ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Riley Hannah Marshall

Investigation of damage and repair of masonry piers affected by fire in the church of Santa Maria del Mar in Barcelona

This Masters Course has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Spain | 2018

DECLARATION

Name: Riley Marshall

Email: rhmarsh803@gmail.com

Title of the Msc Dissertation: Investigation of damage and repair of masonry piers affected by fire in the church of Santa Maria del Mar in Barcelona

Supervisor(s): Pere Roca

Year: 2018

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

University: Universitat Politècnica de Catalunya

Date: July 16, 2018

Signature:

This page is left blank on purpose.

This page is left blank on purpose.

This page is left blank on purpose.

ACKNOWLEDGEMENTS

I would like to acknowledge the support of my supervisor Professor Pere Roca, who gave me the opportunity to work in this beautiful structure.

I would like to express my gratitude to the MSc Consortium for the opportunity to participate in this Master and for the financial support.

Last but not least, I would like to sincerely thank all of my friends and classmates from Guimarães and Barcelona for making this year so special.

This page is left blank on purpose.

ABSTRACT

The church of Santa Maria del Mar is a gothic basilica located in the historic district of Barcelona, Spain. It is built of sandstone masonry units from the nearby Montjuïc hill quarry. It is an exceptional structure due to the slenderness of its piers and the size of its vaults. In 1936, during the Spanish Civil War, the church was set on fire and burned for eleven days. The building withstood the event, however, as a result, the vaults and piers suffered some damages. Subsequent Portland cement interventions have been carried out, largely for cosmetic reasons. However, many of these interventions are falling out, and in fact, they could be causing further damage and are hiding the true state of damage of the piers. Santa Maria del Mar is believed to be stable under gravity loads and has withstood earthquakes in the past. However, due to the slenderness of the piers, the church's seismic stability is dependent on their complete (or nearly complete) integrity. This study was carried out for further analysis of the damage that the fire event caused to the piers, their current condition, and recommendations for future actions to ensure their ideal state of preservation for the future.

This thesis presents a state of the art on the effects of fire on stone masonry, a detailed damage evaluation of the piers, an explanation of the damages caused by fire, recomendations for further research, and a tentative repair plan. The study found the most common and severe damage caused by fire was spalling and sheeting of the outer layers of material. It was also observed that the previous portland cement repairs are failing due to their incompatability with the sandstone. It is recomended that they are removed, both for the preservation of the piers and the saftey of the visitors. The use of high strength rods to anchor the cracks is the other proposed intervention. Overall, montjuic stone was found to be relativley resistant to fire. With a few additional proposed tests and interventions, there should be confidence that piers are in a good state of repair.

This page is left blank on purpose.

RESUMEN

La iglesia de Santa Maria del Mar es una basílica gótica en el distrito histórico de Barcelona, España. Está construido con unidades de mampostería de arenisca de la cercana cantera de la colina de Montjuïc. Es una estructura excepcional debido a la esbeltez de sus pilars y el tamaño de sus bóvedas. En 1936, durante la Guerra Civil Española, la iglesia fue incendiada y quemada durante once días. El edificio resistió el evento, sin embargo, como resultado, las bóvedas y pilars sufrieron algunos daños. Se han llevado a cabo intervenciones subsiguientes de cemento Portland, en gran parte por razones estéticas. Sin embargo, muchas de estas intervenciones se están cayendo, y de hecho, podrían estar causando daños adicionales y están ocultando el verdadero estado de daño de los pilars. Se cree que Santa María del Mar está estable bajo cargas gravitatorias y resistió terremotos en el pasado. Sin embargo, debido a la esbeltez de los pilares, la estabilidad sísmica de la iglesia depende de su integridad completa (o casi completa). Este estudio se llevó a cabo para un análisis más detallado del daño que el incendio causó a los pilars, su estado actual y las recomendaciones para acciones futuras para garantizar su estado ideal de preservación para el futuro.

Esta tesis presenta un estado del arte sobre los efectos del fuego en la mampostería de piedra, una evaluación detallada de los daños de los pilars, una explicación de los daños causados por el fuego, recomendaciones para futuras investigaciones y un plan tentativo de reparación. El estudio descubrió que el daño más común y severo causado por el fuego era el desprendimiento y la formación de capas de las capas externas de material. También se observó que las reparaciones de cemento portland anteriores están fallando debido a su incompatibilidad con la piedra arenisca. Se recomienda que se eliminen, tanto para la preservación de los pilars como para la seguridad de los visitantes. El uso de varillas de alta resistencia para anclar las grietas es la otra intervención propuesta. En general, se encontró que la piedra Montjuïc era resistente al fuego. Con unas pocas pruebas e intervenciones adicionales propuestas, debería haber confianza de que los pilars están en buen estado de reparación.

This page is left blank on purpose.

This page is left blank on purpose.

This page is left blank on purpose.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

This page is left blank on purpose.

1. INTRODUCTION

The church of Santa Maria del Mar is a gothic basilica located in the historic district of Barcelona, Spain. It is built of sandstone masonry units from the nearby Montjuïc hill quarry. It is an exceptional structure due to the slenderness of its piers and the size of its vaults. In 1936, during the Spanish Civil War, the church was set on fire and burned for eleven days. The building withstood the event, however, as a result, the vaults and piers suffered some damages. Subsequent Portland cement interventions have been carried out, largely for cosmetic reasons. However, many of these interventions are falling out, and in fact, they could be causing further damage and are hiding the true state of damage of the piers. Santa Maria del Mar is believed to be stable under gravity loads and has withstood earthquakes in the past. However, due to the slenderness of the piers, the church's seismic stability is dependent on their complete (or nearly complete) integrity. This paper presents a further analysis of the damage that the fire event caused to the piers, their current condition, and recommendations for future actions to ensure their ideal state of preservation for the future.

The analysis included investigation of the phenomenon of fire and how fire and extreme temperatures alter stones on both a mineralogical and macro level and by both chemical and physical mechanisms. A visual inspection was used to document the types of damages that can be observed and map the condition of the faces of each pier. By relating the observed damages to the research and state of the art on the effect of fire on stone, the causes and processes of each damage were hypothesized and are explained in this report. Also included are recommendations for tests that can be used to verify the extent of the damage and repairs that address the structural needs of the piers while following the theory of preservation which seeks to let a structure showcase its history rather than cosmetically covering imperfections.

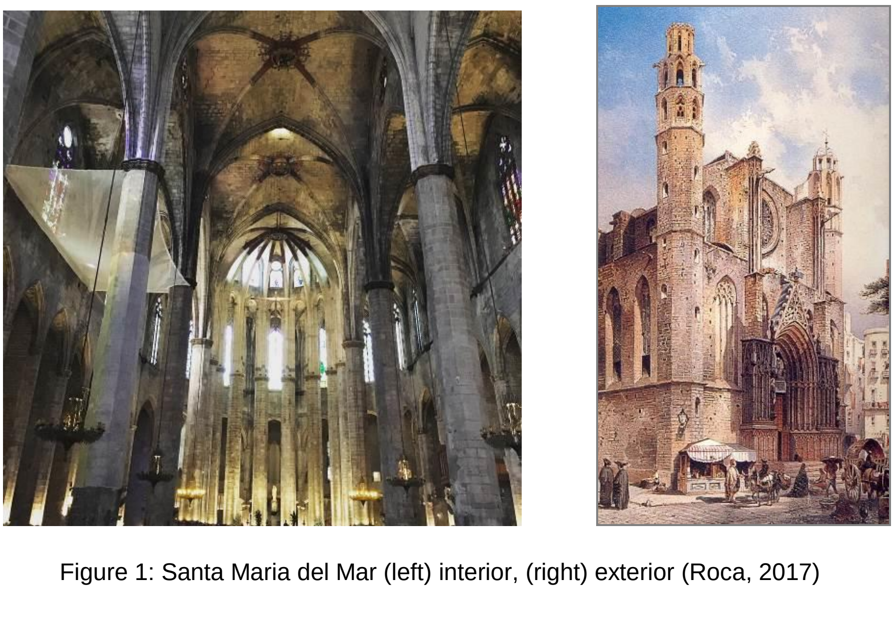


Figure 1: Santa Maria del Mar (left) interior, (right) exterior (Roca, 2017)

1.1 Objectives

The general objective of this thesis is:

To investigate and evaluate of the effects of fire on the stone masonry piers of Santa Maria del Mar due to the fire event in 1936 and provide a tentative repair solution

The general objectives of this thesis are as follows:

- Research the state of the art of the effects of fire on stone masonry
- Preform a detailed inspection of the state of damage in the piers of Santa Maria del Mar
- Identify the damages caused by the fire and assess their severity
- Propose further research to investigate more the state of the columns
- Create a tentative intervention proposal

1.2 Motivation

Santa Maria del Mar is an exceptional structure of great beauty and great historical value. Its preservation for future generation is of great importance and should be prioritized. Because it is known that the piers have suffered damages in the fire of 1936 and that they are essential in providing seismic stability, further knowledge on their true current condition will help guide future interventions to preserve and maintain the church.

