done with the use of lifts or swing scaffolding. However, lifts can only be used on the north side of the building, since the topography and dense vegetation of the James G. Kaskey Memorial Garden prevent access to that façade from the ground. The use of swing scaffold for inspection might be possible, but the protruding columns will pose a challenge, because the scaffold will have to be suspended further away from the building. This might compromise access to all faces of the column flanges. The areas surveyed should include elements that experience different degrees of exposure to environmental action.

The delineation of the representative surveyed area can only be done after a preliminary visual survey is conducted. The goal of the visual inspection is to identify all observable damage and to identify areas of various types of damage and healthy areas that can be sampled in the future. Based on the questions delineated above, a survey plan should be developed. This plan will have to consider two types of evaluations. First, in order to answer the questions regarding the characterization of the concrete, random areas should be chosen for testing. The average of the results will provide the needed information. Second, deteriorated areas should be tested and compared to healthy areas in order to assess which factor is determining for the initiation of the deterioration process.

The tests recommended herein require direct contact with the structure. Although most measurements are quick, they require preparation of the surface, handling of the measuring equipment in addition to some annotation method for the values. Therefore a sound method of vertical access, such as regular scaffolding, is preferable in order to minimize human errors due to the operator's discomfort.

Petrographic analysis can provide a profile of the concrete's microstructure and composition. Core samples should be obtained from the structure representing different concrete batches. It is estimated that every four column elements form one batch. Therefore, it is recommended that one sample is collected for every floor in a tower, so that the results are more statistically accurate. As soon as the cores are obtained, they should be used to measure the carbonation depth of the concrete. If this is done by spraying a phenolphthalein solution on the sample, it should be remembered that the color changes in areas with pH above 9. However, depassivation happens when pH is 11. Therefore, the reinforcement can be corroding if it is close to the color transition indicated by the test. This test has to be analyzed in relation to the concrete cover to see whether carbonation has reached the reinforcement. The samples obtained for petrography should also have their chloride content measured. A result above 0.2-0.4% of chloride per weight of cement represents corrosion risk. Another important way of characterizing the concrete quality is by testing its permeability and surface water absorption. This can be done in-situ with the AUTOCLAM method (described in Chapter 4). Since casting and curing processes can influence this characteristic, different batches should be tested for consistency.

Ground Penetrating Radar can be used to locate the reinforcement on the reinforced concrete elements, and to measure the concrete cover. Locating the reinforcement steel is essential in this case since the drawings that are available are not the final ones, besides, errors in the reinforcement placement during fabrication can cause distortions. Measuring the concrete cover is another essential procedure because when analyzed with the carbonation depth it will determine if the concrete surrounding the steel is providing the necessary protection against corrosion. A thinner cover indicates areas where corrosion will start sooner. GPR equipment should be obtained in a portable format, where a handheld transducer is connected to a computer. The equipment is limited to a surveying depth of 18”, and it is recommended to use antennas with a minimum frequency of 1.5 GHz for better image definition. Since precision depends on the regularity of the measurement intervals, it is necessary to have an electronic distance measuring wheel linked to the system.

The goal of the half-cell potential mapping is to assess whether the risk of corrosion is restricted to the elements that already present some visible damage or if apparently sound precast elements are also at risk. Since the reinforcement of the precast elements at the Richards Medical Laboratories do not maintain the connection from one element to the other, like in cast-in-place structures, each precast piece surveyed will need access to the reinforcement. If the reinforcement is exposed, this can be used for the connection, as long as the rust is removed. Connecting the voltmeter to the reinforcement in sound structural elements will require some concrete removal. If present, any areas where previous repairs have been made should be used for this connection. In order to minimize damage to the building, it is suggested that this survey is conducted in one of the towers and, if it finds no significant corrosion risk areas on sound precast elements, this should be considered enough evidence that further corrosion testing should be restricted to the elements with visible damage. Concrete resistivity should be measured in parallel with potential measurements in order to increase the reliability of the results.

The linear polarization technique provides a measurement of the corrosion rate of the reinforcement steel. This is useful in determining priority areas for treatments, since it gives a location for the areas where corrosion is occurring more rapidly. This technique requires accurate location of the reinforcement and its size, which is why the GPR survey should precede it. This technique should be used in selected areas of the structure indicated by the potential mapping as being of high corrosion risk. This restriction is applied because of the high cost of this equipment and the slowness of data acquisition – each measurement takes between five and ten minutes depending on the instrument used. Decreasing the number of measurements is also important because comparison between them is only possible if they are taken under the same weather conditions – RH in the pores and temperature can influence the results. Since this technique also requires a connection to the reinforcement, it should use the same point of access created for the half-cell potential measurement.

