ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

# Master's Thesis

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# Research on the restoration of heritage structures: Portland cement and concrete repair applications and repercussions

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Logan Strenchock

## ABSTRACT

This paper presents a study of the lasting effects of Portland cement and concrete's acceptance as a restoration material after the technology came of age in the early 20th century. The paper will highlight the development of modern cement technology while also explaining how it came to be accepted as a viable option in the restoration of heritage structures, and the eventual repercussions of such techniques.

Presented in the document are the techniques of early restorations and the most common methods utilized during the grand period of reinforced concrete intervention that occurred during the mid 20th century. After highlighting the various techniques, the mechanisms and modes of deterioration that have plagued such affected structures in the years following intervention will be presented, and likely causes will be identified. Forms of chemical, mechanical, and structural deficiencies all related to the addition of reinforced concrete in systems will be mentioned, and relevant examples will be cited through the use of case studies, with hopes of bringing greater clarity to previously mentioned information within the document. Case studies will be presented where lessons were learned from failures resulting from inadequate restoration practices.

The document will conclude with a summary of all presented material and suggestions on what was learned throughout in the years following case studies where failure, deterioration, and premature degradation were induced by concrete restoration materials. An attempt will be made to suggest steps in the future to ensure that problems are avoided in future restorations, and also what must be done with existing altered structures that may be vulnerable in the future. Also, the question of whether reinforced concrete has a place in the field of restoration technology will be discussed.

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## CHAPTER 1: INTRODUCTION

As the preface to the Venice Charter states, "the historic monuments of generations of people remain to the present day as living witnesses of their age old traditions."[18] It is easy to comprehend the common responsibility we have towards safeguarding these structures for the use of future generations. Historic monuments serve as resources that:

- Display scientific, artistic, and religious accomplishments
- Provide identity to cultures, regions, and inhabitants
- Serve as live documentations of the past; an invaluable learn resources
- Serve as economic resources as cultural/religious landmarks
- Foster diversity and a learning exchange from culture to culture

For these reasons and countless others we realize the importance of historic landmarks and understand that cultural heritage is something that should be treasured and managed to ensure continual influence in the world. In a modern world where globalization and industrialization continues to push cultures towards higher levels of assimilation, and the erosion of tradition and culture is rampant, it is now more than ever a necessity to preserve these landmarks and acknowledge the importance of authenticity in this pursuit. This quest is imperative in ensuring the protection of a proper transcription of our own history, and that of cultures foreign to us.

Structures of architectural heritage present an abundance of challenges that can limit the application of modern building codes and standards. It is a difficult quest to ensure that methodological analysis and repair attempts apply to and satisfy the cultural context of each restoration attempt. Heritage structures, while wide ranging, often fit into a general class that describes the purpose they serve.

- **Monuments**- include architectural, sculptural, and artistic works, or elements of archaeological nature which are of outstanding universal value from the viewpoint of art, history, science or religion.

- **Buildings/Dwellings**- groups of connected or separated buildings, which because of their place in landscape or homogeneity are of great universal value from the viewpoint of art, history, science or religion.

- **Sites**- man made works or the collective works of nature and man, and surrounding archaeological sites which are of outstanding value from the viewpoint of art, history, science or religion.

When dealing with such a wide range of structural layouts, geographical details, material properties, and cultural significance, it is impossible to adopt a standardized format for restoration and preservation, and difficulty in the field lies in the fact that each problem in itself is a special and unique case. It is essential that when examining structures of great importance that much care is taken properly apply the most recent and beneficial conservation and restoration guidelines agreed upon on an international basis, in order to satisfy the needs of all interested parties, and serve in the interests of doing what is best for the structures of importance in question.

### 1.1 Motivation

There is no debate that the development of reinforced concrete at the onset of the 20$^{th}$ century is accepted to be a landmark advance in the history of construction and restoration. While early concrete structures are now being recognized as heritage structures in their own sense, there has been much interest in the effects of the widespread use of reinforced concrete in the restoration of monuments and structures that occurred during the 20$^{th}$ century. The approved use of remediation techniques taking advantage of reinforced concrete and other modern resources has had a lasting effect on restoration approaches and their consequences, whether good or bad.

The acceptance of reinforced concrete did usher in a new age of restoration theory, but the eventual repercussions of the wide ranging use of this once deemed “permanent solution” would not be seen until years following, and are still being more closely examined today. The lack of knowledge present during initial interventions, the overconfidence in concrete’s abilities, and the favorable economic characteristics of the material lead to its rapid acceptance of usage in reconstruction and intervention. Issues regarding reversibility of interventions, durability concerns, compatibility issues, and an altering of dynamic performance of structures have all been addressed since then. Interest and study on the topic has stemmed from the observations of the many methodological and technical criticisms that have arisen regarding the use of reinforced concrete, and the observed effectiveness of such treatments and corresponding decline of many structures expected to be ameliorated by treatment.

## 1.2 Objectives

In this document I will analyze the past and present attempts to restore and analyse heritage structures utilizing Portland cement and concrete, and the success and failure of varying methods. I will inspect the misconceptions and contradictions between theories and applications within the field of concrete restoration, including the use of Portland cement in restorations. The document will focus on modern diagnosis and repair techniques, and how to best apply advancing technology in each widely ranging case of concrete deterioration. The document will track the development of concrete as a building material, and the deterioration mechanisms that have been proven afflict structures with concrete portions. Taking into account the developing theories on historic restoration, I will attempt to use what was learned from past blunders to suggest a common approach for investigation and remediation of structures in every case that will satisfy the standards and guidelines set forth by ICOMOS.

## 1.3 Methodology

This paper is a compilation of the history of the use of Portland cement and concrete in the restoration of historic monuments and structures, and the performance and problems associated with such interventions. In creating this document, portions of articles from journals, online publications, books, and magazines with relevant information were utilized to give practical and real world examples and outcomes of such structures affected by concrete intervention. Comments on the present principles and charters of intervention are referenced from current ICOMOS documents.

## 1.4 Organization of Document

The organization of this document follows this outline:

**Chapter 1-** Introduction, Motivation and Objectives of the paper

**Chapter 2-** Historical overview of the development of Portland cement, its characteristics and early stages of usage, manufacturing, chemical and physical properties, and important of mix details

**Chapter 3-** The history of restoration approaches developed in the early 20th century, acceptance of concrete as a permanent solution, technique of first restorations using Portland cement

**Chapter 4-** Mechanisms and modes of deterioration in structures restored with concrete, causes of degradation and compatibility issues, chemical reactions between original and repair materials

**Chapter 5-** Deterioration of structures linked to structural interventions,
Varying methods of seismic intervention and stabilization and their effects, issues with repair methods and reversibility

**Chapter 6-** Summary of traditional deterioration mechanisms of reinforced concrete structures

**Chapter 7-** Summary of three relevant case studies that provide examples of deterioration patterns that were mentioned in chapters 4, 5, and 6 of the document

**Chapter 8-** Conclusions and suggestions

# CHAPTER 2: HISTORICAL CONCRETE OVERVIEW

## 2.1 Portland Cement Development

Concrete has been used as a building material that has made possible the construction of municipal, decorative, and monumental structures that have gone on to serve as significant landmarks and cultural relics since ancient times. Concrete, the general name applied to any number of compositions consisting of a mixture of sand, gravel, crushed stone and other course materials bound with various forms of cementitious materials, has been used to create an array of structures. Its wide ranging use is a testament to the material's unique versatility characteristics.

The earliest documented use of a concrete mixture was found in the former Yugoslavia, dated back to 5600 B.C. [19] but history suggests that the Ancient Romans were the first to widely use a material that had any connection to modern concrete in their constructions. The Romans discovered that a mixture of a lime based putty, and volcanic ash would solidify under water. The resulting mixture became the first hydraulic cement, and would go on to become a fixture of Roman building practice, especially in large municipal undertakings such as bridges and aqueducts. While the roman concrete had little characteristic resemblance to today's modern Portland cement concrete, as it was never in a plastic state that could be molded, the principles of the process are correlated. There is no clear dividing line between what could be deemed the first concrete and what could merely be described as cemented rubble.

In the Middle Ages, the advancement of concrete technology was brought to a halt, with the general beliefs supporting the theory that the art was lost for a large portion of time. Evidence exists that a similar process was kept alive in portions of Spain and Africa, [19]that documents the Spanish utilizing a form of concrete in the new world at the onset of the 16$^{th}$ century, consisting of a mixture of lime, sand and shell aggregate. These materials, mixed and combined with water, were later consolidated and allowed to set in successive layers. This style of construction was later repeated by early settlers on the eastern coast of the United States. It is not believed that a true form of concrete was once again seen until the 18$^{th}$ century in France, where Francois Cointeraux, a mason experimented with attempting to construct fireproof walls consisting of cementitious mortar combined with crushed earth construction techniques.

The beginnings of modern concrete production are not precisely known, as development was fragmented, with technological advancements and varying construction techniques taking place among different cultures on separate continents. A landmark occasion in the development of modern concrete occurred in 1824, when Joseph Aspdin, an English mason, patented an improved cement formula which he named “Portland Cement” because it produced a concrete that closely resembled a stone quarried on the Isle of Portland. It is accepted that Aspdin was the first to use excessive temperatures to heat silica and alumina materials to a point that resulted in fusion, similar to modern production techniques.

### 2.1.1 Early Stages History of Use

In the United States and Europe, concrete was slow in being accepted as a residential building construction material, as it did not have the social recognition of stone or brick masonry, but it was used large industrial and transportation projects. The Erie Canal in New York, with construction beginning in 1817, is an early example of the use of concrete on a significant transportation structure in the United States.[13] Later, in the 1850s, signs of the use of concrete in residential housing became more apparent as more people became aware of the economical advantages of poured gravel wall construction.

Disagreement exists regarding the first true use of reinforcement in concrete, but the construction of several small rowboats by Jean-Louis Lambot in France in the early 1850s is accepted as the first successful example. In 1854, William B. Wilkinson, an English plasterer, reinforced the floor and roof of his two story cottage with iron bars and wire rope, and eventually took out a patent on the process. He went on to construct several similar structures, and is credited with building the first reinforced concrete buildings. The first usage of Portland cement concrete in buildings occurred in England and France between 1850 and 1880 under the tutelage of Francois Coignet, a French builder, who used iron rods in floors to provide stability. The first use of reinforced concrete in the United States dates to 1860 with S.T. Fowler attaining a patent on a reinforced concrete wall system.

Despite further innovations in the early 1870s like William E. Ward's reinforced concrete home in Port Chester, New York, it was not until after 1880 that innovations introduced by Ernest L. Ransome made reinforced concrete more practical.[13] Ransome contributed much advancement to the development of construction technology, including the use of twisted reinforcing bars to improve bond characteristics between concrete and steel, and the introduction of a new rotary kiln with greater capacity. This kiln allowed mixtures to burn more thoroughly and consistently, which made cement production more economical, uniform, and reliable; advancements that lead to a greater acceptance of concrete after 1900. Throughout the same period in France and Belgium, contractor Francois Hennebique was doing much to promote the standards of reinforced concrete construction, being known to have fulfilled more than 1500 annually when his business was at its peak.

In the early 1900s, the use of concrete was promoted in the construction of a coast to coast roadway system by the Lincoln Highway Association in the United States. During this period, various patches of concrete "seedling," or example stretches were created to display the materials advantages over the existing dirt roads of the time. This obvious advantage led to the United States government supporting the construction of numerous numbered routes later in the 1920s. This was one of the first examples of a large scale infrastructure project being largely composed of reinforced concrete.

From the 1920s on, concrete was used to bring more spectacular structure designs to life, and continuing advances in quality control and fabrication processes increased the opportunities for architects and engineers. Throughout the 20$^{th}$ century a vast range of architectural and engineering structures were built using concrete because it was a practical and cost effective choice that was also valued for aesthetic qualities. Cast in place structures were adapted to modern styles, and recreational structures utilized the range and unique abilities of exposed concrete to advantage. Not to be overlooked, as technology became more refined, concrete also became a popular material for building interiors, as decorative features and purposely exposed structural elements were applied to designs.

### 2.1.2 Concrete characteristics and types of concrete

Modern concrete is composed of fine sand and coarse (crushed gravel or stone) aggregates and paste comprised of Portland cement and water. In a mixture, aggregate is the principal material. Unreinforced Concrete is the term coined to describe the given composite material when it does not contain any steel or reinforcing bars. The ingredients in unreinforced concrete become a plastic mass that hardens as concrete hydrates. Unreinforced concrete, the earliest form of concrete, has largely been replaced by reinforced concrete, which is concrete strengthened with the inclusion of metal bars that increase the tensile strength of concrete structures.

Both unreinforced and reinforced concrete can be either cast in place or precast. Cast in place concrete is poured at the construction site into a previously erected mold that is removed after setting occurs. Precast concrete is molded at a location different than the construction site and then used to erect the structure at a later time. More contemporary advancements in concrete technology include pre-stressed concrete, and post tensioned concrete, which allow for reduced cracking and greater strength characteristics in reinforced members.

During the 20$^{th}$ century gains in strength of ordinary concrete occurred as chemical processes became more refined and quality control measures in production facilities improved. It was also during this time that the need to protect implanted reinforcement against corrosion was first acknowledged. Following this realization, standards for concrete cover over interior steel reinforcement, increased cement content, decreased water to cement ratio, and air entrainment all contributed to the improved material durability.