2. OVERVIEW OF FIRE AND STONE

2.1 Properties of Fire

Fire is a combustion process that produces heat and light. It is created by the combination of fuel, an oxidizer (usually air), and a heat source (McManus, 2007). Combustion leads to the production of many gases, vapors, and particles of smoke, soot and sometimes liquids, and melted or partly burned solid materials. Ash and soot are two solid materials produced by fire. Ash contains the minerals left behind from the fuel. Soot is the partly burned solid that escapes from the containment of the fire (McManus, 2007). The composition and pH of the combustion products depend on what burns and can be alkaline or acidic. The temperature of the fire is also dependent on what burns. Almost all of the materials found in buildings are composed of polymers, which can be divided into cellulose and protein. Materials containing cellulose include wood, paper, textiles and some plastics. Materials containing protein include meat, fur, skins, leathers, wool and silk (McManus, 2007).

2.2 Composition of Stone

The physical and chemical composition of stones will influence the patterns of damage they experience due to fire. For this reason, it is necessary to discuss the different compositional properties of stone types commonly used in architecture. The most important distinction to make when considering the response to fire is between dense stones and porous stones.

2.2.1 Dense Stones

Dense stones include granites and marbles. They are characterized by tightly pack mineral grains; each mineral type having its own thermal and structural properties. Mineral grains in dense stones can range in size and be well or poorly sorted. Dense stones have a very low porosity. Quartz is the most predominant mineral found in granite stones, followed by feldspar and sometimes mica. Marble is composed primarily of calcite and has relatively large crystals. The density of the minerals and absence of much pore space are responsible for the behavior of dense stones under fire conditions as there is no space to absorb thermal expansion.

2.2.2 Porous Stones

Porous stones include sandstones and limestones and are characterized by a large percentage of void space. Porous stones are often friable meaning that they can easily be broken down into smaller pieces.

2.2.2.1 Limestone

Limestone is composed primarily of calcite, and the properties of this mineral will determine its behavior under heat exposure.

2.2.2.2 Sandstone

The physical makeup of sandstone is composed of four parts: the framework grains, matrix, cement, and pore space. The framework grains are sand-sized particles less than 2mm in diameter (Hajpàl & Török, 2004). Quartz is the most common mineral, often accompanied by potassium feldspar and sometimes mica. The pore space is the empty space between the grains; the amount of pore space is influenced by the packing and homogeneity of the grains. The matrix is the fine material present in the pore space. Sandstones can be classified into two categories: arenites, or those with little to no matrix material, and wackes, which have a high matrix content. Most sandstones have either a siliceous matrix composed mainly of silicates or a calcareous matrix composed of calcium carbonates. This chemical difference will cause the two types to behave very differently under fire and extreme heat conditions. The cement is the material that binds the framework grains together. The mineralogy of the cements also varies and can include clay minerals (kaolinite, or mixed kaolinite-illite), ferruginous minerals (hematite, goethite), calcareous (calcite, dolomite) or silica cements (Hajpàl & Török, 2005).
The heat resistance of sandstones depends on the grains, grain size (fine, medium, coarse), cement mineral, grain to cement ratio, and grain to grain or matrix to grain contacts. The most significant factor is the composition of the matrix (Hajpàl & Török, 2005).

3. STATE OF THE ART: CURRENT STATE OF RESEARCH

The current state knowledge of the effects of fire on stone is based on both analysis, tests, and observations carried out after real fire events and on laboratory experiments. The three primary methods used to replicate a fire event are

1. Oven heating
2. Laser heating
3. Controlled flame

Each process can produce different effects or forms of deterioration on the stone. Each has its advantages and limitations which must be understood in order to relate the results to the damages that will occur during a real fire event. One important consideration among all laboratory test is the impact of the sample size used. Fire damage is highly dependent on the temperature gradient of the stone and samples are likely to be too small to exhibit the real temperature gradients of architectural stones (Sasinska, 2014).

3.1 Laboratory Fire Simulation

3.1.1 Oven Heating

When the oven heating methodology is used, samples are heated in an oven over a period of time to a pre-determined temperature. The heating rate, maximum temperature, and duration of heat exposure can all be controlled in order to observe the effects that these parameters have on the stone damage. The oven heating method is an excellent way to observe the specific temperatures at which damages and changes occur. It is best used to understand the effect that temperature change has on stone. Advantages to this methodology are that is highly standardized and can be easily replicated (Gomez-Heras et al., 2009). Many studies have been carried out in this manner, so there is a large database of literature to compare results to (Gomez-Heras et al., 2009). The disadvantage of the oven heating technique is that it does not physically represent the process that takes place during a real fire event (Gomez-Heras et al., 2009). Ovens heat the samples by convection while a fire heats a stone by radiation (Gomez-Heras et al., 2009). Oven heating also does not produce the combustion products and residues that occur during real fires (Gomez-Heras et al., 2009).

3.1.2 Laser Heating

The laser heating method concentrates a highly energetic beam of radiation onto a small area of stone. This allows precise experimentation in small areas and therefore is suitable for small samples and useful for the assessment of micro-scale decay (Gomez-Heras et al., 2009). Laser heating uses radiation, accurately representing the physical process of a fire; it can also produce some combustion products (Gomez-Heras et al., 2009). Another advantage of laser experiments is that they are easily repeatable. Disadvantages include that laser heating is not suitable for big samples or the analysis of bulk changes of the stone. It is also expensive to carry out and limited to research institutions.

3.1.3 Flame Heating

Flame heating consists of exposing a sample to a controlled flame, such as one created by propane, for a given amount of time. It is a realistic approach because the physical burning process, radiation, is the same as in a real fire and combustion products can be produced by the flame (Gomez-Heras et al., 2009). The flame source and size can be varied, and so too can the sample size. Larger flames and samples can produce conditions more similar to a real fire event. The dimensions of the sample can be large enough to experience accurate temperature gradients and stresses. The stone will be touched directly by the flames in a pseudo-random way due to the unpredictable nature of a flame. The amount of time in direct contact with the flame will vary across the stone and some areas may only experience heating due to the temperature of the space around the fire, never coming into contact with the flames (Sasinska, 2014). As opposed to oven heating, the flame creates more localized, catastrophic damage, which may break a stone apart, but it does not necessarily cause systematic damage to the entire sample that reduces its overall performance (Sasinska, 2014). The disadvantage of flame heating tests is that their random nature makes them unrepeatable and difficult to compare. However, it is important to consider that actual fires are random events and so an advantage of the flame heating is that something new can be learned from each experiment (Sasinska, 2014).

3.2 Post-Fire Analysis

Another manner of collecting information on how fire effects stones is by means of analysis after real fire events. A combination of visual inspection and minor and non-destructive tests can be performed. Cores can be drilled, or stones that break away from the structure (if applicable) can be taken to the lab for further testing.

3.3 Laboratory Testing

After heating, burned and control samples are subject to a variety of laboratory test to evaluate quantitatively and qualitatively the effects of fire. The same testing methods can also be used on stone samples taken from real fire events. Common tests and their purposes are described below.

Colorimetry: characterizes a sample’s color by three parameters: a*, the color spectra from green to red; b*, the color spectra from yellow to blue, and L*, the lightness spectra from light to dark. This is based on CIELAB color measurements (Hajpál, 2002).

X-ray powder diffraction and **thermal analyses**: used to measure the mineralogical composition

Polarizing microscope and **scanning electron microscope**: used to observe textural and mineral structure and identify changes after heating. Also used to observe internal fractures in and between grains (Hajpàl & Török, 2005).

Vacuum porosity test: determine porosity

Ultrasonic velocity test: This test can be used to understand the quality of a stone and the change in performance between a control and burnt sample. As the ultrasonic velocity increases the mechanical properties of a stone tend to decrease. A slower ultrasonic pulse velocity (UPV) can indicate cracks and voids, thus the UPV can be an indirect indicator of internal cracking, porosity, and strength (Hajpàl & Török, 2005). This test can also be performed in-situ to analyze stones that have experience a fire event.

Uniaxial compression, **biaxial flexure**, and **indirect tension** test have been used to measure the compressive, flexural and tensile strengths in order to understand the structural integrity of each fire-damaged stone.