5.7. Proposed Method for Analysis and Interpretation of Data

The data acquired through the methods described on the previous section should be performed and analyzed in a particular order so that a test results will guide a more effective use of the subsequent test. Essentially, the first ones, visual inspection, petrography, carbonation depth, chloride content, permeability and GPR, will have to be analyzed together. They will inform the general conditions of the concrete and the positioning of the reinforcement within it. They will indicate if the necessary and sufficient factors for the corrosion mechanism are present in the concrete of the Richards Medical Laboratories. It will be important to analyze the carbonation depth and the concrete cover together for each sample, because this will show if carbonation has reached the reinforcement. This can be done through the construction of a graph where carbonation depth is plotted on the horizontal axis and the concrete cover on the vertical. If for one location the carbonation depth measurement is bigger than the concrete cover, the plot will appear on the right side of the threshold line, which is composed of a 45° angle representing equal values on both axes. This graph will give an idea of the percentage of samples where carbonation is a factor. Taking in consideration that the elements sampled to measure carbonation were randomly and statistically chosen, it would be possible to compare these results with the condition mapping produced by the visual inspection. This will reveal if there is any correlation between visible damage and carbonation. It will also show if depassivation due to carbonation is occurring in elements where no visible damage has occurred.

In order to further prove the hypothesis that there is corrosion in apparently sound elements, the half-cell potential mapping, combined with concrete resistivity, will be done. This technique has the capacity to show the extension of the corrosion enabling environment. It will rely on the reinforcement location resulted from the GPR survey to minimize the damage to the concrete when connecting to the reinforcement. When compared to the shallow coverage areas detected by the GPR, the half-cell potential will show if there is a correlation between them and the corrosion mechanism. This technique will also help to delineate the repair boundaries around the visible damage to increase its effectiveness and durability. These comparisons will be done by composing maps with the results of these measurements on an unwrapped elevation of each column element.

Although these techniques will reveal where corrosion is occurring, only the linear polarization method can provide a measurement of corrosion rate. This data will be necessary if there is a need to prioritize areas of intervention and split the work in phases. This technique will prove the hypothesis that the lateral of the flanges are the areas that are most sensitive to corrosion, as evidenced by previous repairs.

The results of this evaluation will reveal the different phases of the corrosion process experienced by the building. This is essential to inform what will be the next step in the conservation of the Richards Medical Laboratories. Areas experiencing first phase corrosion are candidates for preventive treatments to slow the corrosion rate, such as electrochemical techniques that can repassivate the corrosion reaction. Healthy areas of the structure that are on the imminence of depassivation are also candidates for preventive treatments. Areas presenting a more advanced corrosion phase will need traditional repair combined to preventive techniques in order to minimize the area of patching, as well as the probability of damage reoccurrence.

Figure 5.1- The Richards Medical Laboratories and its relationship with the traditional 19th century campus architecture

Figure 5.2- Hill Hall (Eero Saarinen, 1960).


Figure 5.3- David Goddard Laboratories (Louis I. Kahn, 1964).

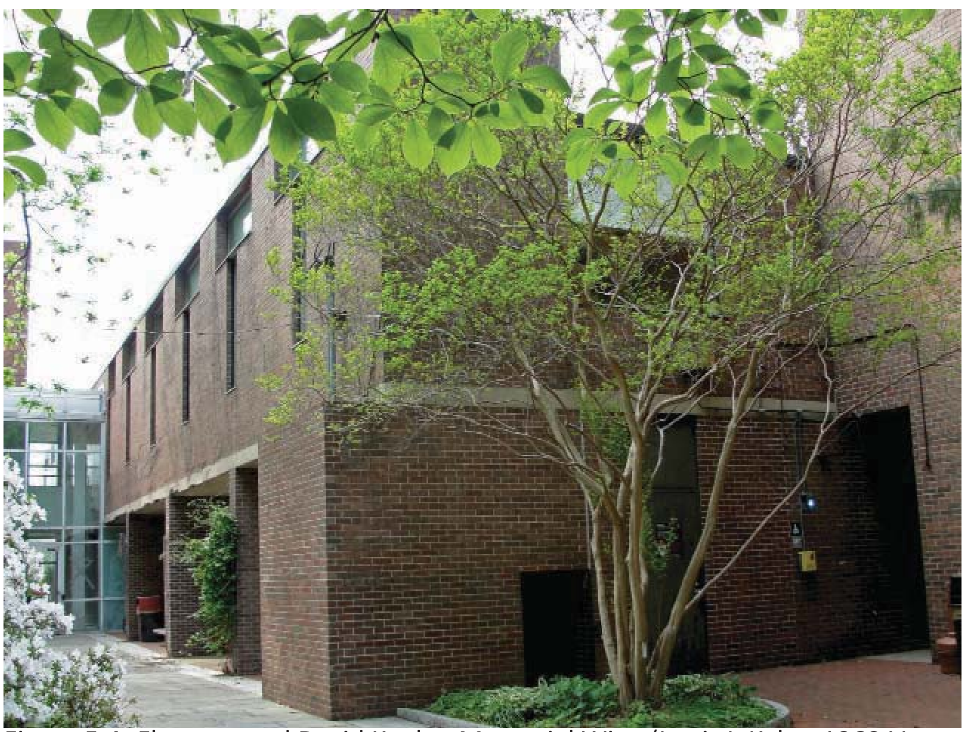
Figure 5.4- Florence and David Kaplan Memorial Wing (Louis I. Kahn, 1960;Vreeland and Schlesinger, 1964).