## 2.2 Portland Cement Characteristics

### 2.2.1 Manufacturing

Portland cement is the binder most often used in modern concrete. A basic understanding of the chemistry of Portland cement makes it much easier to understand the performance and potential deterioration mechanisms of a structure that is comprised of it. Portland cements are typically characterized by their chemical composition, which determine physical properties. It is manufactured by blending limestone or chalk with organic clays containing silica, lime, iron oxide, alumina, and magnesia, and heating the combination to high temperatures in a kiln to induce interaction between materials to form calcium silicates. The aggregate materials comprise nearly ¾ of the total volume of the mixture. The heated substance that results from this process is called “clinker” and develops in the form of dark round pellets that are cooled and pulverized in to a fine powder. The resulting powder is Portland cement.

### 2.2.2 Chemical and physical properties

| Chemical Name | Chemical Formula | Shorthand Notation | Percent by Weight |
|---|---|---|---|
| Tricalcium Silicate | $3CaO{\cdot}SiO_2$ | $C_3S$ | 50 |
| Dicalcium Silicate | $2CaO{\cdot}SiO_2$ | $C_2S$ | 25 |
| Tricalcium Aluminate | $3CaO{\cdot}Al_2O_3$ | $C_3A$ | 12 |
| Tetracalcium Aluminoferrite | $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$ | $C_4AF$ | 8 |
| Gypsum | $CaSO_4{\cdot}H_2O$ | $C\overline{S}H_2$ | 3.5 |

**Figure 2.1 Chemical Compound Constituents of Portland Cement [14]**

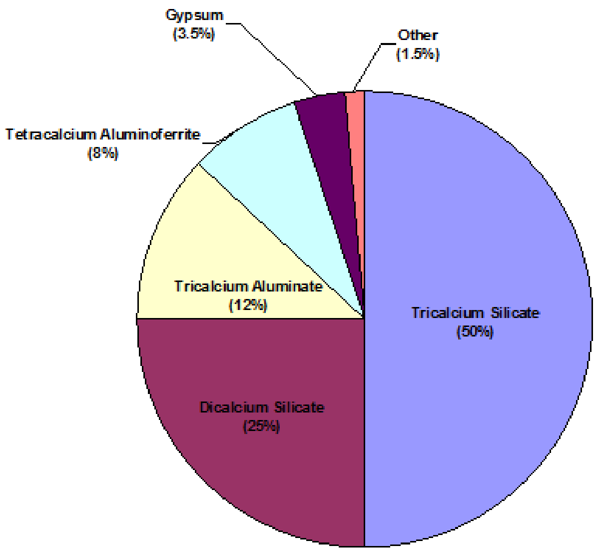


**Figure 2.2 Oxide Composition of a Typical Portland Cement [14]**

When Portland cement is mixed with water each of the individual chemical constituents undergoes a series of chemical reactions that leads to hydration, or the eventual hardening after transformation. The reactions occur at different times and rates respectively, and together their results determine how the cement hardens and gains strength.[14] Figures 2.1 and 2.2 explain the constituents and composition of a typical mix of Portland cement.

- **Tricalcium Silicate** ($C_3S$)- This hardens and hydrates rapidly and is responsible for early strength gains and initial sets. Cements with high $C_3S$ percentages will show higher early strength.

- **Dicalcium Silicate** *(*$C_2S$*)*- This constituent hardens and hydrates slowly and is responsible for strength gains beyond one week.

- **Tricalcium Aluminate** ($C_3A$)- This element hydrates and hardens the fastest. Exudes a large amount of heat immediately and also contributes to early strength. Gypsum is added to Portland cement to retard hydration of $C_3A$, to prohibit flash setting.

- **Tetracalcium aluminoferrite** ($C_4AF$)- Hydrates rapidly but contributes relatively little to strength. Allows for lower kiln temperatures to be used to produce Portland cement, and is usually responsible for color effects in cement.

The result of the hydration of the silicate constituents is the formation of a calcium silicate hydrate, which makes up about 50-75% of the volume of the hydrated paste and controls the behavior of the material.

| **Hydration of Silicates** | **Product** |
|---|---|
| **$2C_3S + 6H$** | **$C_3S_2H_3 + 3CH$** |
| **$2C_2S + 2H$** | **$C_3S_2H_3 + CH$** |
| | **$C_3S_2H_3 \approx$ CSH (calcium silicate hydrate)** |

Gaining a good understanding of the chemical makeup, and the chemical processes occurring during the curing process of hydraulic cements is necessary to fully understand the behavior of the materials, its future structural performance, lifecycle and decay, and future interactions with materials in close proximity. As will be elaborated later, the same chemical constituents that grant favorable characteristics such as high strength and variability to Portland cement based mixes are linked to most of the major flaws that arise in the premature deterioration of structures composed or altered using the materials.

### 2.2.3 Mix Details

The quality of a concrete mix directly correlated to the ratio of water to binder and binder content, quality of aggregate and compaction during placement, and quality of curing techniques after placement. The amount of water used in the mix influences the resulting strength and permeability of the concrete. Excess water present during the hydration process produces more permeable concrete which is more susceptible to the damaging effects of weathering and deterioration. In modern concrete, admixtures are often utilized to further adjust concrete properties, which can enhance the final properties of a concrete batch if utilized properly.[13]

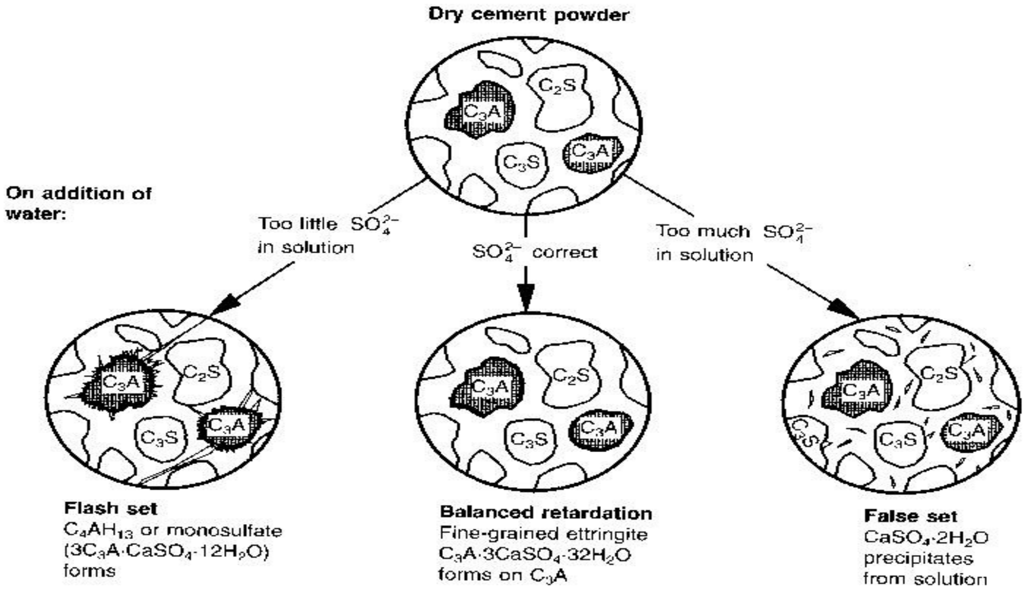


**Figure 2.3 Potential setting problems during concrete hydration process [14]**

# CHAPTER 3: RESTORATION HISTORY AND APPROACHES

## 3.1 Early 20th Century Restoration Theories

In Europe, the restoration theories developed between the end of the nineteenth century and the onset of the twentieth century in Italy and France played a large role in the appearance of the use of reinforced concrete in the restoration of monuments. The theories emerged from these countries because they were the quickest to adopt and support the use of the budding reinforced concrete technology. Studies and developed theories eventually provided the tools that not only led to the acceptance, but encouraged the generous use of all modern materials available for the consolidation of monuments.[12]

### 3.1.1 Philological Restoration and Scientific Restoration Theories

One influential theory instituted during this period, *the philological restoration theory*, inspired by the work of Camillo Boito, stressed that in the fundamental principle in restoration lies in the fact that "historical buildings are a document or stone archives rather than works of art, and that the objective of restoration is, therefore, to guarantee their permanence in time, ensuring their historical authenticity."[12] This Theory approached the conservation of a monument as purely a technical problem, and under its principles it was understood that interventions should be recognizable. Boito identified architectural monuments as both works of art and historical documents, which he then set the principles for restoration techniques based on these facts.

**Early 20th Century Theories:**

| |
|---|
| ***Theory: Philological Restoration*** |
| Premise: everything is reduced to keeping the monument standing, ensuring it a long life with the supports that science and practice suggest. |
| ***Theory: Scientific Restoration*** |
| Premise: Goal of restoration is to preserve monuments: interventions of consolidation and regular maintenance are the most outstanding and most immediately useful points of the theory. |

Under the support of both theories, the use of modern materials including reinforced concrete in restoration was accepted as fully legitimate because it stood out in visual appearance and could be clearly recognized as an addition to the original construction. It was also deemed important that the visual discrepancies between original and modern construction helped give a clear explanation on the necessity of such intervention, even being thought of as an educational tool for unlearned observers.

Interventions of this and similar typology usually resulted in the introduction of new structural elements enclosed within or along side historical masonry structures. Reinforced concrete was used along with alternative materials, often in masonry structures to build support systems or enclosures around problematic areas. During this period not much concern or debate centered around drastic changes in structural performance, or potential incompatibilities between materials that may have occurred, but mainly in changes in aesthetics and other visual issues. A material characteristic that helped encourage the use of reinforced concrete was the relative simplicity of creating invisible strengthening devices do to its nature as a poured substance.

The vision of the period was summarized with great clarity at the *Athens International Conference for the Restoration of Monuments* in 1931, where a charter was produced that solidified the legitimacy of using the material in the preservation of monuments. It was stated that: “the judicious use of modern techniques, and more especially of reinforced concrete,” was approved.[23] It was expected that the means of reinforcement be disguised, but this charter nonetheless paved the way for the onslaught of reinforced concrete remediation that would occur in the years following.

It should also be noted that simultaneously during this period in Europe and the United States, reinforced concrete was being employed on a large scale in the construction and reconstruction of cities, the design of new buildings, and the consolidation of old structures, which all resulted in the great need for the repair and conservation of historically important concrete that we have today. Throughout the 20th century a vast range of architectural and engineering structures were built using concrete to take advantage of its economical and aesthetically pleasing properties. With the aging of historic structures treated with reinforced concrete remedies, and with many early 20th century concrete structures reaching the end of their design life, maintenance and repair projects have become a constant in the construction industry.

### 3.1.2 Technological Advancements

The earthquake events in Messina and Marsica in Italy in 1908 and 1915 respectively were significant events not only because of the catastrophic damage that resulted from them, but also the dramatic shift in restoration theory, building safety, and intervention theory that arose after them. The seismic events occurred at a crucial time in the technical history of Europe, when the once primitive science of reinforced concrete construction had reached maturity, and the influx in concrete building was in full effect. After the earthquake, modern engineers were called upon to introduce this innovative technology to approach the problem of safety of large structures during seismic events. After devastating events like the Italian earthquakes, and other destructive occurrences (i.e. seismic, war damage) that followed, reinforced concrete was continually called upon to aid in the reconstruction and restoration processes.

## 3.2 Reasons Reinforced Concrete as “The Permanent Solution”

Reinforced concrete was accepted to provide the static solution to numerable problems, especially in earthquake zones where previous intervention techniques had been proved to fail. These beliefs were based on concrete’s favorable technical characteristics of structural effectiveness, resistance, durability, faster drying and manufacturing, material control, and economy.[15] The blind faith in reinforced concrete during this period had immediate consequences in the restoration field, as traditional materials were consumed less, skilled artisan laborers became utilized less, and a general loss of knowledge on how to repair buildings with modern materials occurred.

### 3.2.1 Favorable Technical Characteristics:

- **Structural Effectiveness-** Concrete’s resistance to traction led it to be cited as a material that should be used to give compactness to crumbling walls, provide a method to resist bending and shearing action, and in rigidly connecting various parts of a building along with rods and framework

- **High Variability in Shape-** The ability of concrete to be poured in almost any shape made the act of linking new reinforcements to ancient structures. This also allowed greater blending of interventions into already existing structures, which succeeded in answering the governing dilemma presented by existing restoration charters, visibility/invisibility of restorations. Other favorable characteristics including durability, resistance to fire, and economy were also often cited as reasons for use

### 3.2.2 Methodological Reasons for Use

- **Innovation-** Conception of safety based on scientific models and experimental parameters, two concepts linked to materials produced in industrial processes, such as concrete
- **Disagreements in Masonry Theory-** Difficulty in applying the theory of elasticity, and poor interpretation of behavior of ancient masonry constructions encouraged the use of concrete as a stabilizer
- **Identification-** From an aesthetic point of view, concrete interventions were clearly distinguishable from original constructions, which agreed with establish charters that “New materials should always be recognizable” [23]

### 3.2.3 Safety vs. Authenticity

Laws applying to the confrontations between engineers and restorers during the period were diffused through various governmental authorities, and exact definitions of standards and practices were not clarified. Monuments usually were subjected to varying counsels, engineers responsible for guaranteeing safety, and preservationists responsible for protecting and preserving the authenticity of the structures. Harsh conflicts often ensued, but the use of reinforced concrete to treat structures was not deterred during this time.