4. MECHANISMS OF FIRE DAMAGE IN STONE

Fire causes damage in stone for two primary reasons: the *temperature of the stone increases* and *combustion residues accumulate* on the stone's surface. This paper will investigate the consequences of these events and identify and explain the resulting damages.

4.1 Temperature Change in Stone

Increasing the temperature of stone causes changes in both the micro (mineralogical) level and the macro (masonry unit or structure as a whole) level. Another damaging effect of temperature change is thermal shock. These phenomena will be presented on an increasing scale from micro to macro.

4.1.1 Micro-Scale Effects

The decay patterns on a micro-scale are key in understanding the effect of fire on stone. This is true in both in terms of mechanics (fracture mechanisms and failure patterns) and of time (current and future physical behavior). On a mineralogical level, as the temperature of a stone increases, this also means the temperature of the individual minerals within the stone increases. Minerals undergo changes at different temperatures, these primarily include:

- Change in color
- Change in porosity
- Chemical changes
- Mineral structure collapse

4.1.1.1 Color Change

Color change is often one of the most obvious visual effects of fire on stone and is an irreversible phenomenon. Different minerals undergo color changes at various temperatures, however many of these changes are invisible to the naked eye.

Color is characterized by three parameters: a*, the color spectra from green to red; b*, the color spectra from yellow to blue, and L*, the lightness spectra from light to dark. In general, heating causes most stones to shift towards the red and yellow ends of the a* and b* spectrums. Patterns are less apparent for changes in the lightness spectrum, depending on their mineralogy stones can become lighter, darker, or remain the same after heating. (Hajpál, 2002).

The increase in redness is one of the most common and observable color changes in stone and is due to the oxidation of iron minerals such as goethite and jerosite which transform into hematite at high temperatures. Iron compounds begin to de-hydrate at 250-300°C. The transformation to hematite is responsible for the reddening of color. Even a small concentration of iron minerals can generate a noticeable color change upon oxidation and can also mask the color changes due to other mineral transformations. It is important to note that the general trend of an increasing red and yellow spectra with an increase in temperature cannot be uniformly applied. A notable exception is Postaer sandstone, siliceous cemented sandstone, which becomes more red until 750°C and then decreases on the red spectra. Rezi sandstone, jarositic cemented stone, becomes less yellow with heating. (Hajpál, 2002)

4.1.1.2 Chemical Changes

Just as in color change, various minerals experience chemical changes at different temperatures. Often these chemical changes can lead to the collapse of the mineral structure, which increases the porosity and decreases the strength of a stone. The chemical changes that occur in minerals commonly found in stones as temperatures increase are described below and summarized in Table 1.

4.1.1.3 Mineralogical Changes

4.1.1.3.1 Crystals

The crystals, or grains, are the individual particles that make up a rock. In granite and sandstone, quartz is by far the most prevalent grain, followed by feldspars and sometimes mica. Their behavior is relatively similar. At high temperature, stones will first experience inter-granular cracking, or cracking along the grain boundaries (Gomez-Heras et al., 2009). Next, at even higher temperatures, the individual grains will experience internal, or intra-granular cracking.

Quartz

Expect for minor cracks, quartz shows little change even until 900°C. At a temperature of 573°C, quartz grains undergo a transformation from α-quartz to β-quartz (Gomez-Heras et al., 2009). This results in a volume increase which can generate thermal expansion cracks. Micro-cracks first appear at the grain boundaries around 600°C (Hajpál & Török, 2005). Quartz-feldspar grain boundaries are more prone to cracking than quartz-mica boundaries. Later, as temperatures increase, micro-cracks will occur at cleavage lines, pores, and previous cracks. At 750°C micro-cracks will begin to appear within the quartz crystals (Hajpál & Török, 2005). Both types of cracks increase the stone’s porosity and decrease its strength. However, in sandstones this is of minor importance because the matrix is able to absorb much of the expansion stresses (Hajpál & Török, 2005). In granite, a denser, less porous stone, the resulting cracks are more severe and the porosity increase is much greater.

Feldspars

Feldspars, especially potassium-feldspar, are common secondary minerals in sandstones, and granites. Aside from minor cracking they are also stable even until 900°C (Hajpál & Török, 2005). At 600°C, the point at which the quartz transformation begins to create inter-granular cracks, the quartz-feldspar boundaries are the most susceptible to cracking while the feldspar-feldspar boundaries are the most resistant. At 750°C micro cracks also appear inside feldspar crystals (Hajpál & Török, 2005). The internal cracking is denser in feldspar than the other grains.

Mica

Mica crystals also begin to develop internal micro cracks at 750°C, however, of all of the crystals, the cracking is the least dense (Hajpál & Török, 2005). Mica is sheet silicate mineral, and will also experience a widening of its cleavage planes at high temperatures.

4.1.1.3.2 Clay Minerals and Phyllosilicates

Clays are very fine particles of hydrous aluminum silicates and other minerals. Clay minerals, such as palygorskite, smectite, kaolinite and chlorite are very sensitive to heat and undergo structural changes at different temperatures. This can result in a collapse of their mineral structure which reduces the stone strength and increases the porosity slightly. Structural changes can begin at 250°C and shrinkage cracks will develop in clays up to 450°C due to the loss of structural water. (Gomez-Heras et al., 2009)

Kaolinite

The mineral structure of Kaolinite begins to collapse at 450°C and by 550°C cannot be found. Exceptions are when the kaolinite crystals are extremely large and crystalline such as in Ezusthegyi and Postaer sandstone. Here it can still be detected at 600°C. (Hajpál & Török, 2004)

Glauconite

At 900°C, the glauconite structure collapses (Hajpál & Török, 2005).

Illite-Smectite

Illite-Smectite is more stable than kaolinite at 553°C it loses it hydroxyl radicals but can still be detected at 900°C (Hajpál & Török, 2005).

4.1.1.3.3 Carbonates

Carbonates are minerals that contain the carbonate ion CO3; calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)_2$, are the most common carbonates found in stone. Calcite is by far the most prevalent; it is the primary component of both marble and limestone and can be found in the matrix of some types of sandstones. In laboratory experiments, textural changes were visible at 450°C in thin sections, however in general, carbonates are stable up until 600°C, at which point major mineral transformations were visible (Hajpál & Török, 2005). At 750°C, carbonate disintegrates and calcite and dolomite collapse; this is visible by microscope. At 900°C the calcium and magnesium oxidizes form CaO and MgO. At room temperature, CaO will react with the humidity in the air to form a new mineral phase: portlandite $Ca(OH)_2$. This reaction causes a 20% expansion in volume and led to the cracking and the total disintegration of test specimens – a phenomenon observed in limestone (Hajpál & Török, 2005). In calcareous sandstones, the porosity increased to 10 times the room temperature porosity. The portlandite reaction and subsequent disintegration did not occur in the dolomite ($MgCO_3$) based stones (Chakrabarti et al., 1995).

4.1.1.3.4 Iron Materials

As explained in the color change discussion, iron minerals begin to oxidize and transform at 250°C resulting in a color change (Hajpál & Török, 2005). These changes do not have physical consequences and iron is shown to be stable at extreme temperatures. Hematite is the final product of iron bearing materials and is very stable and heat resistant even beyond 900°C (Hajpál & Török, 2005).

4.1.2 Macro-Scale Effects of Heat Increase

Macroscopic structural changes are directly related to the microscopic effects due to fire. However, in order to understand the macro level consequences, it is necessary to understand the way in which a stone is heated during a fire. Fire is an irregular event; its flames are somewhat random or variable, therefore producing different heat gains in different parts of the structure and even within the same element. Fire does not heat the stone as a whole, but rather heats the surface that it comes in contact with. As a fire burns for a longer period of time, the depth of the stone that experiences heat gain can increase. The macro level damages are caused primarily by:

- Thermal Shock
- Differential expansion of adjoining materials

4.1.2.1 Thermal Shock

Mechanically speaking, shock is a mechanical failure generated in a single episode by a unitary stress. When exposed to fire or an extreme heat source, the exterior or exposed surface of stone will experience a temperature change while the interior of the stone will remain unchanged or heat at a much slower rate. The resulting thermal gradient between the exterior and interior creates thermal stresses. This phenomenon is known as thermal shock and can cause cracking, spalling, sheeting, breaking, and granular disintegration (Gomez-Heras et al., 2009).

Spalling is the expulsion of chunks of material, in this case stone. Edges are especially prone to spalling because the heat can work from both sides, thus creating a steeper thermal gradient.