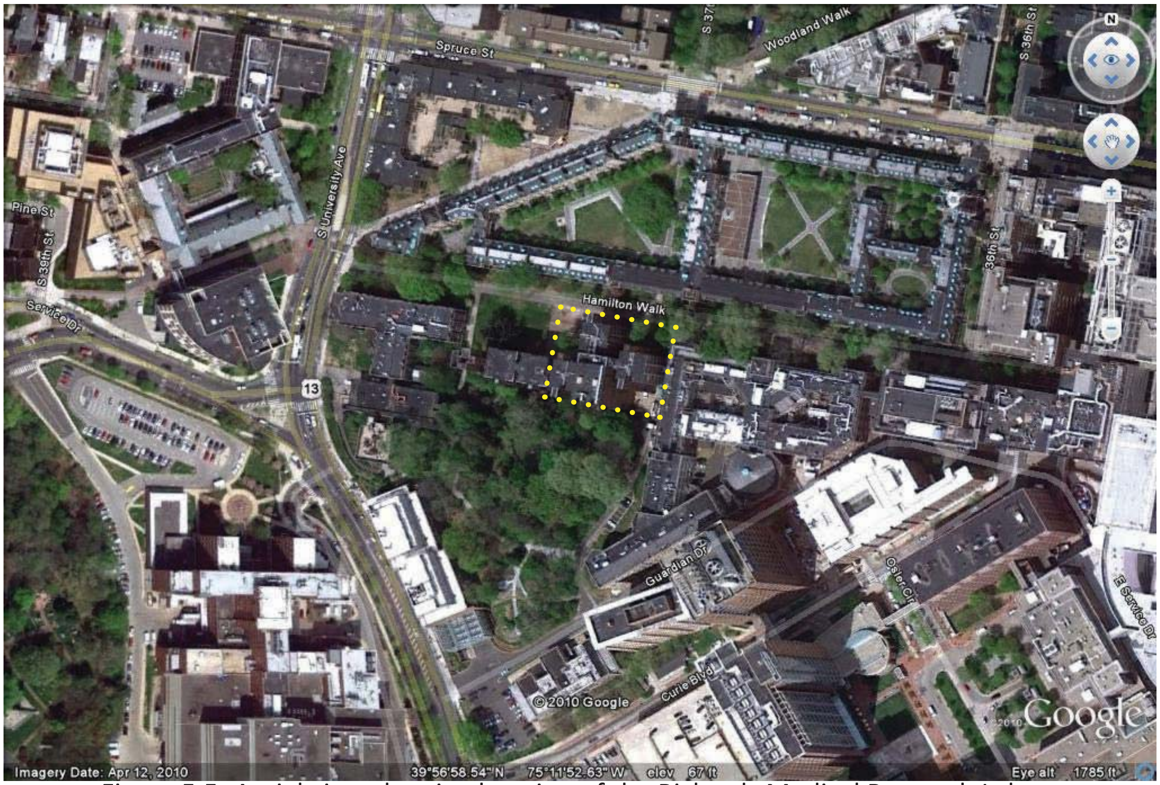

Figure 5.5- Aerial view showing location of the Richards Medical Research Laboratories. (Google Earth, 2010, *annotations added)


Figure 5.6- Connection to the John Morgan Building (Cope & Stewardson, 1904) seen from the service driveway.

Figure 5.7- Quadrangle (Cope & Stewardson, 1895).

Figure 5.8- James J. Kaskey Memorial Garden.

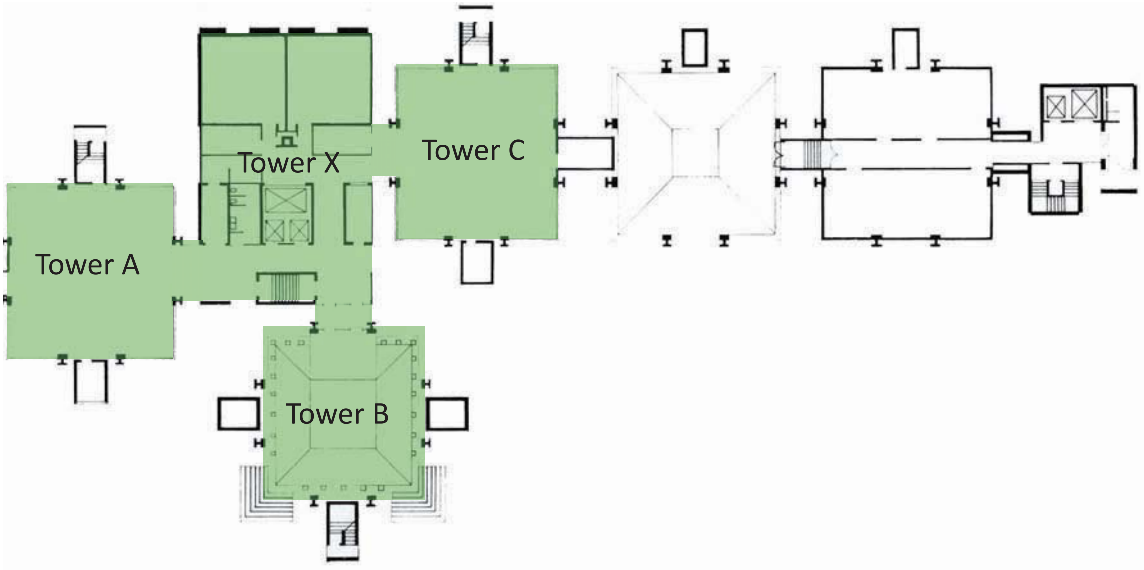

Figure 5.9- First floor plan showing the Richards Medical Research Laboratories (in green) and the Goddard Laboratories. (Komendant, 1975, *annotations added)


Figure 5.10- Enclosed bridge between towers B and X.