### 3.2.4 Early Debates

Although confidence in the ability of reinforced concrete at the onset of the 20$^{th}$ century was at a very high level, a few questions were proposed regarding potential problems that may occur due to incompatibilities between new and old materials. It was standard practice during the time to put greater concern on aesthetic and architectural cohesion rather than structural compatibility, which would open the door to many problematic situations in the future. Questions arose regarding the fact that application of reinforced concrete to medieval buildings meant “introducing in extremely elastic structures elements that are essentially rigid and likely to alter equilibrium.”[12] Controversy aside, the ability of poured reinforced concrete to provide consolidation that did not modify the structural arrangement of existing buildings was realized and cited as the underlying reason for use in most circumstances.

A common problem realized regarding restoration attempts that were eventually proven to be problematic, quite often in the case of applying cement injections and new cement mortars to repair or replace old mortars, was that the interventions eventually caused more damage then benefit, as the improper treatment heightened the effects of the original problem.

### 3.3 Detailed Technique of Early Interventions on Historic Structures

As previously stated, devastating seismic events that occurred in the early 20th century along with the coinciding development of new technology encouraged extensive use of reinforced concrete in restoration and intervention. France and Italy in particular were at the forefront of new practices for a few reasons. France was the leader in the development of the techniques of reinforced concrete, and in Italy the ideas of historical and scientific restorations and their cultural influence were being debated and embraced. Earthquake events also caused great scrutiny toward the seismic behavior of ancient structures. Around the world attention was shifted to solving structural problems in historic landmarks using reinforced concrete.

#### 3.3.1 Primitive Techniques

For restoration purposes, the first uses of concrete were often injection or pouring with goals of consolidating deteriorated masonry and providing stability to foundations. Later, grouting placement in ground spaces and attempts to increase cohesion in sections were also utilized. In the initial undertakings, exact structural logic was not always present, as concrete was used mostly as a “glue” to patch up and fill hollow spaces that developed in structures. The technique could be described as a process of “hopeful interventions for prevention.”[15] The overall structural layout of buildings remained unchanged.

It was not until later that structurally important portions of buildings began to be replaced with new reinforced concrete portions. Examples include the replacement of wooden beams with concrete, and hiding beams in sections of buildings to relieve problematic sections. The relative ease of creating beams of varying lengths due to concrete's properties as a poured substance eliminated the technical problems that usually arose when mounting and inserting replacement sections.

At this time, functional interventions were also introduced, which resulted in the rebuilding of roof and floor portions. During this period when the process was still in its primitive stages, reinforced concrete was limited in use to create single strengthening elements, or rebuilding of parts of buildings with functional purpose.

### 3.3.2 The Grand Period of Reinforced Concrete Construction and Restoration

The mid-20$^{th}$ century can described as the grand era of reinforced concrete restoration as the method was utilized greatly in Europe for many situations. In most industrialized countries reinforced concrete technology was quickly inserted as a viable option in restoration methodology. The interventions performed can be classified into a few summarizing categories:

- **Use of Concrete to increase sections of elements to provide traction resistance**- This process was generally used for consolidation of columns and pillars. Two methods were utilized, either the use of external "jackets" of reinforced concrete to surround sections, or though the perforation of elements to create internal sections of concrete.
- **Use of concrete to bind elements**- Often, concrete was used both with and without reinforcing elements to consolidate deteriorated sections of masonry or foundation grounds. The goal was to restore continuity within sections and return cohesion to each element. The technique usually involved pouring concrete into specially bored holes or existing voids, and in many case rods were inserted into the corresponding sections.
- **Use of concrete to create new traction resistant elements-** Reinforced concrete was utilized in many situations to construct tension resisting elements within structures, such as chains or hoops to surround towers.

- **Use of reinforced concrete to build new load bearing structures-** Interventions carried out partially or totally unburden portions of existing structures by introducing new reinforced concrete frames were performed quite often. These types of interventions were prevalent in bell towers where compressive stresses were to be reduced by the introduction of concrete frameworks.
- **Stabilization of foundations and roof replacement-** Many cases of injections to stabilize foundations, and instances where reinforced concrete tie beams were used to consolidate the tops of entire buildings also had great effect on the structural performance of historic buildings.

It is necessary to take note that while reinforced concrete was often used to solve existing structural problems, it was also used as a preventive material with hopes of avoiding potential deficiencies that may have been in their infancy. In many cases concrete was used as for simple reinforcement with hopes of preventing major problems that would call for any of the interventions previously mentioned.

As reinforced concrete technology was developing rapidly at the onset of the 20$^{th}$ century, it became one of the most widely used materials for the construction of new buildings due to its favorable economic and performance characteristics. In Europe and the United States during the period, reinforced concrete became the material of choice when constructing churches, factories, housing developments and many large infrastructure projects that looked to take advantage of this burgeoning technology.

Concrete was used in a wide range of both architectural and engineering structures, and was cited for its aesthetically pleasing properties as well as its service characteristics. Concrete also reached a dominant position in the construction of facades and balconies due to the prefabrication process in the 1960s and 1970s. The expanded use of concrete created many new opportunities for architects and engineers, as the systems offered the ability to create much larger spans economically, while also enabling the construction of slender structures with much thinner support mechanisms and higher working stresses to be built.

Much of the concrete repair work in the first half of the $20^{th}$ century was relatively simple from a material standpoint because it primarily involved replacement of damaged sections with Portland cement based concretes, mortars, grouts, or sprayed mortars. [16] One of the complications when dealing with primitive structures is that before the early 1900s, the term "Portland Cement" was used to describe a wide range of artificially created cements of varying quality. Also, when examining historic structures it becomes nearly impossible to expect to easily understand all facets of their original construction because the early structures are the result of imported technology being erected by engineers and contractors with limited knowledge and experience, with systems developed by empirical testing rather than analysis[20].

From the early period of reinforced concrete construction, to the situation we are currently faced with today, with an aging of infrastructure and many of the first structures reaching the end of their expected life along with the premature deterioration of many newer structures due to environmental conditions, maintenance and repair of reinforced concrete has become more important than ever. A wide range possibilities have been developed for the remediation of damaged concrete, including replacement of complete elements, removal of contaminated portions, surface applications, re-passivation techniques, chemical treatment and numerous others, but in any case it is necessary to take into account the properties of each structure as well as the effects and modes of deterioration in determining the most effective remediation actions. A better understand of the chemical properties and deterioration modes of reinforced concrete is necessary to gain a full understand of the problems found in structures both fully comprised of concrete, and partially restored with the substance.

# CHAPTER 4: MECHANISMS AND MODES OF DETERIORATION: PORTLAND CEMENT BASED CONCRETE AND MASONRY

## 4.1 Causes of Degradation between PC and Masonry

As stated previously, one of the most cited methods in which Portland cement has been utilized in historic preservation has been to provide cohesion to degraded masonry constructions. This process usually entails binding elements or filling gaps with concrete mortars and grouts. Quite often this process of cementing, either reinforcing walls with injections or applying new mortars to restore old, has caused more damage then benefit due to the interaction of the cement and the original building materials. In many cases, after an initial period of apparent improvement due to restoration and consolidation, historical buildings deteriorated more severely and rapidly than before intervention. This infliction of degradation is especially disheartening not only because of the severe damage that modern cement is known to inflict, but more importantly because of the fact that much of this damage could have been avoided if the cultural landmarks had been studied closer and researched properly before hasty repairs were undertaken. The reoccurring idea of concrete as a "permanent solution" did much to influence early restorers to act quickly, before fully understanding the original makeup of each heritage structure.

### 4.1.1 Compatibility Issues

When examining masonry structures it is important to gain an understanding of the chemical makeup of the mortar used to bind masonry units in order to predict how it will react with restoration materials applied to the structure. A structure's performance after remediation with Portland cement based mortar is highly dependant on the original mortar used to give cohesion to masonry units. In Europe and the United States, if a building was produced prior to the late 1800s it can be assumed that a traditional mortar was used in masonry construction. Between 1880 and 1920, it is typical to find various combinations of lime and early cement, and after 1920 most mortars were comprised of Portland cement based mixtures. It is necessary to note that there are cases of building constructed in the 1950s and 1960s that utilized traditional mortars in their constructions.

### 4.1.2 Masonry Unit Hardness Issues

During the 20th century masons began to use mortars with a high percentage of Portland cement when replacing the deteriorated mortar found in joints in masonry walls. Portland cement was a popular choice for masons because it was simpler to use and more workable than other mortars. Historic mortar, particularly in the buildings constructed before 1920, is much softer and had less compressive strength than the masonry blocks it held together[10]. This mortar expanded and contracted due to changes in humidity and temperature, or to settlement. This process helped reduce stress on masonry units, which made them less likely to crack or spall. If a mortar mixture that is harder than the masonry units is used in repointing, which was sometimes the case in restorations using Portland cement, over time it is likely that bonds would break and cracks would proliferate, allowing passage of moisture. This damage would result in accelerated spalling, or loose, cracked units. In cases where Portland cement based mortars were used with softer units, such as sandstone and primitive bricks, serious problems often resulted.(Figure 4.1) Most masonry units created past 1930 were hard enough to be used with Portland cement.

**Figure 4.1 Cementious Repointing: cement mortar harder than stone units, accelerating decay [22]**

**Figure 4.2 Hard cementious repointing: Loss of permeability of joints, loss of original character and color scheme of masonry[22]**

### 4.1.3 Chemical Processes

Along with the many chemical and physical processes that threaten individual masonry units naturally, the introduction new restoration materials since the beginning of the 20th century has contributed to many cases of premature deterioration in structures. The new materials introduced that have been noted to cause damage in historic structures are largely based on hydraulic lime and cement. It has been accepted that mixtures having hydration products containing hydrated calcium silicates and aluminates that react with sulfate particles in masonry, including hydraulic lime and Portland cement, can be thought of as having similar effects after application[11]. Hydraulic lime produced in the past and Portland cement are both derived from natural mixtures of limestone and clay. As previously stated, their compositions are largely made up of Calcium Hydroxide, $C_2S$, and CA, and in applications, the damage mechanisms caused by hydraulic lime and Portland cement can be accepted to follow the same format. Both binders contain $C_3S$, $C_2S$, $C_3A$, and $C_4AF$ to provide hydraulic performance. The hydration products of these mineralogical compounds are responsible for the interference with other compounds in the original masonries, and in most cases, sulfate salts.[11]

### 4.1.4 Altering Existing Material Properties

Portland cement based binders gain their hydraulic abilities due to the formation of hydrated calcium aluminates and silicates (CHS, refer to section 2.2.2). When Portland cement is used in close proximity of original hardened mortars, this chemical process may make original mortar left in place more water resistant. This change makes the original mortar more susceptible to the negative interactions with calcium sulfates naturally occurring in masonry units. The presence of sulfates in masonry may come from direct employment in the form of gypsum alone or combined with lime as an orignal mortar, or in mortars used in later restorations. Bricks can also contain a noticable amount of hydrosoluable sulfates naturally which can be carried from water in wet masonry. The capillary rise of water containing sulfates from foundations, or by way of wind transportation from marine environments is also entirely possible.[11] In contact with a limestone based mortar, such as Portland cement, the salts produce bihydrated calcium sulfate, (gypsum) which is a weak binder that cannot resist the leeching effects of water.

### 4.1.5 Moisture Transfer Problems

Along with leading to unfavorable chemical reactions, the inability of cement to transfer moisture through masonry leads to many problems. Typical historical structures created with lime mortars were constructed with multiple layers of bricks. The natural porosity of masonry typically allows moisture to enter, but not fully penetrate walls. In cases where penetration did occur, the breathability of original mortars would have filtered water into the structure in the form of vapor.[10] When attempting to escape the masonry, the water would commonly escape through the mortar joint. Repointing mortar joints with cement causes moisture to look for a new escape method, which is often through the brick itself. This causes bricks to retain moisture, putting the masonry at a more susceptible state that encourages salt formations and problematic freeze/thaw issues.

### 4.1.6 Altering Natural Processes

Alternatively, the original mortar can retain the trapped moisture which jeopardizes its integrity. Historic lime mortar has a natural ability to heal fissures within itself by lime re-carbonation, where water in cracks carries free lime solution to the surface where it meets air and hardens. When modern cement based mortar are used in surface pointing, water loses its ability to escape, leading to remaining state of saturation of its interior, where free lime never re-hardens. This results in far weaker mortar holding the building together, and in some cases mortar can deteriorate to the point of failure. [11]

### 4.2 Production of Ettringite and Thaumasite in Masonry

When a hydraulic mortar based on cement is used in restoration work, the formation of hydrated calcium aluminates and hydrated calcium silicates is possible. This occurrence, combined with the presence of calcium sulfate and moisture in masonry units makes possible the formation of ettringite and thaumasite which both result in rapid deterioration of restoration mortar. Also, if cement grouts are used for injection purposes to consolidate voids in masonries, the production of ettringite and thaumasite can compromise the statics of the building, leaving stuctures susceptible to damage by expansive forces.