The surface of the stone is an important factor in the type of damage that will occur. Flat surfaces experience sheeting, or the breaking and expulsion of stone in flat planes or layers. This is because the localized thermal gradient is likely to be the same across the surface of the stone in an area. More intricate surfaces such as those with decorative carvings or those of sculptures will experience a more complex spalling patterns due to the irregularity of the surface and thus the temperature gradient will not be a flat plane within the stone.

Due to the irregularity of fire, in long and tall elements, the thermal gradient and a distribution of stress is not uniform across the entire length. Small transverse cracks will form along the length of the element, creating divisions which will scale separately. The stone's structure also effects its failure pattern due to thermal shock. Schist stones and mica will fail at their cleavage planes. Capillary cracks are also likely to become spots of failure or breaking.

Thermal shock can also occur during the extinguishing of a fire, especially when water is used. The water causes a rapid reversal of temperature on the surface of the stone and this can also cause cracking and spalling.

4.1.2.2 Differential Expansion of Adjoining Materials

Each mineral has its own unique thermal and structural properties. This means that when a stone undergoes heating, its individual minerals will react differently at different temperatures and undergo thermal expansion at different rates. Dense materials will experience internal physical breakdown due to the micro-cracking generated by the thermal expansion of minerals (Gomez-Heras et al., 2009). On a larger scale, the different thermal properties between the stone and the mortar, such as soft sandstone and rigid mortar, generates increased stresses and micro-cracks in the materials upon heating. Another cause for differential thermal expansion is the uneven heating due to the random nature of flames.

Table 1: Changes in Stone with Increasing Temperature

Temp [˚C]	Changes
250	• Structural changes in clay particles begin (250-600°C) • Iron oxidation begins, color shifts to red for iron minerals, BUT change occurs at different temperatures for different minerals (250-900°C)
450	• Clay minerals in cement begin to crack: related to the shrinkage of clay minerals due to the loss of structural water • Kaolinite mineral structure mostly collapses • Porosity increases dramatically EXECPT is silica cemented stones
500	• Organic matter turns into char residue (Hajpál, 2002) ○ Some stones contain a small amount of organic substance which can't be seen and is seldom found in analysis

573	• Quartz inversion: a-quartz to b-quartz (in reality 573-595°C)
	  ○ Volume increase
	  ○ Thermal expansion cracks
	  ○ Internal rupturing of quartz grains (Hajpál & Török, 2004)
	  ○ Quick heating can cause explosive collapse of quartz-rich stones (Hajpál, 2002)
	**** However, the resulting porosity increase and decrease in strength are of minor importance quartz-rich sandstones, much more significant is the change in clay matrix

600	• Micro-cracks at grain boundaries (Quartz and K-Feldspar) • Total disintegration of Kaolinite (550-600°C) • Most significant decrease in pulse velocities observed (for test at intervals 300,600,900°C) (Kompaníková, 2002) ○ Likely due to the quartz inversion
750	• Micro-cracks in quartz and feldspar crystals • Calcite collapses

900	• Portlandite forms (from reaction with humidity)
	  ○ Absorbs air and water
	  ○ Extreme volume expansion
	  ○ Collapse of sandstone structure
	• Iron minerals still resistant to structural change
	• Except minor cracks, quartz, feldspars and micas do not show any changes even at 900°C

4.2 Combustion Residues

Perhaps not as obvious as temperature increase, another equally destructive effect of fire is the accumulation of combustion residues on the surface of stone. Combustion residues refer to the fumes, smoke, oils, and ashes that are byproducts of a fire. They accumulate not only on the surfaces exposed to the flames, but also on other surfaces in the vicinity of the fire. The immediate effects are the formation of a dark or black crust layer on the surface of the stone. However, this has long term consequences as well.

The soot and combustion products introduce materials such as carbon, sulphur, nitrogen and phosphorus and organic compounds, such as oil and waxes, that can coat the stone surface and fill near-surface pores. The combination of these elements with other elements of stone and atmosphere can generate salts, such as sulphates, nitrates, and phosphates which can be transported through the stone in the presence of moisture or humidity (Gomez-Heras et al., 2009). The oils and waxes coating the stone's surface will reduce its permeability. The combination of these processes results in the crystallization of salts, often behind the less/impermeable surface coating. This can cause spalling of the surface material which leaves exposed a weaker surface that is more susceptible to further salt crystallization and moisture ingress. The increased porosity and stresses from salt crystallization in the newly exposed surface can cause rapid granular disaggregation (Gomez-Heras et al., 2009). This is the phenomenon where the grains of the stone become loose and fall out leaving a pitted surface. This can become a cyclical pattern of damage to the surface material.

4.3 Exploitation of a Stress Legacy

While it has been stated that the primary mechanisms in which fire creates damage in stone is through heating and combustion residues, an indirect consequence of fire is the exploitation of the stress legacy it leaves behind. A stress legacy is defined as the weaknesses inherited from a previous event; it includes the cracks, spalls, stresses and micro-damage that the stone experiences due to the fire (Sasinska, 2014). As a stone undergoes its natural weathering processes such as temp and moisture cycles, salt crystallization, and exposure to eroding forces, the weakness left behind by the fire can be exploited and worsened by the weathering mechanisms and background factors. This results in later detachment and spalling especially around corners. Studies have shown that burned stones experience higher rates of decay from the same weathering events than do unburned stones (Hajpál, 2002).

5. CHURCH OF SANTA MARIA DEL MAR

Santa Maria del Mar is a church located in the Born district of Barcelona, Spain. It is a three nave structure of the Basilica plan and Catalan Gothic style. Santa Maria del Mar has unique characteristics both in its structural form and construction sequence, making it an important piece of architectural cultural heritage.

5.1 Structure

A striking feature of the structural design of Santa Maria del Mar is that the lateral naves are almost as tall as the central nave, giving the sensation of a wide and massive “unitary” space. In fact, the lateral vaults are positioned at the height to take the lateral thrust of the central vault, eliminating the need for flying buttresses. The longitudinal arches of the central nave are diaphragmatic and likely originally supported a wooden roof. All of the vaults are ribbed vaults. The central vaults are square: 13.5 meters by 13.5 meters (Caballé et al, 2008). It is a unique feature of Santa Maria del Mar that the transverse arches are so wide and it contributes to the feeling of a “unitary” space. The lateral vaults are half as wide as the central vaults, measuring 13.5m by 6.75m. The fill of the central vault is a combination of medieval concrete and empty pottery, used to reduce the weight. The lateral vaults are fully filled with concrete in order to take the trust from the central nave (Roca et al., 2008).

The cathedral has 16piers; 8 in the nave and 8 in the choir. The piers have a height of 22.7 meters to the spring line of the lateral arches and a circumscribed diameter of 1.6 meters (Caballé et al, 2008). They are very slender for their height. Each pier is octagonal and a previous seismic tomography study has found that they are composed of a square central stone surrounded by four hexagonal stones in a rotating pattern to eliminate continuous joint lines as shown in Figure 5 (Roca et al., 2008). It is the current condition of these pillars that this paper will seek to evaluate further.

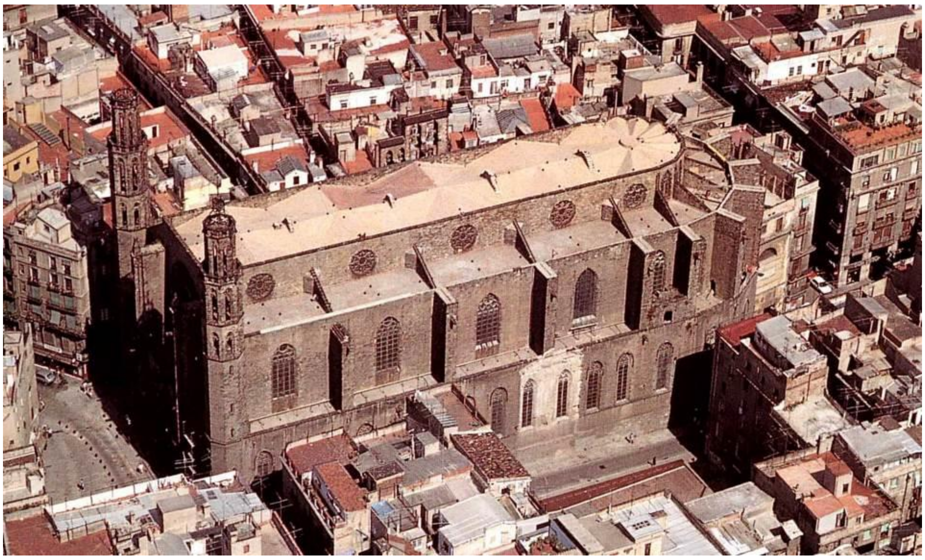


Figure 2: Santa Maria del Mar aerial view (Roca, 2017)