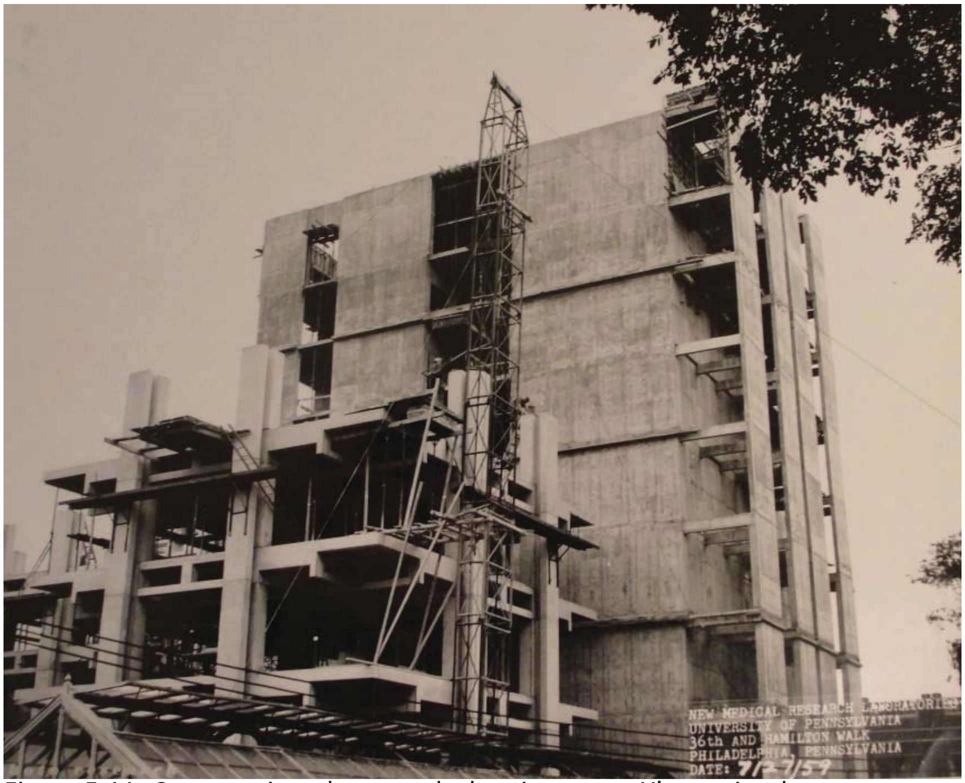

Figure 5.11- Construction photograph showing tower X’s cast-in-place structure. (The Architectural Archive, University of Pennsylvania, 030.IV.A.490.12.42)

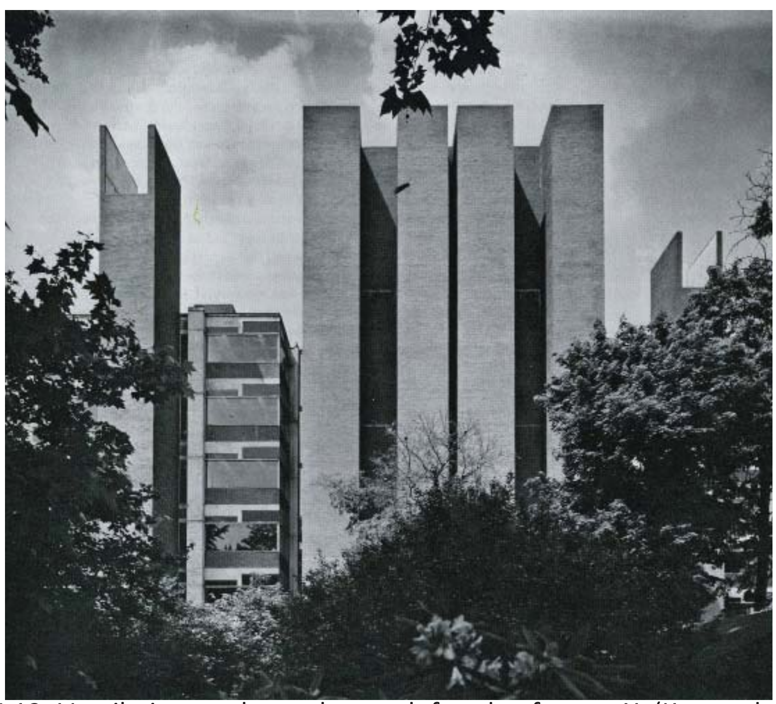

Figure 5.12- Ventilation stacks on the south façade of tower X. (Komendant, 1975)

Figure 5.13- Construction photograph showing the cast-in-place structure of a subsidiary tower and the precast structure of a laboratory tower. (The Architectural Archive, University of Pennsylvania, 030.IV.A.490.12.45)

Figure 5.14- North façade of towers A and B soon after completion. (The Architectural Archive, University of Pennsylvania, 030.IV.A.490.5.3)

Figure 5.15- Column tendons being connected during erection of the pre-cast structure. (The Architectural Archive, University of Pennsylvania, 030. IV.A.490.11.1)