#### 4.2.1 Ettringite Production

For Ettringite production to occur the following conditions are necessary:

- The presence of sulfates in masonry
- The presence of calcium aluminates in repair mortar
- The presence of moisture in masonry

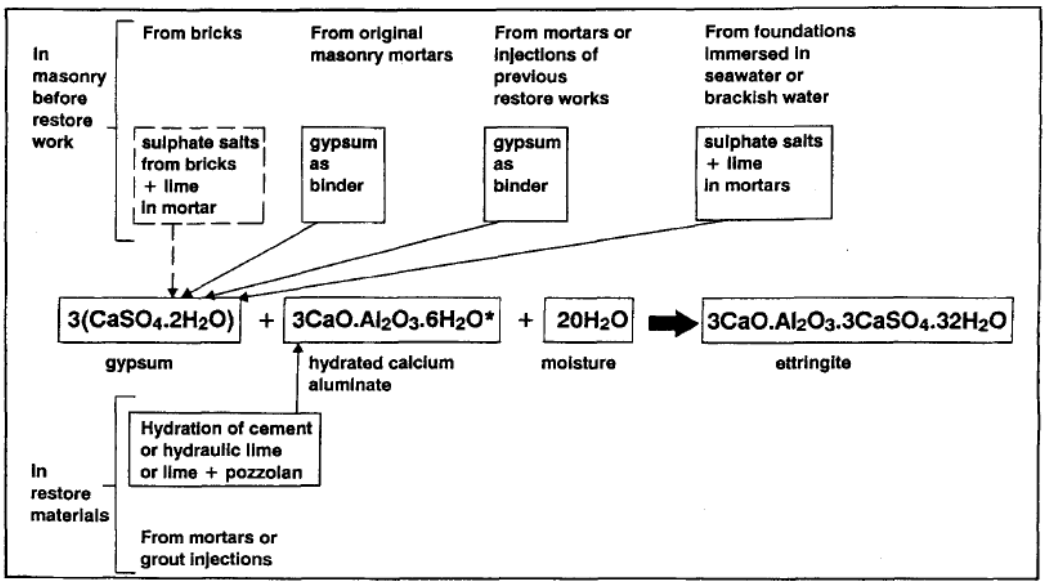


**Figure 4.3 Interaction of Limestone Mortar and Sulfate Salts to Produce gypsum leading to Ettringite[11]**

### 4.2.2 Thaumasite Production

For this Thaumasite production to occur the following conditions are necessary:

- The presence of sulfates in masonry
- The presence of calcium silicates in repair mortar
- The presence of moisture in masonry

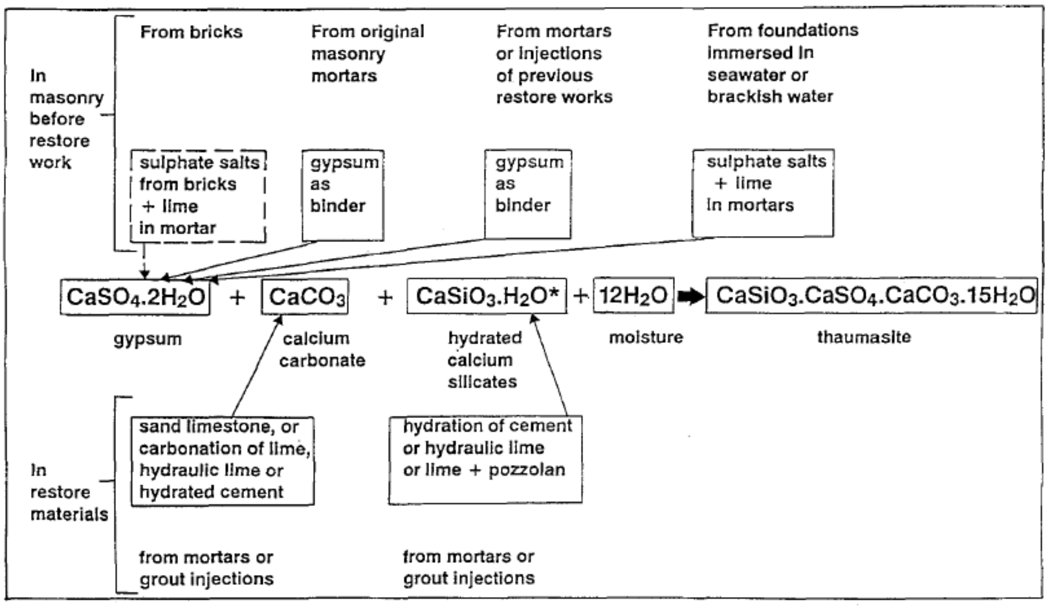


**Figure 4.4 Interaction of Cement Mortar and Sulfate Salts to Produce gypsum leading to Thaumasite[11]**

### 4.2.3 Sources of Gypsum in Historic Structures

Gypsum can be found in Historic Structures if:

- It was used as a binder for gypsum mortars in original constructions, or in later repairs
- It was formed by the reaction of sodium or magnesium sulfate from bricks with lime or C-S-H in rendering mortar
- It was formed in situ by reaction of $SO_2$ with oxygen, water and lime or calcite on surface mortar, usually occurring in polluted environments of industrial areas
- It was formed by the reaction of sulfate ions with lime of C-S-H in the cementious materials in walls and capillary rise water, usually in structures in close vicinity to seawater

When gypsum is present for one of the reasons mentioned, thaumasite or ettringite formation can occur following one of the processes shown in figures 4.3 and 4.4

### 4.2.4 Potential Problems

The formation of ettringite is linked to expansion, swelling and loss of strength in cohesion.[11] Thaumasite production does not cause significant expansion, but after formation the mortar loses its resistance properties and be transformed into a disjointed mass in the presence of moisture. This can result in a progressive removal of mortar due to washing out by rainwater. Ettringite forms more rapidly than thaumasite, but the presence of thaumasite usually precedes the formation of ettringite depending on temperature and moisture conditions. Low temperatures favor both processes, and in cold climates the formation of thaumasite is especially accelerated.

**Figure 4.5 Severe deterioration of mortar stemming from thaumasite attack [5]**

#### 4.2.5 Temperature Effects

Thaumasite remains stable even in the absence of alumina, and at temperatures higher than room temperature. Alumina impurities and low temperatures are proven to accelerate thaumasite formation, especially when ettringite is already present. In any case, historic buildings with mortars based on hydraulic lime or lime-pozzolan mixtures, repaired with Portland cement, ettringite and thaumasite can be formed as long as gypsum and water are present.

#### 4.2.6 Diagnosis and Properly Planned Restorations and Treatment

The damages described above have led to the awareness of the importance of ensuring the compatibility of restoration materials in order to ensure no further damage is produced by restoration. In most cases a properly planned intervention requires a careful preliminary diagnostic survey so that deterioration mechanisms can be clearly identified. Although ettringite and thaumasite are commonly found in deteriorated cement mortars, it is difficult to evaluate their presence with the most readily available method, X-Ray diffraction[10]

Ettringite is reversibly affected by a decrease in relative humidity and increase in temperature. Thaumasite is largely affected by temperature increases and requires a large amount of time for structural recovery. This makes the process of properly diagnosing thaumasite very difficult when it has been decomposed by thermal conditions. Excess drying can decompose ettringite and thaumasite and prevent X-rays from recognizing their presence. Both ettringite and thaumasite are detectable by X-ray diffraction, as long as specimens are moisturized. Rewetting before analysis favors the intensity increase of the X-ray lines of the products.[8]

#### 4.2.7 Prevention

The most effective way to discourage ettringite and thaumasite formations, even in the presence of water and gypsum in structures, is to ensure that sulfate resistant binders are utilized in restoration purposes. Additional measures and alternative protections measures are largely based on the prevention of water from penetrating walls. In the permanent absence of water, ettringite and thaumasite cannot of form, even if gypsum is present. Surfaces can be treated with hydrophobic products such as silane to hinder rain water absorption, and metallic or polymetric sheets can be inserted into walls at ground level to block the capillary rise of water. Silane can also be injected to give water resistant properties to wall interiors.

### 4.3 Degradation Caused by Alkali Amorphous Silica Reaction

From the chemistry of concrete it is known that cement alkalis can react with amorphous silicas present in stone or concrete units to produce voluminous products, usually hydrated sodium or potassium silicates that cause accompanying expansive and disruptive phenomena on wall surfaces.[11] For this to happen the presence of moisture with masonry is necessary. If original stone units contain amorphous silica or partially crystallized forms of cristobalite and tridymite, the following reaction can take place when cement binders used in restoration are rich in alkalis.

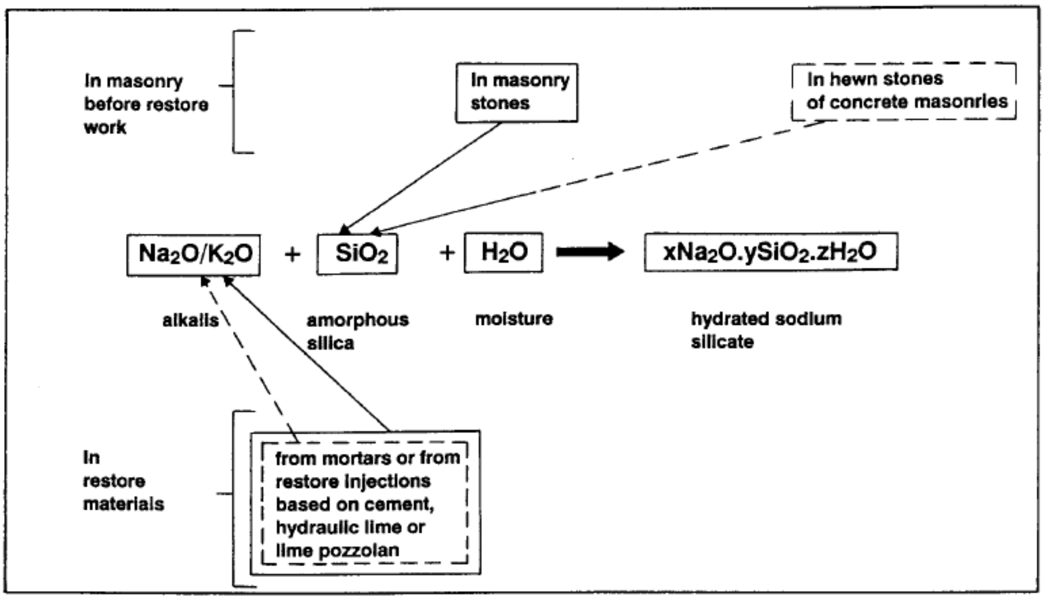


**Figure 4.6 Interaction between cement binders and silica of stone and cement masonry units (Cement Units-Dashed Line)[11]**

### 4.4 Material Properties Mortar vs. Portland Cement

The correct choice of materials for any mortar re-pointing attempt is integral to the future success of the intervention. Traditional lime mortars are absorbent, elastic, and easily renewed. Portland cement mortars are stiffer, almost impermeable, and excessively strong to the point that repairs tend to break away in large sections. Also, in certain cases consistent weathering of a structure destroys the softer brick or stone mortar units before the Portland cement re-pointing. In cases of consolidation, in any wall or pier it is desirable that cores should be as strong and stiff as facings, and should be well bonded to them in all scenarios. Portland cement mortars for grouting are often criticized for their excessive hardness, lack of permeability, and lack of elasticity, and in all cases a thorough examination of the original composite structure must be carried out to avoid causing further harm.

# CHAPTER 5: STRUCTURAL INTERVENTIONS USING REINFORCED CONCRETE

Reinforced concrete was used in many cases where restoration experts strived to increase the structural safety of historic buildings. Reinforced concrete was assumed to be a reliable material that brought homogeneity, isotropy and elasticity to historic structures which were more often than not heterogeneous (varying sizes of stone and brick with differing binders), and anisotropic (due to joints between materials), and an overall resistance compression and plastic behavior.[15] These contradictions help spread the use of concrete as a material to secure these otherwise questionable properties of typical historic construction materials.

## 5.1 Earthquake Damage Protection

Reinforced concrete was believed to better withstand earthquakes because of properties that produce “homogeneity that allows for vibration and acceleration that is not destructible”[20] and also the resistance to the post earthquake effects of fires that typically occur. Masonry structures are were accepted to be constructed of nonhomogeneous, non elastic, low strength materials with elaborate three dimensional shapes and large, indefinite dimensions.