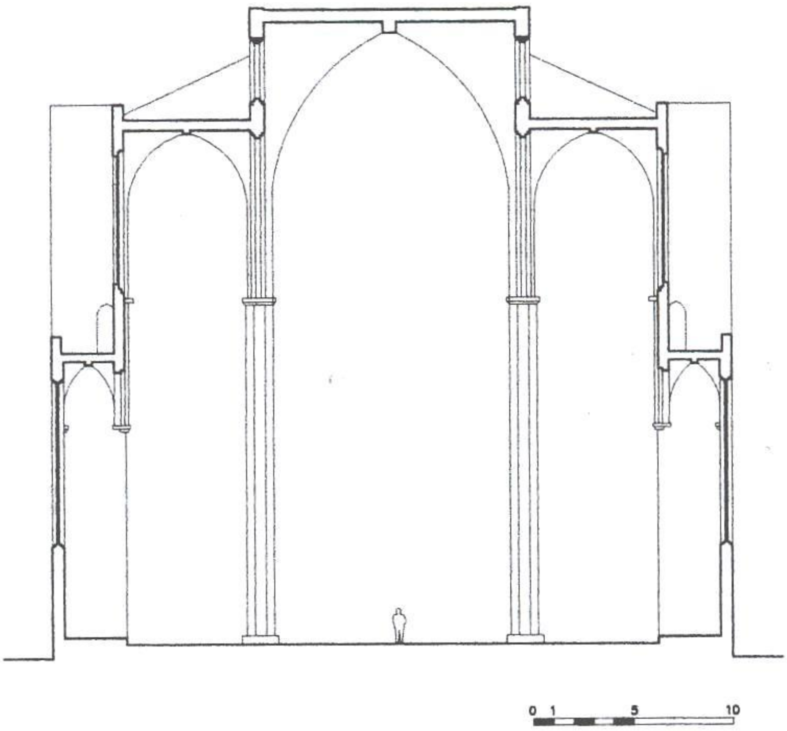


Figure 3: Typical Section (Roca, 2017)

Figure 4: Main and lateral naves, note the unitary space (Roca, 2017)

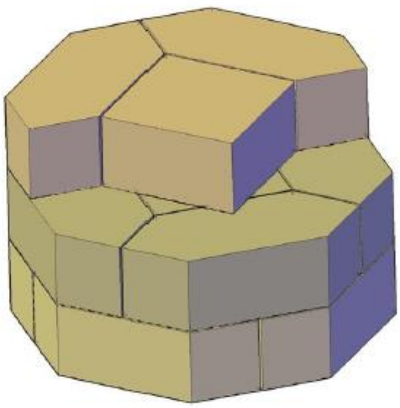


Figure 5: Arrangement of stone blocks in octagonal piers (Caballè et al., 2008)

5.2 Construction Sequence

The construction of Santa Maria del Mar began in 1329 and was completed 55 years later in 1383 - a very short duration for the time. The sequence of construction differs from the majority of gothic cathedrals which were built starting from the choir, bay by bay, finishing with the front façade. Instead, the construction of Santa Maria del mar began with the perimeter: the foundation and footings, lateral walls, buttresses, chapels, façade, and choir. This would provide a stiff structure to function as a lateral buttress for the remainder of the construction process and continue to perform a structural role and load bearing support upon completion. This is also in contrast to the typical gothic cathedral in which the walls are not load bearing.

Next, the piers were built followed by the lateral and transverse arches. The arches provide lateral support to the slender piers and are the reason for their very minimal drift. The vaults were built next, beginning with the choir. The vaults are ribbed vaults; first the two diagonal arches were built followed by the membrane. In the same manner, the vaults of the nave were built, bay by bay. First the lateral vaults and then the central one. The short timeframe and uniformity of the construction indicate that the process and plans for the cathedral were completely designed before construction began (Caballé et al, 2008). Santa Maria del Mar has had no significant later architectural alterations, making it a very pure example of its era and a building of very uniform structural form (Caballé et al, 2008).

5.3 Materials

Santa Maria del Mar is a sandstone masonry structure with historic lime mortar. It is built with Montjuïc sandstone from the nearby Montjuïc hill which had a quarry from Roman times until the beginning of the 20th century and was the primary source of stone used in Barcelona's construction during that period (Navarro & Gimeno, 2016). This stone has proved to be very durable. Its structural and mineralogical properties are summarized in Chapter 5 of this report. It is important to note that in the few studies that have been carried out, the strength properties of various samples have shown a significant range.

5.4 Historical Events

Although for the most part architecturally unaltered, there were a few damaging events in the history of Santa Maria del Mar which are essential in understanding the current state of the structure. These include an earthquake in 1373 which caused the collapse of one of the clock towers; a fire during construction in 1379 which damaged scaffolding and caused premature compression in the last bay; and the earthquake of 1428 which caused the rose window to collapse. However, the most significant event which has caused damages still visible and relevant today was the fire in 1936. The fire was set by anarchist during the Spanish Civil War. It was set by burning the pews and caused the cathedral to burn for eleven days. The fire caused damages in the piers, arches, and keystones. This paper will seek to further evaluate and characterize the damages in the piers due to the fire and hypothesize their true current condition.

Figure 6: Historic photographs after 1936 fire (left) choir, (right) nave (Roca, 2017)

6. MONTJUIC SANDSTONE

6.1 Characteristics

Montjuïc stone is a silica cemented sandstone of course detrital material. It is primarily composed of quartz and silica and secondarily of feldspar clasts. Its clasts are very well sorted. Montjuïc sandstone has excellent cementation by silica. It has excellent mechanical properties and a high resistance to decay. It has an optimal durability in the Mediterranean climate due to its porosity and permeability behavior. The color is described as "Yellowish Grey 5Y 8/1" based on the Munset color chart (Navarro & Gimeno, 2016).

6.2 Petrophysical Characteristics

As described in the report (Navarro & Gimeno, 2016), below are listed some of the most important petrophysical behavior characteristics of Montjuïc sandstone.

- Optimal water mobility: easy absorption and desorption
- High resistance to salt crystallization (no significant mass decrease after)
- High resistance to frost cycles (no significant mass decrease after)
- Moderate inter-particle porosity
- Strong fluid flow at temp below 50°C
- Poor evidence of compaction

6.3 Macroscopic Features

Montjuïc stone is characterized by moderate lamination (layered composition) and cross bedding.
It contains iron rich minerals which cause its phenomenon of red staining. The oxidation of iron rich minerals, especially common in presence of moisture (with acid) or after cleaning turns the stone a reddish color - this is irreversible (Navarro & Gimeno, 2016).

Figure 7: Montjuïc stone macroscopic view (Navarro & Gimeno, 2016)

6.4 Composition

Below, Table 2 shows the composition of Montjuïc sandstone. As previously mentioned, it shows that Montjuïc stone is a silica cemented sandstone with framework grains primarily composed of quartz and also a significant presence of potassium feldspar. The presence of iron minerals is important to note because they can affect the appearance after heat exposure.

Table 2: Composition of Montjuïc Sandstone (Navarro & Gimeno, 2016)

Framework Grains	• Quartz 35% • Oligomictic rock fragments 20% • K-feldspar 9% • Plagioclase clasts • Mica grains rare
Cement	• Silica • Iron rich
Minor Secondary Minerals	• Alumite • Kaolinite • Iron oxide • Barite • Titanium Oxide

6.5 Mechanical Properties

Tables 3 and 4 contain the mechanical properties presented in two different studies: Navarro and Gimeno (2016) and Oliveira (2000). Navarro and Gimeno present the results of a study that consisted of petrographic and mineralogical characterization, and a large number of petrophysical test on cubic samples of Montjuïc stone and other stones commonly found in Spanish heritage. The properties presented in Oliveira (2000) are the result of laboratory compression test on 10 cylindrical specimens of Montjuïc stone. The Young's modulus was computed in the [30%-60%] stress interval by linear regression. While the average is shown, the result produced significant scatter. This could be in part due to the fact that the samples were extracted from distinct stone prisms, which in their history could have experienced different events and stresses.

This can also help to explain the variation between the results presented by Navarro and Oliveira.