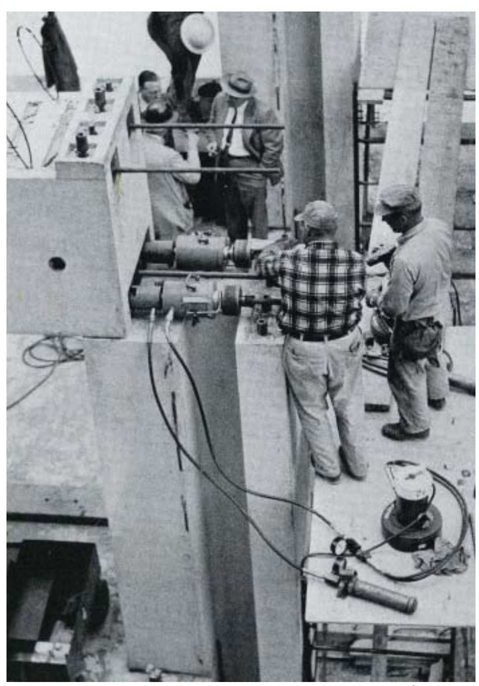

Figure 5.16- Tensioning process in a Vierendeel beam. (Komendant, 1975)

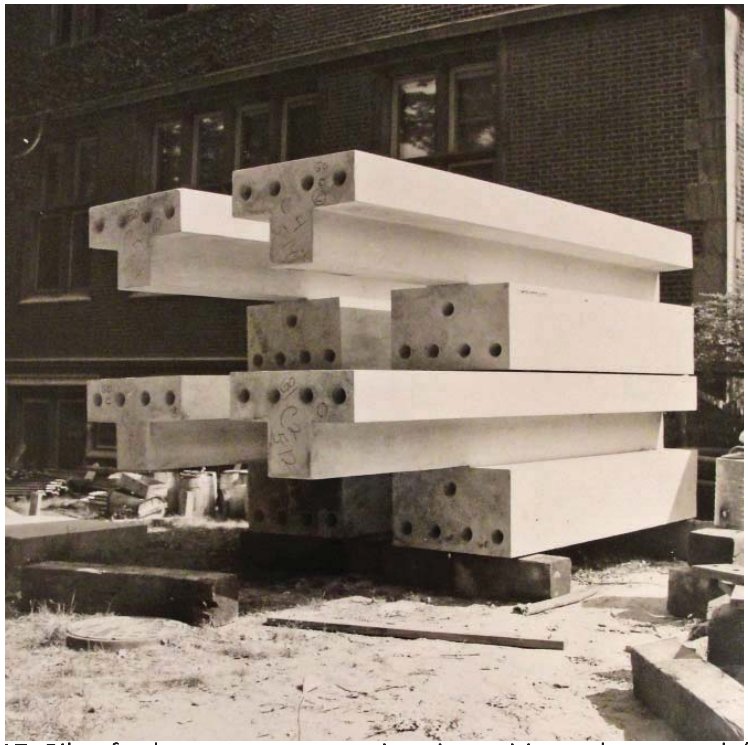

Figure 5.17- Pile of columns on construction site waiting to be erected. (The Architectural Archive, University of Pennsylvania, 030.IV.A.490.9.2)

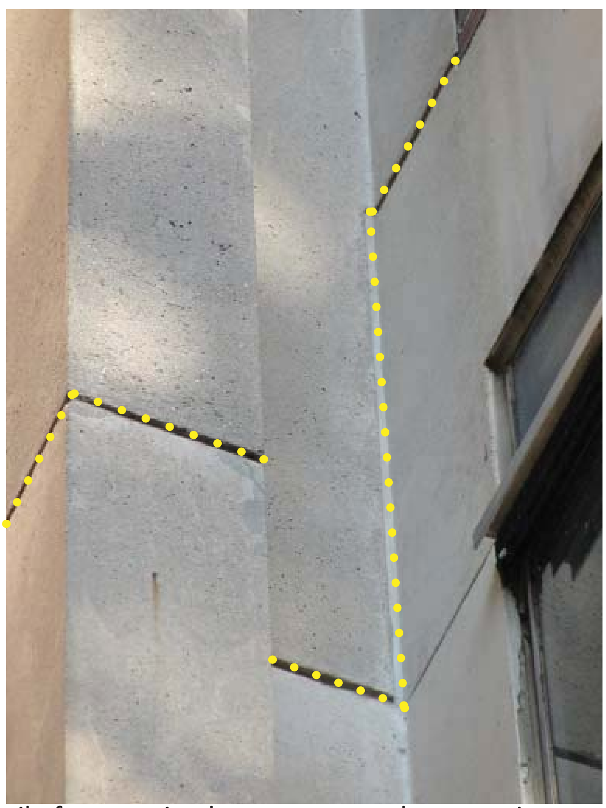

Figure 5.18- Detail of connection between two column sections and a beam.