Concrete was implemented in bearing walls, horizontal ligaments, roof reconstruction and vertical and horizontal consolidation. Criteria was established for the improvement of walls, arches, domes and floors, using injections and the addition of lintels, with goals of improving stability in each case. Engineers cited the principles that consolidated buildings would behave elastically and if proper connection with all elements was ensured, greater resistance would be offered. To guarantee this in some cases a small thickness of concrete was applied around buildings in a box form to oppose seismic stresses. This form of framing would often be introduced in foundations and vertical and horizontal openings in covers with hopes of creating an “elastic cage around inner workings to prevent wall splitting”[15] Confinement methods of this nature were attempted in foundations, walls, vaults and domes based on the precedence of combating tension, compression and shear in the vertical and horizontal planes.[15]

### 5.2 Repair Options for Structures

- **Walls**- Replacement, Injection, Nailing, Coating with Reinforced Concrete
- **Columns and Lintels**- Reconstruction, Replacement, Increase section, injection, hooping, removal, changing structural organization
- **Arches and Domes**- Bracing, Injection, Hooping, Beam addition, Concrete Slab addition
- **Roofs and Floors**- replacement, bracing, beam addition

### 5.3 Walls and Anchoring Systems and Restoration Techniques

#### 5.3.1 Grout Injection

To consolidate walls, techniques typically followed a procedure of creating holes in walls with up to 40 mm diameter drills before adding rods and injecting cement grouts. This method hoped to fill gaps in walls and to reach a state of elastic continuity based on adhesion and resistance to traction of the concrete interventions. This process was also utilized to fill the gaps between two or more leaves of a wall when badly connected.[2] Grouted anchors installed properly increased the tensile strength of existing masonry. These actions were based on the principle of improving homogenization of otherwise heterogeneous masonry units, allowing the masonry to act as a completely autonomous structure during its life cycle. (Figure 5.2)

The goals of grouting can only be reached with good precision when a complete knowledge of the walls and their compositions are known, in order to avoid chemical and physical incompatibility. Also existing crack distribution and connection, size and percentage and distribution of voids should be known before grouting. Improperly installed systems were known to have the opposite effect on walls, reducing their strength properties and acceleration loss of cohesion. Modern practice states that a wall with less than 4% voids as non-injectable. The use of Portland cement as the primary binder in consolidation can contribute to greater than desirable strength and shrinkage in grout than a wall can handle.[7] This can be avoided by taking the necessary preliminary steps before work is implemented to make sure that walls can handle the properties of a cement grout.

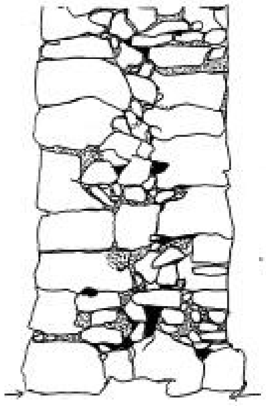

**Figure 5.1 Poor Masonry Section with low void content[2]**

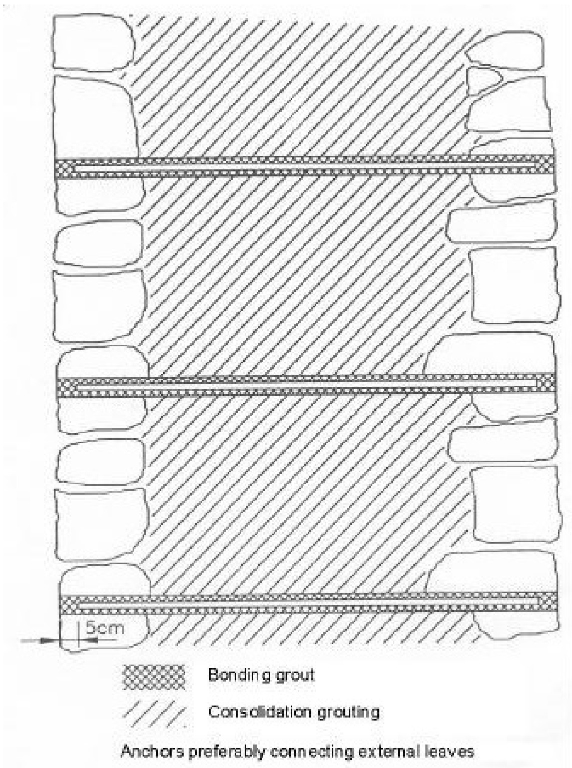


**Fig 5.2 Grouted and Anchored Masonry Wall[9]**

### 5.3.2 Key Factors in a Successful Consolidation Project

Modern process for a successful consolidation project in historic structures includes:

- Preliminary Investigation and Evaluation
- Grout mixture composition decision
    - Fluid properties
    - Physical properties after hardening
- Grouting methodology decision
    - Mixing equipment
    - Pumping equipment
    - Pumping pressures
    - Grout confinement
- Retaining masonry integrity

## 5.4 Pier and Wall Jacketing

The jacketing technique often utilized on walls and piers is comprised of the positioning of a reinforcing net on both faces of a wall, connected by steel ties, and then covered on both faces by a cement based mortar. Goals of the technique were to improve the connection of the wall, and to increase tensile and shear strengths and ductility.[2] The technique was commonly used to irregular multiple leaf stone masonry walls. In many cases the inhomogeneity of the walls, and the cost and problems associated with connecting both faces, made carrying out the process is quite difficult. Common mistakes in this intervention technique often include:

- Lack of proper connection between nets in walls and in correspondence with floors, causing discontinuities
- Lack of overlapping between two different sheets of the net
- Missing or over-spaced steel connectors causing separation of reinforced layers from walls
- Use of short connectors
- Insufficient cement cover leading to steel corrosion
- Lack of uniformity of distribution of repaired areas in structures, causing torsion stresses due to non uniform stiffness

**Figure 5.3 and 5.4 Discontinutites caused by lack of proper connection between nets in masonry rehabilitation[2]**

**Figure 5.5 Corrosion of netting in rehabilitation[2]**

## 5.5 Roof and Floor Substitution

In many old structures concrete beams were utilized to replace floor timbers and mixed concrete and clay blocks were used in place of roofs. In this process a concrete tie was placed at each floor, positioned along the four sides of a structure to serve as a linking point from floor to wall. The goal of this technique is to induce the structure to work in the form of a stiffened box to resist horizontal seismic loads. Altering existing buildings in this form required partial demolition of each wall section to insert concrete ties into each section. This fact made it very difficult to ensure a stiff connection to existing walls, especially in the cases of multiple leaf irregular stone masonry. Typical damage patterns in buildings altered in such a fashion includes: partial eccentric loading of walls, and poor connections of tie beams to walls. (Figure 5.6)

**Figure 5.6 Eccentric loading damaged influenced by concrete tie positioning [2]**

### 5.5.1 Post Intervention Phenomena "The Block Effect"

Recent post seismic event studies in Italy and Portugal have identified the need to better understand and define the typical mechanisms of large blocks of houses where buildings are attached together in rows. In such cases these buildings have been identified as "building blocks." Studies have identified interesting cases of failure during seismic events, especially when one or more of the houses in the "blocks" have been altered from their original makeup, which have changed the theory behind ensuring safety in such constructions.[2] In post seismic event studies done on block structures of this nature, it was noticed that the first and last buildings in each block have seemed to endure the most damage in the form of local collapse and large cracks. When collapse occurred in the interior of such blocks, it was always an unrepaired building surrounded by two repaired structures.[2]

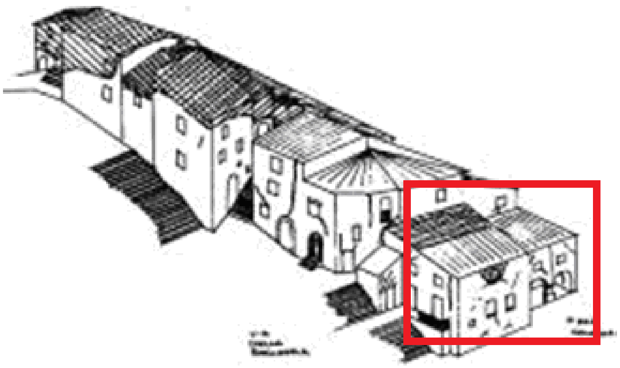

**Figure 5.7 Block effect damage in rows of buildings, failure at end of row[2]**

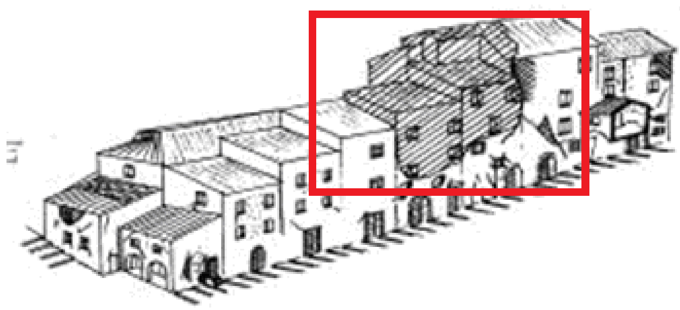

**Figure 5.8 Block effect damage in interior of row; unchanged interior buildings surrounded by repaired structures[2]**

In most cases, the repairs in masonry based houses of this layout were typically replacement of timber floors and roofs with reinforced concrete slabs. In typical structural models, single structures in each block were modeled as separate entities, but after actual events it was noted that for horizontal loading, namely seismic forces, that this approach was flawed. Such structural system when under the force of horizontal loading have been identified to absorb and distribute forces as a whole entity, not house by house as previously believed. The structural performance of modified buildings, such as the case of structures with floors and roofs replaced with reinforced concrete, affect the structural performance of every house in the rest of the block.[6] Specifically, reinforced concrete floors and roofs induce severe changes in stiffness in the buildings, which is known to produce damage through pounding effects. This topic is explained in greater detail in Case study 3.

### 5.6 Foundations

In problematic foundations, to improve performance and adherence to soil, holes were drilled for the application of metal bars and were followed by the injection of Portland cement to develop “reinforcement based networks of resistance.”[15] Portland cement injection allowed to create a new deep foundation that was incorporated into the original materials without disturbing the static equilibrium of the existing structure, while increasing rigidity, a quality presumed suitable for absorbing vibrations. The basic idea was to strengthen the soil mass, improving its low resistance and reinforcing it with the use of tension resisting bars. Similarly, reinforced concrete pile drilling was used to better connect structures to ancient foundations. Pile drilling of this sort, while having an irreversible impact of the structural systems of ancient monuments, has also been criticized for its damaging effects on archeological remains hidden beneath certain structures.

### 5.7 Columns and Towers

In many ancient Greek and Roman temples reinforced concrete was used to transform pillars, columns and towers into more rigid systems. Typically, external coatings were added to structural elements to provide a protective “jacketing” layer of reinforced concrete. Alternatively, elements were punctured and injected with cement to form a solid cohesive nucleus of reinforced concrete. Towers were also stabilized using tension-resisting hoops composed of reinforced concrete. Interventions of this type altered the original structural behavior of the system and are completely non reversible. Also, they do much to introduce material heterogeneity to systems and modify the material histories, and structural bodies in an irreversible ways.

### 5.8 Potential Problems with Repair Options: Non Reversibility

It is possible to list countless intervention methods that were implemented during the peak era of reinforced concrete usage. The cementification of heritage structures spread rapidly due to the low cost and relative ease of construction. Common examples include underpinning by piles and micro-piles, adding footings and beams connected to ancient masonry, grouting and nailing, replacement of original wooden elements, addition of concrete roofs and covers, transformation of columns into monolithic pillars, consolidation of masonry walls by concrete plates, and the construction of reinforced concrete shells on masonry domes and vaults. In many cases these modifications to structures were permanent and forever altered the layout of each structure. Some drastic examples of this include the construction of extra floors, enlargement of existing facade openings, wall removal, and additions of new concrete members

Current restoration philosophies encourage measures that are reversible, and that if need be, can be replaced, removed, or improved in the future. This philosophy stands true keeping in mind that in many situations it is nearly impossible to guarantee error-free methods, which highlights the importance of attempting to make all restoration attempts reversible should better techniques and materials be developed. Unfortunately, many complications still arise in situations where reversibility is neither possible nor suitable, and in cases of this nature, no decisions can be made in haste.

# CHAPTER 6: TRADITIONAL DETERIORATION MECHANISMS: REINFORCED CONCRETE

## 6.1 Overview

In many restoration cases where reinforced concrete was utilized to enhance a structure, the structures became susceptible to the typical deterioration mechanisms that have been proved to hamper traditional reinforced concrete. Much research has been completed in this field and we have reached a point where a wealth of information is available regarding the causes and remedies for such damaging effects.

During the great period of concrete intervention the potential deterioration and compatibility issues of the modern concrete used in various structures was not often cited as a high risk cause of eventual deterioration. Towards the end of the 20$^{th}$ century it became apparent that many restorations made with reinforced concrete showed themselves to be incompatible with elements because of internal characteristics of the concrete itself, and due to problems with work techniques and execution [15] While this document does not attempt to explain in detail each form of deterioration and its appropriate remedy, a familiarity with typical forms of reinforced concrete decline mechanisms is useful in properly diagnosing monuments containing the building material.

Concrete deterioration usually is a result of corrosion of embedded reinforcement, degradation of the concrete itself, or use of inadequate material and techniques in original construction. Combining reinforced concrete with alternative materials, as occurred in many early restorations, only enhances the probability of potential of future concrete deterioration due to the complications that arise regarding original construction techniques and chemical reactions occurring between original and repair materials.

## 6.2 Corrosion of Reinforcement

### 6.2.1 Carbonation

While steel reinforcement did much to expand the applications of concrete in the 20$^{th}$ century, it can also be cited as the cause of most deterioration in historic concrete. Steel reinforcements are typically surrounded by a passive oxide layer that, when in proper form, protects steel from corrosion and aids in the bonding of steel and concrete.[13] When the stable alkalinity of concrete (typically between 12 and 13)is compromised and steel is exposed to water vapor, or high humidity, corrosion of steel reinforcement takes place. Reduction in alkalinity is a result of the process that occurs and carbon dioxide in the atmosphere reacts with calcium hydroxide and moisture in concrete, called carbonation. When carbonation reaches the level of reinforcement, concrete no longer has the protective abilities. Carbonation is caused by the effect of carbon dioxide and moisture penetrating concrete, and chloride attack caused by chlorides present initially in concrete mix or invading over time in marine environments or due to de-icing salts or acid rain

Corrosion related damage is the result of rust formation and expansion. This causes the reinforcement to take up more space than at the time of insertion, creating expansive forces that cause cracking and splitting of adjacent concrete. Cracks can vary in depth, width, direction, pattern and location. The load bearing capacity of the structure or intervention is diminished by loss of concrete and loss of bond between reinforcement and concrete, and by the decrease in thickness of section of reinforcement.