Table 3: Mechanical Properties (Navarro & Gimeno, 2016)

Density	2.13 g/cm3
Porosity	24%
Uni-axial compression strength	60.16 MPa
Flexotraction resistance	7.2 MPa

Table 4: Mechanical Properties (Oliveira et al., 2000)

Average Elastic Modulus	15.5 GPa
Average Compressive Strength	83.9 MPa

7. DAMAGE OBSERVATIONS

A visual inspection was carried out in order to document and map the damages and decay patterns on the piers of Santa Maria del Mar. The piers were studied to a height of 4.5 meters for complete damaging mapping as this was the distance the naked eye could observe well and the most severe damages due to fire are suspected to have occurred at lower elevation on the piers, closer to the flames. Photo documentation was also collected for all eight faces of each pier, this includes the entire height of the piers, so any significant damages to the upper portion of the pier was documented from this. The damage maps can be found in Appendix A.

7.1 Damages as a Result of Fire

7.1.1 Vertical/ Diagonal cracks contained in a single unit

One type of damage observed in the pillars of Santa Maria del Mar is vertical cracks that are contained in a single masonry block. Some of these cracks have a slight diagonal inclination as shown in Figure 8. This particular crack is located near the edge of the face. The single unit vertical cracks tend to be located near the edge or in line with the mortar joint of the stones above and below. It should be noted that the vertical cracks contained in one unit were far less common than the vertical cracks that crossed many units.

Figure 8: Single block crack

7.1.2 Multi-block Vertical Cracks

One of the most prominent damages observed is the presence of vertical cracks that extend through multiple masonry blocks. These cracks are consistently located around the mid-height of the pier and extend often through five or more masonry units. This type of crack is found in the center of the pillar face and aligns with the mortar joints that occur on the center of the face in alternating units. These vertical cracks are often found at the same height on successive faces of the same pier. They are a common phenomenon, occurring on four of the eight piers of the main nave. It is important to notes that the cracks occur at approximately the same height on each pier.

Figure 9: Multi-bock vertical cracks (left) shows successive faces

7.1.3 Horizontal cracks in base

Horizontal cracks were observed in the base stones of two piers, 3 and 5. They occur around the mid-height of the stone, and in the case of pier 3 are found on multiple successive faces.

Figure 10: Horizontal base crack in Pier 3

7.1.4 Spalling

Another widespread damage typology found on the pillars is spalling of the masonry at the corners of the faces. Often the spalls extend through many units. While spalls also occur on the pier faces, they are most prominent on the corners - the least confined area of the pier. In most cases, the spalls are patched with a Portland Cement repair as shown Figure 11 (left), however some are also still exposed as shown in Figure 11 (right). In some cases, the Portland cement repairs have also spalled from the pier due to inadequate bonding between the repair material and the sandstone. Sometimes, corroded iron connecting elements are left exposed after the repair material has spalled. Spalling is one of the most common damages and is found on every pier with varying severity.

Figure 11: Spalling (left) patched, (right) unpatched

7.1.5 Sheeting

Sheeting, also known as scaling, is the spalling or loss of material in even sheets or planes. This occurs both on the faces of the piers and at the edges. Most of the sheeting observed extends across the surface of multiple blocks. The depth of the material loss is between 2 and 6 cm. Often areas of sheeting are adjoined to areas of more uneven spalling.

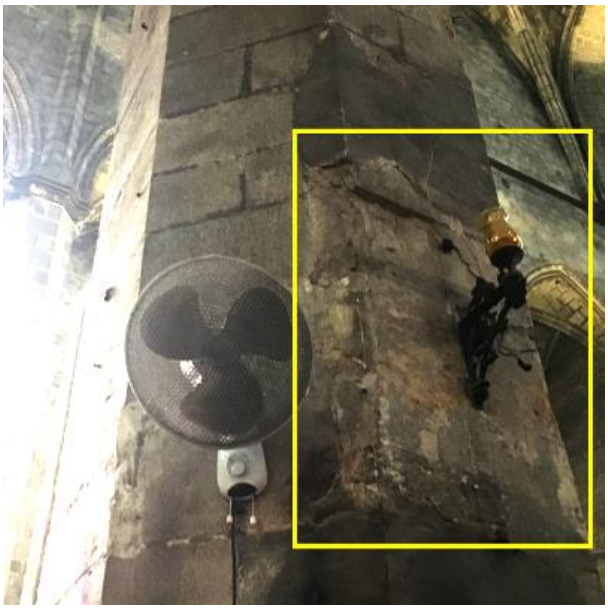


Figure 12: Sheeting damage on Pier 2

7.1.6 Mortar Loss

Patches of missing mortar are visible on every pier. Also, repointed joints are extensive, suggesting that the extent of mortar loss was much greater than can be observed today.

7.1.7 Color change

Color change of the stone was visible on most of the piers, but was most significant on Pier 3. Colors observed were pinks, yellows, and darkening such as greys and browns. Black soot coating was also observed but will be addressed separately. As shown in Figure 13 multiple color changes could be observed in a single area such as the one shown in Pier 3.

Figure 13: Color change on Pier 3 (note reds, yellows, and darkening)

7.1.8 Pitted Texture

A pitted texture on the surface of some stones was observed on many of the piers in the choir and in Piers 4 and 5. As can be seen in Figure 14 this damage tends to be confined to a single stone, but occurs on the surface of multiple stones in the same area.

Figure 14: Pitted texture on choir pier

7.1.9 Speckled/textured staining

Often dark staining is found on the piers in speckled pattern. It is more frequently observed on the lower portion of the piers. It is most likely a residue on top of the stone and not a color change of the stone itself.

Figure 15: Speckled staining (left) Pier 1, (right) Pier 8

7.1.10 Soot Accumulation

Dark black soot accumulation is found on many piers. It usually covers large areas across many stones, however small patches of soot are present too. In many cases, the soot layer is partially spalled from the pier. It is likely that the soot coverage was more widespread immediately after the fire, but some has been cleaned or spalled from the surface.

Figure 16: Soot accumulation on Pier 7

7.2 Repairs to Damages

7.2.1 Portland cement patches

Many of the spalls and sheeting damages in the pillars have been patched with a Portland cement material. It is visible because it has a very obvious color difference from the original stone. However, a variation in the darkness of the replacement material was observed across the piers and even on the same pier.

7.2.2 Portland cement mortar repointing

Joint repointing is found on all of the piers and ranges from isolated areas in some to almost the entire pier in others. It has a darker color than the original mortar and is often found bulging outside of the joints.

Figure 17: Joints repointed with Portland cement mortar (note darker color)

7.2.3 Stone replacement

Stone replacement is observed on some of the piers, especially at the bases and around the mid-height of the piers, usually around the corners. It is visible as a break in the typical masonry pattern of the pillars. Stone replacement is especially common on the piers of the choir. The depth of the replacement and bonding to the original material are not known. Theses repairs can also be hiding significant damage.

Figure 18: Stone replacements in choir (left) mid-height, (right) base

7.3 Damage of the Repairs

Many of the spalls and damages in the pillars have been patched with a Portland cement material. However, this intervention has been the cause for additional damages due to its incompatibility with the sandstone and the bonding methods used. It can also be hiding important damages from view. The additional damages due to the Portland cement repair are as follows:

7.3.1 Cracking of Portland cement repair

Cracking is noticed in most of the repaired sections. Many of these cracks are likely shrinkage cracks and are only superficial, however some of the larger cracks could indicate structural problems or weaknesses.

Figure 19: Cracks and spalls in Portland cement repair

7.3.2 Spall of Repair Material

In repaired areas with many cracks, often portions of the repair material itself have spalled from the pier. In many cases it appears imminent that further material will spall soon. In addition to being unsightly, this can be dangerous for visitors to the Cathedral.

7.3.3 Horizontal Cracks in Portland cement repairs

One specific cracking pattern in the Portland cement repairs is long horizontal cracks occurring near the base of successive stones in large areas of repair. This trend is noticed on Pier 2.