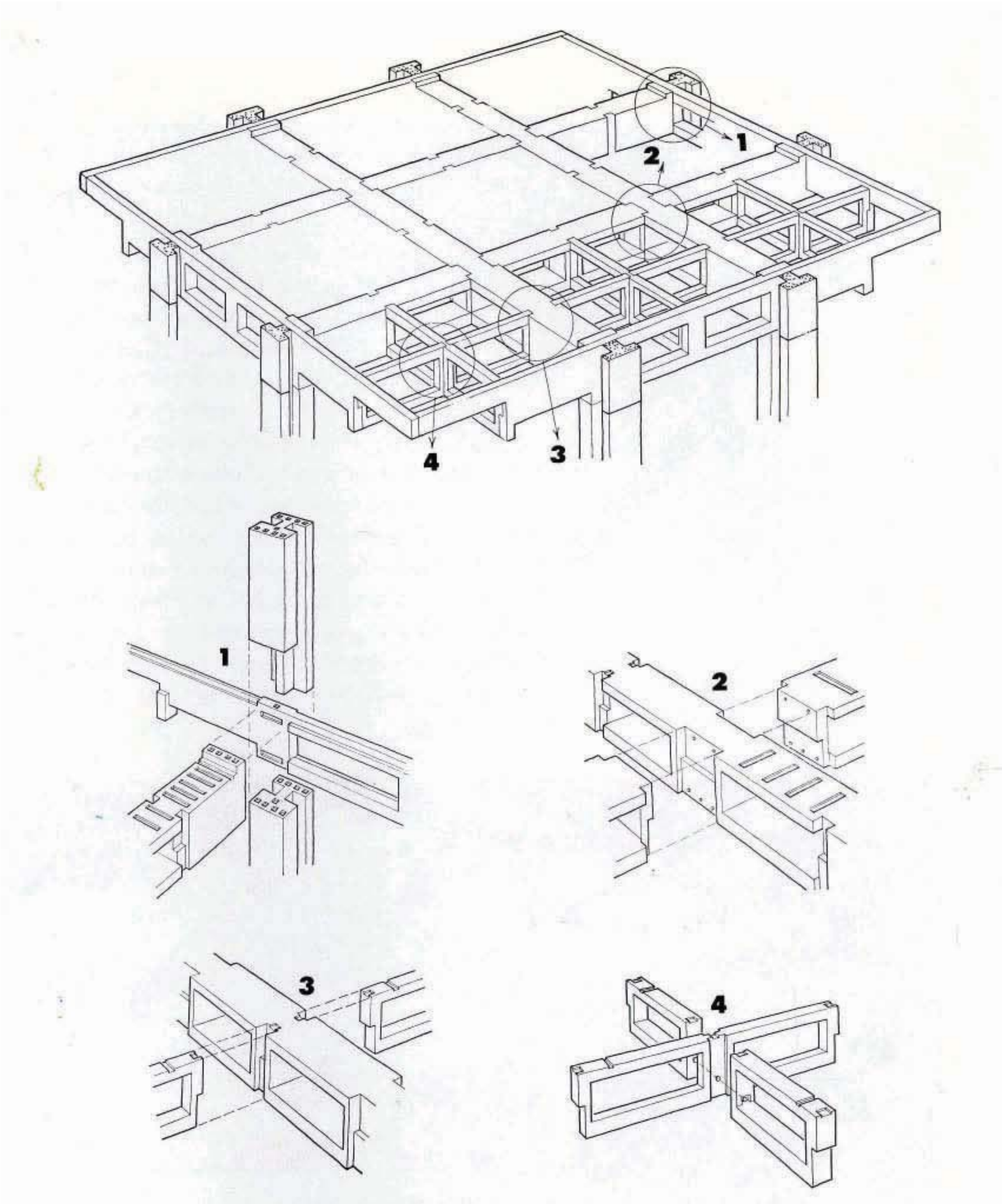

Figure 5.19- Model of the precast structure showing different types of connection. (Komendant, 1975)


Figure 5.20- Detail of corner window and brick masonry wall.


Figure 5.21- Column in situation less exposed to environment action.


Figure 5.22- Detail of soiled surface.


Figure 5.23- Corrosion stain associated with spall.

Figure 5.24- Corrosion stain associated with exposed reinforcement.

Figure 5.25- Cracks that can develop into spalls.

Figure 5.26- Longitudinal crack.

Figure 5.27- Crazing.


Figure 5.28- Spall on a column flange.


Figure 5.29- Spall on a window corner.


Figure 5.30- Exposed reinforcement, originally lacking concrete cover.


Figure 5.31- Exposed reinforcement on edge beam.

Figure 5.32- Repair on the edge of column flange.

Figure 5.33- Patches on the ground floor level section of the northwest column on the north façade of tower.