Lack of proper maintenance of building elements like roofs and drainage systems contribute to water related deterioration of concrete, particularly when concrete is saturated with water while exposed to freezing temperatures. Water within concrete freezes and exerts expansive forces that also result in cracking and delamination. This type of deterioration is often most prevalent at the point of interface between joints, and interface between alternative materials. In the case of heritage structures, maintenance and water transport problems are especially prevalent due their relatively exposed nature, natural aging process and original design deficiencies of structures.

## 6.3 Concrete Disintegration

### 6.3.1 Freeze-Thaw Exposure

Concrete is a very brittle material that is susceptible to internal tensile stresses due to expansion processes inside concrete. The porous nature of concrete makes it prone to the expansive forces of freezing water if saturation levels in systems reach dangerous points. The freezing water trapped within the concrete can create hydraulic pressure that can lead to mechanical damage within the internal structure of concrete, leading to loss of strength and cracking.[17]

### 6.3.2 Ettringite Formation

Ettringite formation can occur in concrete stemming from a chemical reaction caused by sulfate materials in hydrated cement. Concrete mixtures can be naturally contaminated by sulfates, but sulfate can also form during excessive thermal treatments during the curing process.[17] Ettringite mineral crystals form on walls of the pores in concrete, decreasing its frost resistance. Ettringite reactions lead to concrete deterioration either as a result of frost weathering or from the pressure created by the filling of pores which causes cracking.

### 6.3.3 Alkali Silica/Alkali Carbonate Reactions

Certain aggregates used in the original cement mixture can eventually result in the deterioration of concrete used in restoration. Alkali aggregate reactions occur when naturally present alkalis in cement react with certain types of aggregates, causing the propagation of an expansive gel. This white gel substance when exposed to moisture expands and causes cracking of concrete matrixes.[13]

## 6.4 Workmanship/Placement Issues, Problems in Early Concrete

While much of the concrete restoration work performed in the early 20th century utilized relatively simple materials, the application process using such treatments was often complicated and a potential source for problematic behavior. In a few cases sea water or beach sand used in concrete mixes jeopardized concrete mixes by infusing damaging salts into systems. The sodium chloride present in seawater and sand accelerates the rate of corrosion of reinforced concrete.[13] Early concrete was not always vibrated when poured into form, which often lead to voids at congested areas. Design defects, such as an inferior amount of protective covering over reinforcement bars often results in premature corrosion.

### 6.5 Signs of Deterioration

- **Cracking**- occurs in most concrete but varies in depth, width, direction and pattern; labeled active or dormant, with many dormant cracks a results of curing process; structural cracking can be caused by overloads, foundation settling, seismic forces, design inadequacies, or response to thermal actions
- **Spalling**- the loss of material often associate with freeze thaw cycles as well as cracking, and delamination; stems from reinforcement corrosion and expansion
- **Deflection-** bending or sagging of elements; can identify problems in strength and reliability of concrete
- **Staining-** can be traced to soiling from atmospheric pollutants or contaminants, organic growth, or serious problems such as corrosion of reinforcements, improper surface treatments, efflorescence, AAR reaction, or deposition of soluble salts on concrete surface

Determining causes of deterioration is the key step in developing a repair plan that will best serve the structure. Understanding of the original construction techniques and all previous repair methods of each facility being observed is often the most important, but most problematic step to developing causes of existing deterioration and remedies to halt their propagation.

### 6.6 Compatibility Issues

Just as many of the reinforced concrete structures produced in the early 20$^{th}$ century reach the end of their service life, so too do many of the interventions using the material created during the time. In any rehabilitation of a structure composed of reinforced concrete, important decisions must be made regarding the selection of repair materials and systems. Compatibility of repair materials with existing structures is necessary to ensure that after repair, a structure can withstand stresses induced by volume changes, chemical and electrochemical effects.

- **Compatibility-** a balance of physical, chemical, and electrochemical properties and dimensions between a repair material and the existing substrate that will ensure that the repair can withstand all the stresses induced by volume changes and chemical and electrochemical effects without distress and deterioration over time.[16]

The early standards of concrete repair work largely encouraged simple replacements of damaged or deteriorated concrete portions with Portland cement based grouts, mortars, and patch concretes. These simple solutions were utilized for many decades before many reported instances of less than satisfactory performance were recorded. Repair concrete was exposed as performing inadequately in aggressive exposure environments, such as instances where concrete was exposed to chemical attack or in conditions of high abrasion and erosion. The process of creating a durable repair starts with a close examination of the physical material properties of the structure to ensure compatibility of original structure and repair material. In any case of concrete repair, or in cases where the material is being used to repair a system, steps much be taken to ensure dimensional, chemical, electrochemical, and permeable compatibility.

- **Chemical Compatibility-** selection of repair material that does not have any adverse affects on the repaired component or structure
- **Dimensional Compatibility-** Repairs can become de-bonded from original materials if: excessive shrinkage strains in Portland cement, excessive thermal expansions followed by cooling occur during settling and hardening, or excessive high thermal expansion in repair materials during seasonal change occurs. Size, shape and thickness of repair section affect dimensional compatibility
- **Electrochemical Compatibility-** a repair system must inhibit corrosion of reinforcement, both within the repair area, and in the surrounding non repaired reinforced concrete
- **Permeability Compatibility**- the permeability of the repair material must be similar to that of the substrate; repair materials which are impermeable to moisture vapor should be used with caution

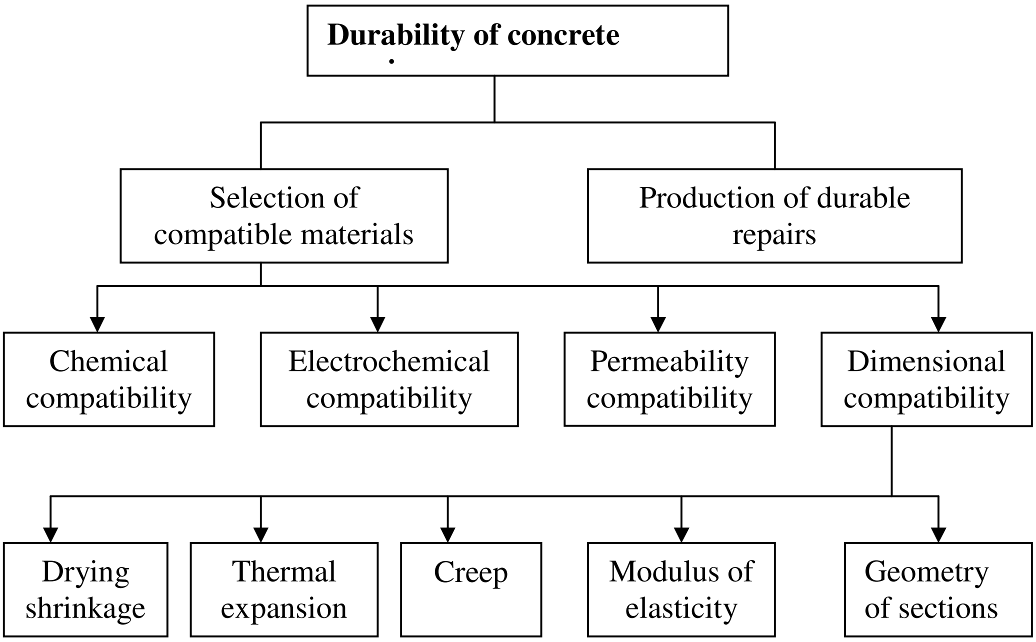


**Figure 6.1 Considerations affecting potential concrete durability**

In any repair attempt an approach should be adapted where all influencing parameters are taken into account in design and implementation. Compatibility between all materials is necessary to ensure a long and successful surface life of the repair section, and all surrounding sections. External conditions must not be ignored, and the use of Portland cement based repair materials in extreme environments must be monitored carefully. In most repair situations, there is often more than one correct repair method, but economy will often dictate which solutions will be chosen, but taking this into account, it is of paramount importance that attention is paid to how repair materials will interact with existing systems so that damage is not initiated during the remediation.

# CHAPTER 7: CASE STUDIES

## 7.1 Damage Investigation: Molise Earthquake 2002, Umbria Earthquake 1997

Recent earthquake events in Italy have done much to expose the fact that the seismic vulnerability of many historic structures in the region has increased due previous reinforcement works using concrete that have been carried out in the last 50 years[1] The Umbria-Marche region suffered much damage after an earthquake in 1997, and more recently, on October 31, 2002 a magnitude 5.9 earthquake struck the regions of Molise and Puglia. The Molise and Puglia earthquakes caused widespread damage in 50 villages and killed 30 people, 27 of whom were young school children who were trapped in the collapse of their elementary school. Previous restoration works in both cases included replacing original wooden roof structures with new reinforced concrete elements, inserting reinforced tie-beams into masonry, and adding new reinforced concrete floors. Also, concrete jacketing of shear walls was widely used throughout the region.[1] Interventions of these types were known to have contributed to greater seismic forces because of increased weight, and deformations incompatible with masonry walls.

### 7.1.1 Restoration History in Region

After World War II many of the original structures in towns were altered using reinforced concrete. In many cases, additional stories were added, and little was done to ensure continuity with the already existing stories. The buildings of mixed constructions also proved to be especially vulnerable during the earthquake.

Historic churches in the area were proven to be particularly susceptible to seismic forces, and this fact was exacerbated by retrofits that were proven to be incompatible with the natural vibrations of the original masonry walls. Roofs that were constructed of reinforced concrete, and the addition of thick concrete tie beams and floors dramatically increased the inertial forces that could not be accommodated by the original structures.[1] In most cases, seismic retrofitting was the predominant reason for roof replacement. An example of this was found in the village of Santa Croce di Magliano where two recently retrofitted churches, Sant Antonio da Padova, and San Giacomo suffered severe damage and partial collapse, while abandoned Greek churches already in poor states showed only slight worsening of damage.

**Figure 7.1 LEFT) San Giacomo Church; the spire of the bell tower which was recently reconstructed in reinforced concrete has collapsed, original unreinforced masonry bell tower left undamaged RIGHT) collapsed school in San Giacomo, visible: heavy concrete slab of second floor was supported by the now collapsed poor quality stone masonry units[3]**

### 7.1.2 Collapse Mechanisms

Damage mechanisms first viewed observed in the 1997 earthquake were repeated once again after the Molise earthquake in 2002. 75 churches in the earthquake epi-central and surrounding areas were inspected to identify various collapse mechanisms and causes of damage, and the most common damage patterns included: damage due to crushing and shearing of masonry pillars due to increased weight of reinforced concrete tie beams and slabs on vaults, sliding and overturning of bell towers as a result of increased rigidity and weight after intervention, and damages in apses from reinforced concrete roofs. Observations confirmed that the monuments were particularly vulnerable to seismic actions largely because of details such as slender walls and heavy architectural elements.


**Figure 7.2 Churches damaged by Earthquake In Umbria Region presumed to be caused by added weight of concrete roofs A) cracked supporting walls B)caused total collapse of walls C) damaged external wythe curtain walls[4]**

Buildings in the area that underwent modifications during their lifetime were proven to be more vulnerable during the seismic event. A common modification was the replacement of old wooden floors with newer, heavier reinforced concrete beams, which were installed without upgrading the strength of masonry bearing walls. The post earthquake study showed that alterations and interventions often took place without heed of any regulations or seismic design criteria. The earthquake was particularly ruthless on these buildings because the floors were not tied through the original masonry walls and did not contribute to holding them together, which increase the chances of collapse. While new floors may have originally given the false sense of security that the structure has been improved, the incompatibilities that such systems created only increased each structure's seismic vulnerability.[1]

(a)

(b)

**Figure 7.3 Out of plane failure of façade gables; common failure mechanism in structures where wall is not well connected to roof, hammering effect insues[4]**

Figure 7.3 depicts the out of plane failure of gable end walls. Failures of this type are common in structures where walls are not well connected to roofs. Inertial forces corresponding to the weight of the was itself are thought to ensure failure, but in these cases post earthquake study postulated that failures showed the effects of hammering of the rood on the masonry below.[4] It is believed that the increase of weight and stiffness on the roof led to an increase in the horizontal seismic forces that induced collapse of the masonry walls, with the stiffness of the topmost tie beam obstructing the natural vibration mode of the masonry, in turn inducing high local stress in the masonry.[4]

**Figure 7.4 LEFT: Reinforced concrete floors retrofitted onto old buildings without wall ties; contributing to damage RIGHT: two buildings of mixed construction lost their façade and floors because of lack of ties between floors and walls[1]**

### 7.1.3 Future Considerations

The Umbria and Molise earthquakes both did much to expose the fact that monumental buildings represent interesting case studies because current practices do not require "seismic adaptation" to the safety level required for new constructions, but only "seismic improvement" in safety levels due to the fact that preservation guidelines discourage invasive interventions. In the cases of many of the heritage structures in both the Umbria and Molise regions, this deficiency has been proven to be potentially catastrophic in seismic situations. Most of the failures occurred due to lack of knowledge of the intervention materials and of building construction details, which led to the wrong choice of repair technique, and a poor application of it. It can be said that it is often not bad restoration techniques that cause damage, but only inappropriate and poor applications due to lack of knowledge and skill.[2] Post event studies have done much to stress the argument that proven interventions are necessary, whether invasive or passive, even if they do not preserve the structural scheme and behavior of the original building, and must be implemented to ensure better performance in future events.