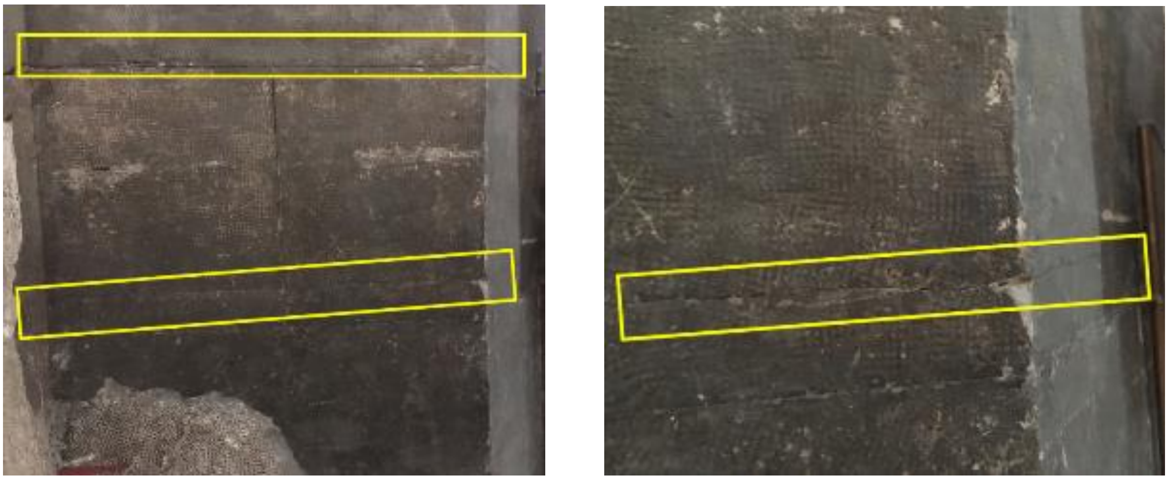


Figure 20: Horizontal cracks in Portland cement repair Pier 2

7.3.4 Crusting of Portland cement repair

Crusting, or the spalling of a "sheet" or layer, of the repair material is a common phenomenon. This is especially true at the bases of the piers, which are in more direct contact with human activity and are more likely to be touched, bumped, come in contact with the pews etc.

Figure 21: Crusting of repair at base

7.3.5 Exposed corroded iron elements

In the locations of the crusting and spalling of the Portland cement repair material, exposed corroded iron connection elements are found in some areas.

7.4 Other Damages

7.4.1 Vertical Cracks Below Fixtures

Another type of multi-block vertical cracks is identified to occur below fixtures mounted in the pillars such as lights and fans. The depth and severity are not known. While the candle holders could have been present during the fire, the fans and electrical installations were not, so the cracks occurring due to these are post-fire damages.

Figure 22: Cracks below fixtures

7.4.2 Exposed brick and iron mounts for fixtures

Brick additions with iron connection elements are found on many piers, they were likely an intervention to allow mounting an object to the pier. Today, the iron elements are corroding.

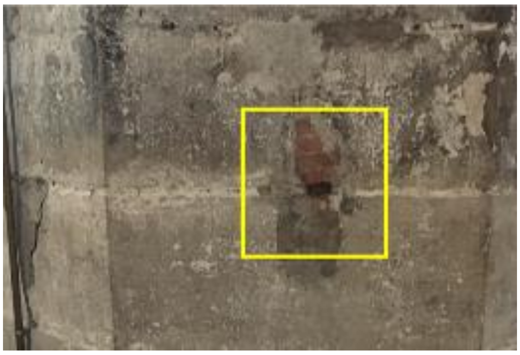


Figure 23: Brick mount with corroded iron

8. STATE OF DAMAGE

As discussed in Chapter 7, a visual inspection was performed and the types of damages found were documented and discussed. In addition, the damages on the first 4.5 meters on the face of each column were mapped and are included in Appendix A. Complete photographic documentation of each pier face was also completed as part of the analysis. This chapter presents further analysis on the state of damage in the church of Santa Maria del Mar as a whole. Figure 24 provides a key so that each pier can be located within the church and the face of each pier can be identified. Piers 1-8 correspond to the piers of the nave and piers 9-16 correspond to the piers of the choir. It is important to note that the choir piers are actually located at the corresponding black dot on the map, the numbers are shown outside for clarity. Also, the internal composition of the stones, shown in the plan view of the pier, rotates 45° with each stone layer, the configuration shown in only an example.

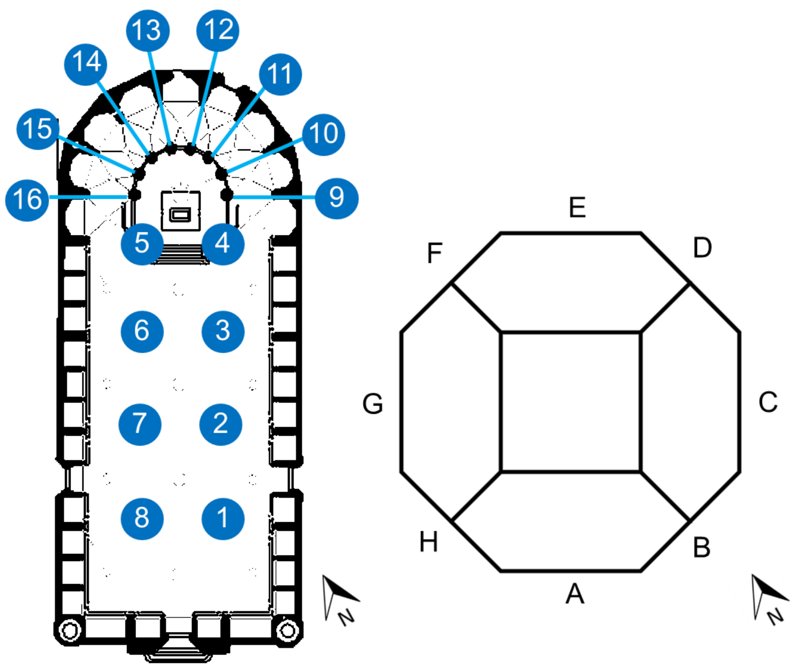


Figure 24: Key for pier numbering and face orientation

8.1 Piers of the Nave

Shown in Table 5 is the distribution and severity of the damage types described in Chapter 7 on the eight piers of the nave. The final row contains the general condition of each pier considering the types and amount of damage it has sustained. In the table capital letters refer to the face(s) of the pier that the damage is found lowercase letters separated by a slash refer to the edge of the two corresponding faces. The most severe of the damages in several categories occur on piers 3 and 6. Pier 7 was also found to be in very bad condition, however, during the time of the investigation, it was wrapped in mesh to prevent spalls from falling on visitors, so it is assumed that much of the damage is hidden. However, the presence of the mesh indicates that the stone underneath is not in good condition. Piers 4 and 5 have many replacement stones visible on the surface. Because the depth of the replacement stones and any damages they hide are not currently known, it can only be commented that from the exterior the piers appear in good condition, but further evaluation is needed to understand their true state. However, with the presence of replacement interventions, it is likely these columns suffered a significant amount of damage and spalling due to the fire. Overall, piers 1 and 8 are in the best condition and appear to have suffered very little due to the fire.

Table 5: Damage type summary for columns of the nave

Damage	1	2	3	4	5	6	7	8
Single Stone Cracks			Many			Many B,C		H
Multi-Stone Cracks	F,G	F,H	B,C,D,E,F, G			D,E,G	D, F (others not visible, mesh cover)	
Horizontal Base Cracks			B,C,D		C,G (in new stone base)			
Spalling	Minor: a/h Edge, B	Moderate/ Severe A,B,E,G	Everywhere Worst: G, H, a/h edge			Severe: A,G,H, a/b	Moderate: c/d, g/h	Very Minor
Sheeting	Bases: A,G,H	G Bases: A,B,G,H	Everywhere : Worst: G,H			Severe: A,B,C,D	Bases: C,D,H	
Stone Replaceme nt			Base: E,F,G,H	New Base, Replacement along height	New Base, Replaceme nt along height	Bases: A,G,H		
Pitted Texture				Many Stones	In small localized areas			
Color Change	Staining, darkening	Mild staining	Red, yellow, darkening, staining	Red	Red	Red	Darkening staining	Staining
General Condition	Good	Moderate Damage	Most Severe Damage	Appears good BUT many replacement stones	Appears good BUT many replacement stones	Severe Damage	Bad Condition *covered in mesh	Very Good

8.2 Piers of the Choir

Due to the nature and distribution of the damage patterns found on the piers in the choir, their condition has been documented differently. Because each column shows the same trends, Piers 9-16 will be described by a representative example. It is obvious that interventions have been performed on the choir columns after the fire, therefore most of the damage is not visible. The bases of the columns have been rebuilt. The lower two-thirds of the columns have many replacement stones; these are easily seen as a change in the typical stone pattern shown in Figure 5. The piers of the choir have also been almost completely repointed. Aside from some stones with a pitted texture, the piers of the choir appear in very good condition with no spalls, sheeting, or cracks visible. However, this could be misleading because the extend of interventions indicates they suffered a lot of damages.