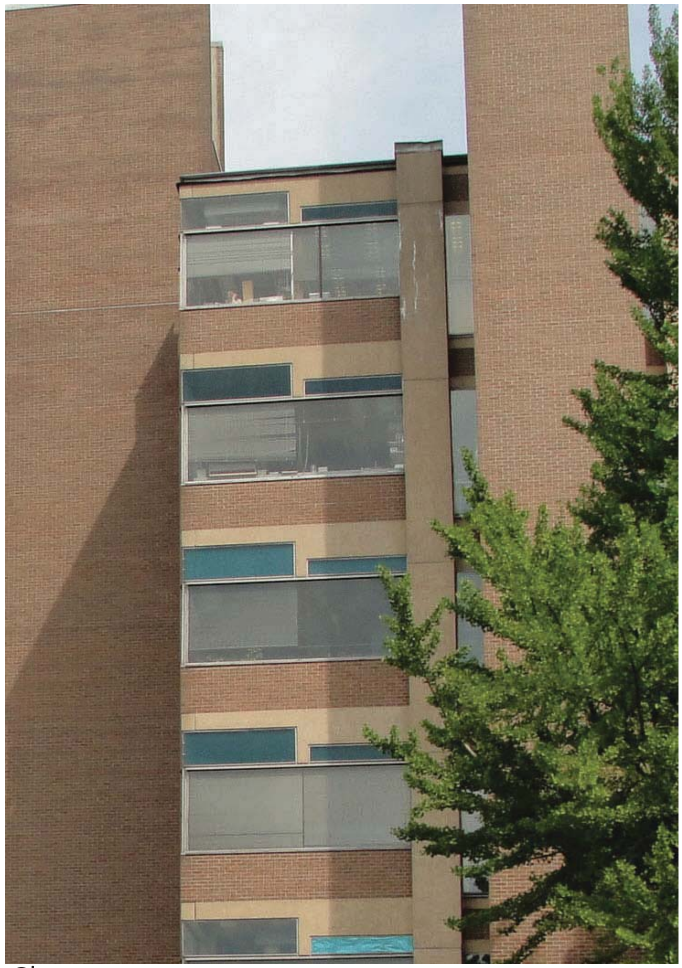

Figure 5.34- Glossy areas.

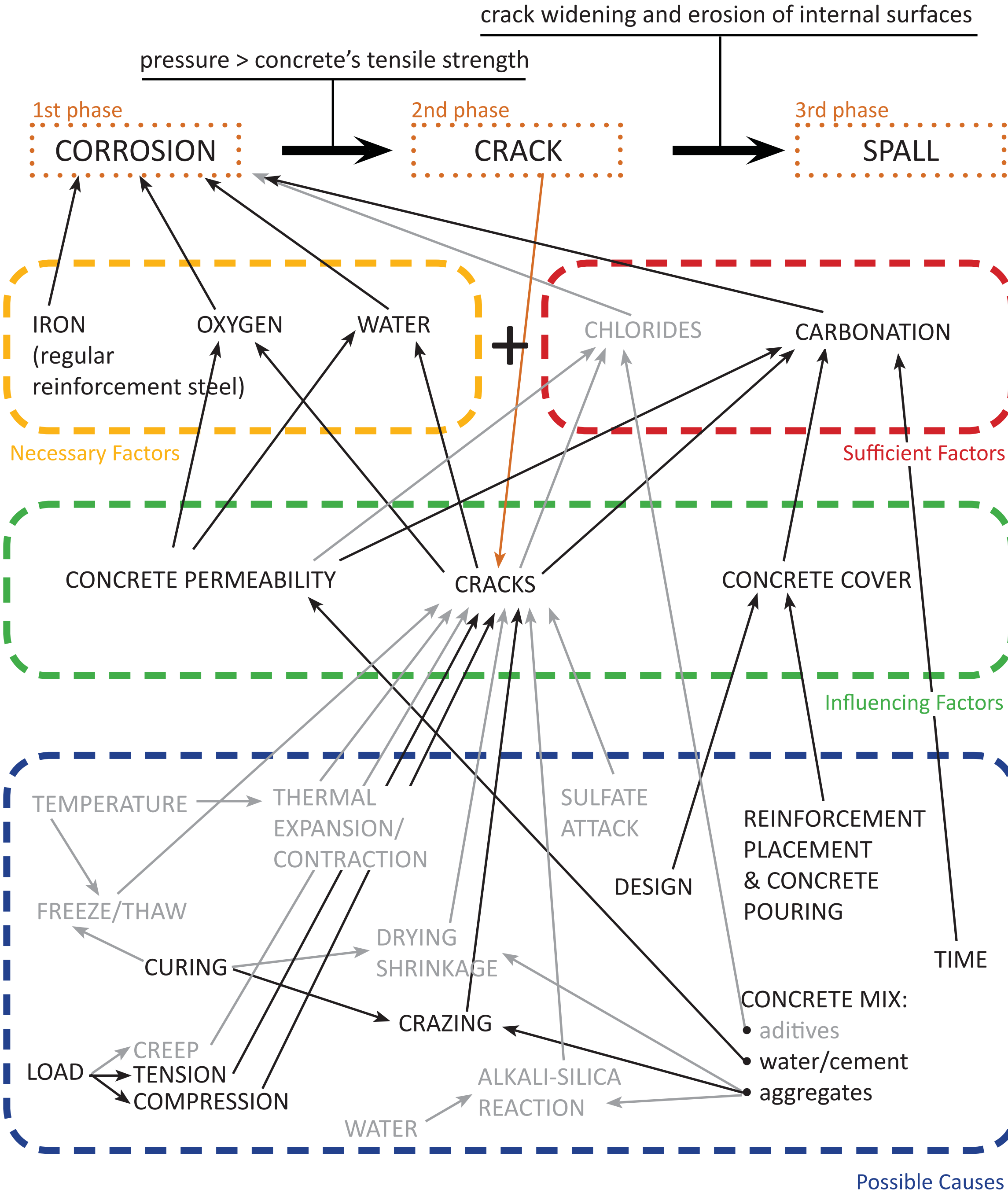

Illustration 5.1- Diagram of the hypothesis of the corrosion mechanism at the post-tensioned precast reinforced concrete in the Richards Medical Laboratories.