**Figure 7.5 LEFT: Failure of exterior masonry wall not properly connected with concrete slab RIGHT: Detachment and shifting of top story comprised of reinforced concrete from bottom floor stone masonry wall [3]**

### 7.2 Case Study: Improper Intervention in two Structures in Ancona, Italy

As stated previously, it is known that one of the leading causes of deterioration of mortar in brick masonry structures is related to the proliferation of sulfate salts. When masonry containing sulfate salts is repaired with a hydraulic mortar such as Portland cement, failure is very common. Cited earlier, deterioration occurs in the presence of humidity between sulfates in masonry units and calcium aluminate hydrates in mortars to produce ettringite, or with calcium silicate hydrates of mortars to produce thaumasite.

Sulfates in masonry can be present naturally, appear from the direct application of gypsum as an original binder, or in mortars used in later interventions, or be transferred to brick units through capillary rise of water from the surrounding environment. Particularly destructive environments include the severe conditions in modern city centers, where the heterogeneous oxidation of sulfur dioxide found in emissions of both light and fuel oils is known to wreak havoc on high porosity mortars.[5] The mentioned mechanisms responsible for sulfate contamination have lead to much awareness of ensuring that compatibility of materials is reached during restoration, in order to avoid unnecessary damage from the action itself.

In a case study in the ancient town of Ancora, Italy samples were removed and examined using X-Ray diffraction from two historic structures that were known to have been restored at various times during their life span. These buildings differed in age, historical interest, and exposure conditions and were chosen to compare the level and cause of ettringite and thaumasite formation in their masonry units. Testing attempted to pinpoint absence or presence of ettringite and thaumasite, and gypsum, and explain reasoning for development in each situation.

### 7.2.1 Building I: 17-18th century structure in historical city center


**Figure 7.6 Deterioration of mortar in Ancona historic center caused by A)ettringite and B)thaumasite [5]**

Structure Details:

- Built during 17th-18th century
- Rests behind harbor, not directly exposed to marine conditions
- No particular historical or architectural relevance
- Endure multiple restorations with varying techniques throughout its life span

X-Ray Diffraction Results:

- Presence of gypsum and ettringite found in interior mortar attributed to migration phenomena
- Presence of gypsum and ettringite found on exterior mortar evidence of hydraulic binder incompatibility during later interventions
- Absence of thaumasite attributed to washout by atmospheric agents
- No capillary rise observed in masonry, ettringite attributed to sulfate attack from environment

### 7.2.2 Building 2: Vanvitelli's Mole Historic Monument

**Figure 7.7 Vanvitelli's Mole location in Ancona[5]**

Structure Details:

- Monumental building with historical significance
- Erected in 18th century
- Located inside of Ancona harbor
- Foundations directed immersed in sea, direct exposure to sea water
- Endured varying restoration attempts throughout its life span

X-Ray Diffraction Results:

- Interior jointing mortar proven to be composed of lime and sand
- Exterior jointing mortar proven to be a cement based hydraulic binder, applied during past intervention, contained gypsum, ettringite and thaumasite
- Traces of cement identified in rendering mortar
- Deterioration traced to environmental conditions: exposure to marine spray and high levels of sulfur dioxide in atmosphere

### 7.2.3 Case Study Conclusions

Samples of rendering mortars removed from the interior and exterior of two buildings located in close vicinity, both showed similar signs of deterioration even though the sources of sulfate introduction in each case were different. It was concluded that environmental sulfation was the responsible deterioration mechanism in each case. The study showed the presence of ettringite and thaumasite formation in the mortars in both cases, leaving proof that a hydraulic cement based binder was used in restorations in both sites. The cement based mortars were not compatible with the sulfate generated due to the harsh environmental attack that both buildings were susceptible to. It can be said that the presence of ettringite and thaumasite were proof of incorrect intervention[5] In future cases, it would be recommended to use a sulfate resistant binder in any repair work. This case presents interesting and useful factual information regarding proper actions for the future in restorations in many urban landscapes, where sulfur dioxide levels will continue to rise until our dependence on the combustion of fossil fuels is lowered.

### 7.3 Case Study: Block Effect Modeling in Portugal

The historical center of Lisbon, Portugal is known to contain many important structures that have much value as cultural and architectural landmarks. The famous downtown area, or "Baixa Pombalina" which was rebuilt after a catastrophic earthquake in 1755, has special significance due to its design and layout. The area is composed of sixty blocks, with most being rectangular in shape, and within each buildings were constructed consecutively, usually seven buildings in a row, with all of them sharing the same gable walls.[21] Since their construction, a large assortment of structures within the groupings have undergone serious modifications, in a gradual process, with single buildings in each consecutive grouping being altered, changing the material and structural homogeneity that existed originally.

#### 7.3.1 Changing Modeling Theories

Recent structural analysis has examined the potential effects of seismic activity, specifically horizontal forces, on the blocks and has exposed the problematic nature of such structural incompatibilities existing in such building groupings. Originally, models for seismic forces were completed in a building by building basis, with each structure being examined separately. In the case of vertical loading, this approach has been deemed acceptable, but in the case of horizontal loading due to typical seismic forces, the singular investigative process has been determined to be flawed due to the tendency of buildings in such groupings to act as an extended structural system, not just a singular structure.[21] In particular, it has been noted that singular structures that have undergone modifications or interventions have experienced changes in structural behavior, while at the same time dramatically changing the behavior of the entire block in which they are located.

The original buildings grouped in rectangular blocks had five floors, including a ground floor and an attic, and each block had stone masonry internal and external walls. The first floors in each structure were composed of masonry arches and vaults. The typical alterations that have occurred through the years on such structures include: construction of extra floors, widening of façade openings and removal of original walls and pillars, and the addition of steel and reinforced concrete elements. It was noted that a random distribution of 12% of the buildings were totally replaced by reinforced concrete.[6]

### 7.3.2 FEM Analysis

In the proposed study, a historically significant block was chosen and analyzed and modeled to assess the global block effect on such structural arrangements. The finite element model concluded that stress peaks were over 3.5 times higher in areas where columns were replaced by reinforced concrete than in original masonry columns. (Figure 7.8) The increased stress statistics have been linked to the stiffness and weight properties of the concrete sections that differ drastically from that of original materials. It was also noted that areas where reinforced concrete elements were implemented would experience much smaller displacements that unchanged sections, which would lead to increased damage linked to pounding or collapse of slabs, if masonry bonds are not strong enough to resist high forces imposed on them. Modeling has also predicted the failure of corner buildings due to their inability to produce structural behavior necessary to withstand predicted seismic forces.(Figure 7.9) The results of past events have corresponded with the study's predictions as that the large masses associated with such concrete elements has usually resulted in the untimely collapse of masonry walls, such as in the case of block arrangements in the Umbria and Molise Earthquakes in 1997, and 2002 respectively.

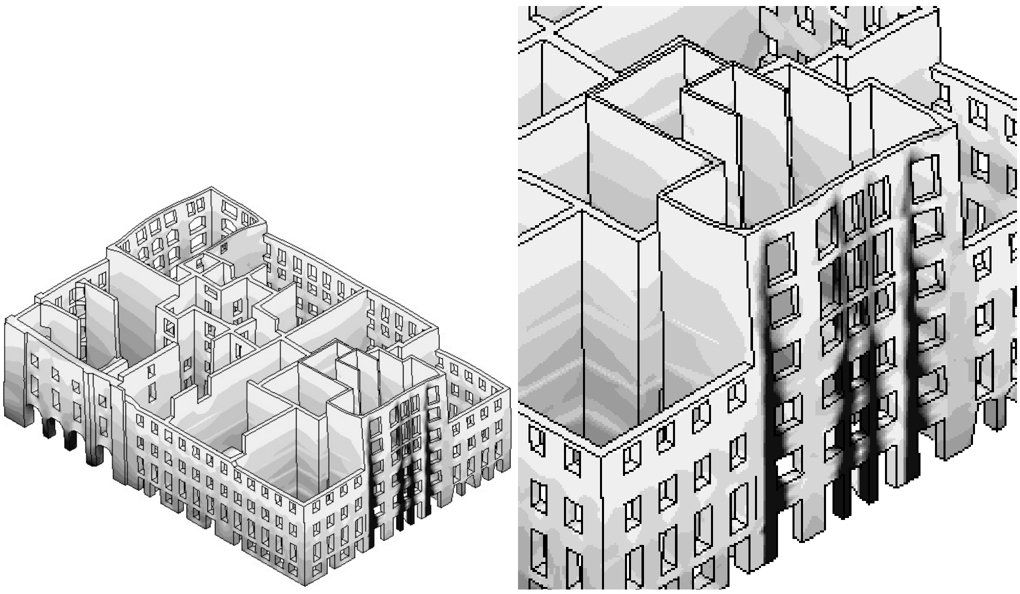

**Figure 7.8 FEM model highlighting increased stresses in RCC elements within altered structures[21]**

### 7.3.3 Study Results

This study has proven the erroneous nature of modeling singular structures in such arrangements in hopes of gaining an estimate of actually performance when exposed to seismic forces. It has identified the changes in behavior of blocks as global structures if even one singular building in each group has been altered by intervention. The authors have recommended safer and more thorough modeling theories that must be undertaken to accurately predict potential performance of such block types in seismic events, and what actions must precede any future alterations to any structures within each grouping.

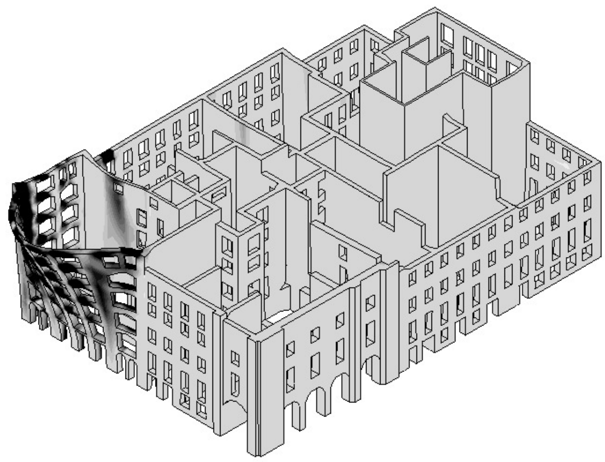

**Figure 7.9 Predicted failure in corner building of model analyzed as entire block for horizontal loading[21]**

# CHAPTER 8: CONCLUSION

## 8.1 Summary

With the knowledge available today of the present state of structures that have undergone restoration attempts throughout their history stemming from inspections and performances studies, and the mass of knowledge available regarding chemical interactions between existing and repair elements, it is possible in most cases to cite situations where attempts at restoring structures with reinforced concrete led to more harm than protection. Although we may now be only close to identifying most of the potential problems associated with both chemical and mechanical incompatibilities that arise when modern materials are used in contact with original materials in historic structures, we must take heed of this information when diagnosing existing buildings and preparing for new restorations that become necessary in the future. To avoid the same costly mistakes of the past, it is useful to identify the most often occurring mistakes that were made in order to ensure that actions are not again repeated in new interventions.

## 8.2 Causes of initial restoration errors

The cause of poor performance of interventions utilizing reinforced concrete on heritage structures can usually be linked to one or more of the following scenarios that were occurred during the time of inclusion:

- **Lack of knowledge in existing structural system performance; physical interaction between new and old materials**- In the case of many historic structures, a full understanding of the interaction of existing structural elements was not known before the introduction of new concrete elements. While we do not look to blame engineers and researchers of the past for techniques and approaches that were later proven to be faulty, we must acknowledge the lack of full understanding of the diagnosis, assessment and intervention design process that plagued many projects. During the early to mid 20$^{th}$ century, although the basic mechanics and statics of most structures were well understood, the identification of the effects of current degradation and damage states were not fully comprehended, nor were the changes that would arise in overall system mechanics once new materials were introduced. Concrete elements were assumed to be "protective," or an improvement on existing, older materials in almost all cases. It was assumed that a stronger, more durable material such as modern cement, would automatically improve the states of older materials such as ancient masonry structures, but engineers of the time were unable to foresee that this would not be the case. It was not identified until later that this was far from the case, when modern elements introduced during interventions were shown to have caused premature degradation, or induced failure during seismic events. These problems may have been avoided if a better understanding of the interaction of the original elements of such structures was known, but in the case of ancient and historic monuments, even with the modeling technology available today, this still may not be such an easy task.

- **Overconfidence in the ability of repair materials-** At the onset of the 20th century confidence in the new construction technologies being developed was at a high, and this brash self assurance led to less well thought out and researched interventions. A governing interest in aesthetic uniformity rather than actual future performance helped usher in the era of rampant usage of easily poured and molded modern cement, and its favorable strength and workability characteristics caused an overestimation in its beneficial effects on historic structures. It was assumed that new technology was assuredly better technology, but these assumptions were quickly proven to be false and unjustifiable.

- **Hastily settling for the economic benefits of modern materials-** As in any case of restoration, economic concerns often overshadow the best needs of the actual structures being examined. One of the main reasons for reinforced concrete's quick acceptance as a repair material was its low cost and relative ease of use and application in varying situations. Its high variability in shape and accepted structural effectiveness led to a wide range of uses, and the ease of application made the amount of highly skilled labor necessary to complete projects less, resulting in major cuts in cost for projects. This settling for economy over authenticity led to the disintegration of skilled restoration work involving original materials such as ancient masonry units and mortars, and led to an ignorance of proven technologies that existed long before the inception of modern cement technology.

- **Lack of knowledge regarding the chemical interaction between new and old materials and their environment-** It is understandable that the damaging chemical reactions between modern cement repair materials and existing elements would not be foreseen during early periods. Chemical incompatibilities were often overlooked in the cases of structures that were diagnosed based on largely visible structural deficiencies. The degradation of modern cement due to chemical interaction, whether stemming from interior reinforcement corrosion, interaction with existing materials, or interaction with environmental materials, was not something that would be fully understood until many years after interventions were implemented, when research was carried out to study rapid decline in restored structures.

- **Poor craftsmanship and application of interventions-** It must also be noted that even in cases where sound engineering judgment was used, and interventions were designed with all potential compatibility issues taken into account, poor application of such interventions stemming from negligence and a misunderstanding of building details, and the application process of interventions often made structures much more vulnerable to environmental and seismic threats. Details such as correct application of repair mortars, and ensuring proper connections between beams and walls, and functional ties between confinement layers were often overlooked, quickly becoming sources of weakness in structures.

**8.3 Summary of common deterioration mechanisms**

The deterioration of interventions stemming from the use of reinforced concrete can be categorized into a few scenarios. It is necessary to note that multiple deterioration mechanisms can plague structures, and during any inspection it is wise to take all potential destructive mechanisms into consideration.

- **Chemical incompatibilities**- Repair materials must be selected that do not create any adverse chemical reactions with the repaired structure. Chemical incompatibilities could lead to alterations of the natural properties and damage of masonry units in close proximity of the concrete repair material, and damage to concrete repair materials themselves. A few examples of these reactions include alkali aggregate activity, chloride ion transfer induced reinforcement corrosion, and reactions with gypsum if present in original binding mortars. Also, the proliferation of ettringite and thaumasite in masonry units is a major threat due to concrete's naturally occurring hydrated calcium aluminates and silicates.

- **Dimensional incompatibilities-** A lack of dimensional compatibility between repair material and original structure, often results in partially debonded repairs, or repairs that will be less durable than expected. Portland cements naturally occurring shrinkage strains during curing, and excessive thermal expansion and contractions when affected by temperature often precipitate premature cracking and damage, and to avoid this phenomenon it is ideal to choose repair materials that are considered to be volumetrically stable, or have a high enough modulus of elasticity and low volume change properties.
- **Electrochemical incompatibilities-** In repairs where reinforced concrete is utilized, corrosion of the confined reinforcement must not be proliferated due to adverse reactions between original and repair materials. Galvanic corrosion has been proven to develop in areas where unrepaired sections lie adjacent to areas repaired with Portland cement, and it is suggested to use cement mixes with high electrical resistivity properties.
- **Permeability incompatibilities-** Cement's drastically different permeability characteristics can completely alter the performance of masonry sections. After repointing, cement's inability to transfer moisture can cause moisture trapped within units to find new points of exit, which leads to cracking, spalling and other forms of damage. Also, moisture can become trapped within units making them more susceptible to the adverse affects of changing temperature cycles. Cement repointing interrupts the naturally occurring regeneration processes in lime mortars by blocking their ability to transmit water, leading to loss of integrity and disintegration.
- **Hardness Issues-** The hardness of modern replacement mortars can alter the performance of many masonry systems originally binded with lime mortars, as the natural stress relieving expansion and contraction cycles absorbed by original mortars could be halted with the inception of harder cement mortar. Also, in cases where much harder mortars are combined with softer masonry units, the rapid disintegration due to environmental actions is often a consequence.

- **Adverse structural system alterations-** Some the most dangerous and most severe consequences of improper restorations using Portland cement occur when complete alterations of monument's structural performances are caused by partial replacement of original sections, or the addition of new members with drastically different strength, weight, and stiffness properties. It has been shown in many examples how if not installed properly, the concrete sections, while in their own right exist as stronger elements than the replaced portions, when combined and not secured correctly with less capable original portions of structures, actually induce failures in buildings especially when tested in seismic events.

### 8.4 Other troubling aspects

Besides taking into account premature damage and deterioration linked to problematic interventions, it is also important to consider the non technical problems that are present when modern materials are used in the wrong way in ancient structures. Low cost and ease of application helped usher in an age of rapid cementification of many structures, but during this time not much attention was paid to the fact that these modifications were permanent alterations to structures that had previously stood for hundreds, or even thousands of years on their own. In some cases, structures were completely rebuilt using new materials, largely altering layouts and essentially modifying the structures forever. In other cases, the addition of new floors, rooms, roofs, and openings in facades changed visual appearance. While these irreversible alterations did not always instigate premature deterioration or cause damage, their inception should be though of as just as troubling due to the fact that they clash with the main principles within the philosophies of restoration, intrinsically leaving permanent traces of intervention on structures that should be kept as authentic as possible. Damage of this type, while not technical in classification, does much harm in less calculable ways, by eroding a structures cultural, spiritual, and emotional value.

### 8.5 Reversing or preventing damage caused by improper intervention

Going back and correcting the mistakes of the past may be impossible in some situations, but in each scenario steps can usually be taken to discourage further damage originally induced by improper restoration. A few necessary steps need to occur to ensure this process.

- **Slowing/stopping chemically based degradation-** In cases where the interaction between repair materials and original elements has been proven to occur, further deterioration must be prevented in order to avoid major problems. In most cases this issue will involve controlling the transmission of moisture within systems. Various measures are available to accomplish this depending on the deterioration mode. In masonry sections most damaging chemical reactions stem from the introduction of chemical carried by moisture. As previously stated, surface treatments with hydrophobic products can hinder rainwater absorption, and measures such as inserting polymetric sheets at ground level of walls can prevent capillary absorption. In the case of corrosion of reinforcement within repaired sections, if applicable typical patching, rebonding, cathodic protection, and re-alkalization can all be considered, but in many cases may not be possible. Replacement should always be thought of as a last resort, and in most scenarios, proper future maintenance and inspection will be the least invasive and expensive form of correction.
- **Rethinking and monitoring past structural alterations-** We have reached a level of knowledge where we can now understand the mistakes made in certain restorations where original elements were replaced with concrete elements with drastically different mechanical properties. To ensure proper performance, if possible, it should be advised that structures that are known to have been altered at some point during their lifecycle be reevaluated and monitored to see how these changes have altered their structural performance, and their potential performance in seismic events. While this process may be expensive and time consuming, it is essential if we hope to ensure safety and continuing lifespan.
- **Securing past structural alterations-** In structures that have been identified to contain potentially problematic combinations of new and old building materials, steps must be taken to ensure that original construction techniques were sound, and that all inhomogeneous composite sections be secured and existing in proper form. Many early restorations, while fundamentally sound, failed due to

lack of detail during initial construction, whether it be improper connection of fastening. These are mistakes that can be corrected before being exposed in the future, especially during seismic events.

- **Removal and replacement of foreign materials when possible-** If we wish to retain the identity of structures, the most loyal answer in many cases would be the removal and replacement of foreign repair materials with original constituents of construction. While this process is essentially the most detailed and requires the most amount of skill and knowledge, repairing a structure with materials as close to those utilized during its original construction has been proven to prevent many of the mistakes that have shown themselves over the years. This is a paramount dilemma in many projects, as we strive to do little harm to what already exists, and in any case, the best possible outcomes result in projects where the right choices were made the first time, not attempts at going back and correcting past blunders.
- **Strive to develop new techniques-** As these dilemmas continue to challenge us we must strive to develop new techniques that will help us better understand and better treat the problems we find in monuments. New testing and modeling techniques will expand our understanding of the mechanical performance of structures, and the problems that threaten them. At the same time, we must continue to develop non evasive remediation techniques while keeping in mind and remaining loyal to many of the original processes and construction techniques that were used to create these structures.

### 8.6 Conditions that must be satisfied

With today's technology and research capabilities, combined with modeling and seismic performance prediction software, and chemical analysis we have been able to identify most of the cause and effect scenarios in the premature deterioration of heritage structures altered in restorations. Along with all the principals of structural restoration set forth by ICOMOS charters, these considerations must be taken into account before interventions are enacted in order to ensure the success of each project.

- **Satisfy compatibility issues-** In order for all future problems to be avoided, all potential compatibility issues must be taken into account before an intervention is applied in any situation. To ensure durability of repairs, the selection of materials that will prevent chemical, electrochemical, permeability, and dimensional compatibility issues from arising is necessary. The most effective way to ensure this is to intensely scrutinize each structure and its surroundings through research and preliminary evaluation before applying any form of treatment. In dire situations where immediate repairs are called for, the least incompatible materials must be temporarily applied and then monitored during the time of usage.

- **Retain aesthetic integrity; keep open possibility for reversibility-** As outlined in the accepted restoration charters put forth by governing societies that handle all preservation projects, the aesthetic integrity of structures must be taken into account to ensure a successful project. Interventions should not drastically change the appearance of a monument or structure and should blend in as seamlessly as possible. While preventing further deterioration and improving structural safety and performance in each case is paramount, the aesthetic integrity of the original construction is not something that should be jeopardized unless absolutely necessary. It is to be noted that all repair options should be reversible if possible, leaving the door open for the inclusion of better designed, more effective technology that may be developed in the future.

- **Retain structural integrity-** Along with aesthetic integrity, it is noted that the structural mechanics of a building or monument should not be significantly altered by an intervention. As stated, many interventions using reinforced concrete completely altered the structural performance of some buildings, and more often than not, for the worse. Unfortunately, this phenomenon usually becomes apparent in after a dramatic failure of a structure following such events as earthquakes and other natural disasters. It is necessary to taken into account how the introduction of concrete materials with completely different material, strength, stiffness, and weight properties will affect structures before implementing such measures.

- **Use modeling in preliminary assessment to advantage**- Before initiating interventions, the current structural performance must be understood so that the potential impact of any interventions could be fully anticipated. Also, when modeling structures, it is not only necessary to model the singular units themselves, but make sure to take into account all buildings in close proximity, especially in the case of buildings attached in rows, such as in the case of many ancient city centers, where consecutive buildings and their properties will affect each other during seismic events. Modeling can help predict the changes that will occur once interventions are introduced, and the properties of each structure are altered. It is necessary to note that modeling should not be accepted as an exact prediction of future action, but as a useful guide for better understanding of the behavior of elements.

**8.7 Recommendations: Modern cement as an intervention material**

Any rehabilitation of a heritage structure must be made only if there is full certainty that the eventual repercussions of such elements introduced are fully understood. This encompasses both an understanding of the new element's effects on structural behavior and chemical interactions. A multidisciplinary approach must be taken in each case, as all situations are unique and will require varying fields of research to come to correct and useful conclusions regarding each project. Technical safety codes and practice standards may not always apply to heritage structures and in each case before intervention occurs, a structure's respective vulnerabilities and potential damage mechanisms must be identified in order to apply the most suitable intervention technique.

Historic monuments and structures are unique in the fact that unlike the repair of modern buildings, the assurance and quest for the highest level of safety is compromised by an underlying requirement to retain the original aesthetic and structural properties of the heritage structures in question. The idea of preserving the original structural scheme and mechanical behavior is something that is just as important as improving seismic performance, and this premise often conflicts with many methods of structural improvement. It is up to the engineer to design interventions that avoid invasiveness, and come to a medium between being loyal to the original layout of a structure, while assuring adequate level of safety and durability.

It has already been noted that in most cases of failed interventions, a lack of knowledge of building materials and construction details typically lead to premature failures or poor future performance. It has also been accepted that as opposed to labeling certain intervention techniques as “poor” or “inadequate” we should in turn reexamine the conditions of their inception and application, where the mistakes will typically be identified. This becomes especially clear when examining the use of new techniques and modern materials for interventions, such as in the case of modern Portland cement. In every case, modern cement is not necessarily the cause of each premature failure or deterioration, but rather a lack of knowledge or an improper application of the material. Modern cement is a remarkably versatile material that under the right conditions can be utilized in many cases to satisfy the needs of declining structures.

It is up to us as engineers and scientists to embrace the technology of the present while not forgetting the proven technology of the past, all while making sure we take into account the potential hazards and threats of each action. While complicated restoration cases will continue to challenge us into the future, as structures age and new aggressive environmental threats plague us, we must remember to give proper respect to each monument, and not overlook simple engineering principles in search of a quick fix for any situation. In many cases adequate preliminary planning and accurate research will be the first and most pivotal step in designing interventions that will best serve and honor the priceless monuments that have given so much back to us. It is up to us to do what we can to ensure their continuing part as historical and educational icons to future generations.

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