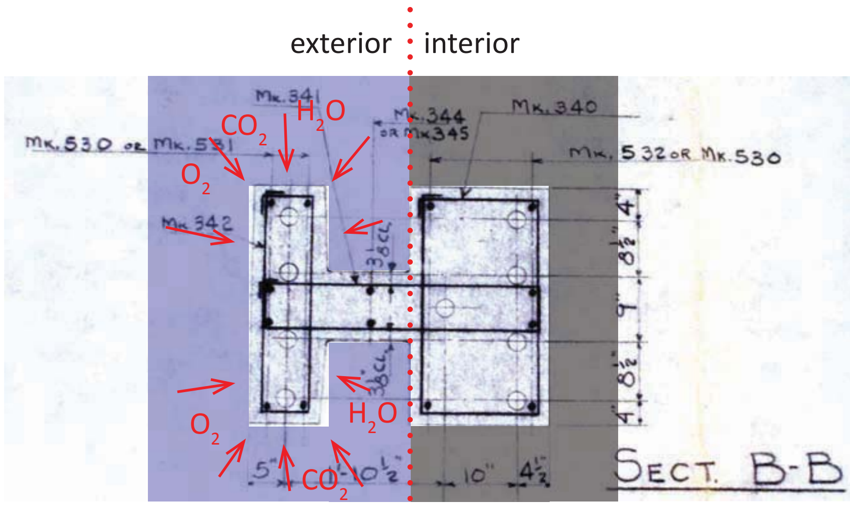

Illustration 5.2 - Section of precast column showing how the geometry increases the surface area making the flanges particularly sensitive to the environment. (The Architectural Archives, University of Pennsylvania, 030.I.C.490.009, *annotations added)

Chapter 6 – Conclusions

The information gathered in this thesis on the corrosion of concrete reinforcement and on survey techniques used to detect corrosion was analyzed against the principles that guide building conservation allowing several important conclusions to be drawn.

First, the material fabric of mid-to-late twentieth-century heritage buildings carry historic and aesthetic values similarly to heritage buildings associated with other, older, historic periods. Therefore, the principles that have guided conservation of older heritage are applicable to buildings of recent heritage. These principles include the effort to minimize material loss through prevention and through the use of the least invasive repair techniques.

Second, reinforced concrete, when exposed as an architectural and structural material in mid-to-late twentieth century buildings, poses special challenges with respect to the above mentioned principles. The repair techniques to remediate mechanical damage to the concrete caused by reinforcement corrosion are necessarily invasive and destructive to the historic fabric. Therefore, with the current state of development in the field of concrete repair, the best approach to conserving exposed reinforced concrete in heritage buildings is through prevention.

Third, the study of the corrosion damage process in concrete reinforcement reveals that the process is characterized by three well-defined phases. Each phase affects the concrete to a different degree. In the first phase the passivation of the corrosion reaction is broken and iron oxides begin to accumulate in the concrete/reinforcement interface. This phase might produce some concrete staining, but the concrete surrounding the reinforcement remains undisturbed. Minimally invasive and minimally destructive treatments are possible during this phase. However, once the corrosion products have enough volume to cause cracks on the concrete mass, these treatments are no longer an option, unless preceded by conventional repair techniques.

Fourth, minimally invasive and minimally destructive intervention in the corrosion process in exposed reinforced concrete is only possible if the corrosion process is detected in its earliest stage, prior to the emergence of signs of damage on the concrete surface. Early detection, and the associated responses of minimal treatments, are inherently preventive.

Fifth, a fully preventive conservation approach relies not only on early detection of the problem, but also on a thorough knowledge of the factors contributing, directly or indirectly, to the corrosion mechanism. Preventive conservation focuses actions on eliminating the causes of damage in order to minimize material loss or keep loss from happening, hence a sound diagnosis of the mechanism and identification of risk factors are essential. Consequently, there is a need to employ techniques capable of detecting the presence of factors that can lead to reinforcement corrosion. This thesis' research has showed that there are many techniques capable of providing the data needed to support a preventive conservation approach to exposed reinforced concrete in buildings of recent heritage. Most of these techniques are well established in the construction industry. It is important to recognize that each technique provides a specific type of information, and each has certain limitations. These limitations can be overcome by using the equipment under the appropriate conditions and by interpreting the results in conjunction with data acquired by other techniques in order to minimize the chance of false results. Even under a campaign of preventive conservation, some degree of damage will be necessary for testing, because some testing techniques, like petrographic analysis, provide essential data.

The case study involving the Richards Medical Research Laboratories, designed by Louis I. Kahn and finished in 1960, demonstrated the complexity of corrosion in exposed reinforced concrete. The complexity relates to the different factors that contribute to the initiation of the corrosion process, as well as factors that can affect the rate of corrosion. This case study showed how different damage mechanisms that affect the same area can influence each other, as in the case of cracking and increased water penetration in the concrete. The Richards Medical Laboratories is the perfect example of a modern monument where structure and architecture, material and aesthetics were intertwined in design and execution. In this case, to preserve the executed material is to preserve the design intent. As Louis Kahn would have put it: we have to honor and glorify the material in order to express it. This can only be achieved through a preventive conservation approach.

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