Figure 25: Piers of the choir

8.3 Analysis of damage by location

After the documentation of the damages and the damage mapping and classification, they were analysed to understand what conclusions could be drawn about the fire and the distribution of the destruction in the church. Figure 25 presents in plan view the distribution of three types of damage phenomena that could be the most consequential: the multi-block vertical cracks, sheeting and spalling, and problem in the base which include significant cracking, material loss, and replacement stones. It can be seen from the sheeting and spalling map that the most severe damage occurs in piers 3, 6, and 7. It is also likely that piers 4, 5 and the piers of the choir suffered a large amount of spalling and material loss, as these piers have a high concentration of replacement stones suggesting previous damage. This indicates that the greatest amount of damage occurred in the choir and the piers closest to the choir, suggesting that as the center of the actual fire event. The map of the columns with problems in the base also indicates this pattern. It should be noted that the bases of the choir piers were all rebuilt likely due to their damaged condition. When looking at the map of the multi-block vertical cracks, it can be seen that this damage does not follow the same location pattern. In fact, this damage was not observed in any of the piers of the choir or the closest piers of the nave, the locations where fire damage has been the worst. Also, these cracks were observed in Pier 1, which suffered almost no other damages due to the fire. Considering their distribution away from the majority of the fire damage, and their height on the piers, above most of the damage and direct contact with flames; this further analysis suggests that perhaps the multi-block vertical cracks are not due to fire. Their true cause will be further explored in Chapter 10.

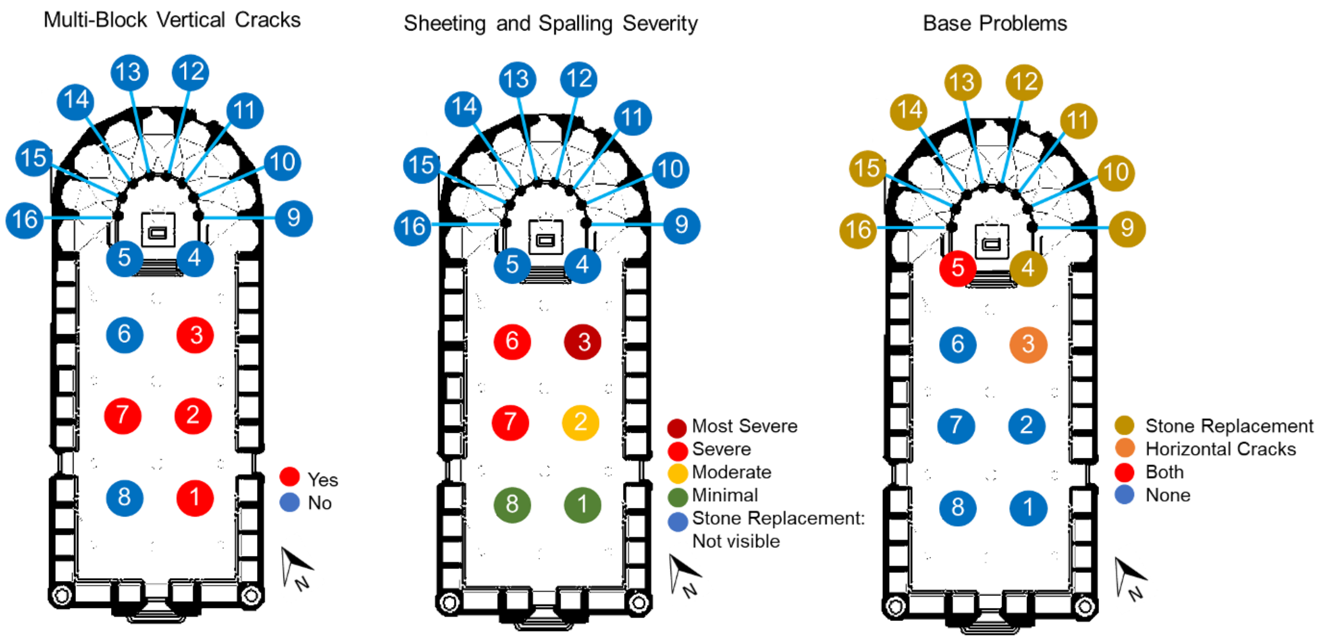


Figure 26: Damage type and location summary

9. RELEVANT PREVIOUS STUDIES

9.1 Seismic Performance

Due to the slenderness of the piers and the large dimensions of the vaults, it has been suspected that Santa Maria del Mar has limited seismic strength. To study further the ability of the church to resist earthquake events, a tension-compression damage model was used to carry out a non-linear finite element analysis in a typical bay (Murcia 2008). When subjecting the structure to gravity loads, it was found it could withstand up to three times its self-weight. The seismic behaviour was studied with a static non-linear pushover analysis, which found it to be resistant to a group acceleration up to 0.12g. The study concluded that “the structure of Santa Maria del Mar Church can be considered as safe and strong enough to resist the seismic action with acceptable levels of damage” (Murcia 2008).

However, another study (Mazziotiti, 2016) is not as optimistic. In this study the N2 method of Eurocode 8 found the highest vulnerability of the cathedral in the longitudinal direction. This can be explained by the stiffness of the cathedral in this direction, resulting in a displacement capacity lower than the seismic demand. A non-linear dynamic analysis, also a part of this study, confirmed the weakness of the cathedral in longitudinal direction: the church was able to withstand the earthquake in the transversal direction, while in the longitudinal one the analysis stopped in correspondence to the peak of the accelerogram (Mazziotiti, 2016).

It should be noted that the pillars have a more critical role in the resistance of an earthquake in the transverse direction and a smaller role in the resistance in the longitudinal direction. Even so, with a higher capacity in the transverse direction, they must still be in a good condition to provide resistance.

9.2 Laboratory Test

In one highly cited study the effect of heat was studied on seven German and three Hungarian sandstone types. Nearly 1500 cylindrical specimens were core-drilled from the stones (Hajpàal & Török, 2004). The specimens were heated in an oven to 6 different temperatures (150, 300, 450, 600, 750, 900 °C). The samples were then tested for mineralogical composition, bulk density, porosity, water absorption, ultrasonic velocity, indirect tensile strength, and uniaxial compression strength. Color change was measured with the CIELAB method. Of the seven stones tested, the German Postaer Sandstone most resembles Montjuïc Stone. Table 6 shows a comparison of their properties. They have very similar porosity and matrix material which are the most important factors in determining a sandstone’s behavior under extreme heating conditions. The two stones also have almost identical compressive strengths. For these reasons, it can be expected that the Montjuïc stone’s response to heating would be similar to that of the Postaer sandstone. The results from the study can be used to hypothesize the changes that occurred in the pillars of Santa Maria del Mar during the fire of 1936.

The findings of the study for Postaer Sandstone are as follows:

- no color change until after 750°C
- by 900°C change to pinkish pale brown with reddish brown spots
- Very minimal porosity increase (2.4%)
- Decrease of compressive strength 60.63 to 41 MPa (loss of 32%) at 600°C
- Decrease of compressive strength 60.63 to 37.28 MPa (loss of 39%) at 900°C

Table 6: Comparison of Postaer and Montjuïc Sandstone

	Montjuïc	**Postaer**
Density	2.13 g/cm3	
Porosity	24%	23%
Compression strength	60.16 MPa	60.63 MPa
Cement Type	Siliceous, iron rich	Siliceous - kaolinitic

9.3 In-Situ Test

9.3.1 Hole Drilling Test

The hole drilling test is used to measure the work stress in masonry. A set a strain gauges placed around a small drilled cylindrical hole can determine a biaxial stress state. In order to measure the eccentricity of the load at the base, the test can be performed on two opposite faces of a pier. In Santa Maria del Mar this test was carried out on both a well intact pier and one severely damaged by fire. The study found that in the intact pier, the compressive stresses were 3.8 and 2.1 MPa, corresponding to an eccentricity of 4 cm. In the more damaged pier, the fire damaged surface measured a compressive stress of only 1.5 MPa (Roca et al., 2008). This eccentricity is very minimal, however it is important to observe the stress differential, which indicates, at least on the exterior some of the material is not providing full resistance.

9.3.2 Seismic Tomography

2D tomography was carried out on a sample of the piers in order to identify the internal morphology and the quality of the materials. The processing showed that the section is made of four hexagonal stones surrounding a square interior one.

For the test, a single section was investigated using a very dense ray pattern, which provides a diagram with improved accuracy and detail in the position of internal joints and distribution of possible damage. Some superficial deterioration was identified, possibly caused by the fire of 1936. (Roca et al., 2008)

Figure 27: Seismic tomography image showing internal composition of piers

10. CAUSES OF DAMAGE

10.1 Vertical/ Diagonal cracks contained in a single unit

Cracks contained within a single masonry unit could be a result of thermal shock, or the buildup of stresses due to the temperature gradient between the surface and interior of the stone. This cause cracking, especially in naturally weak parts of a stone. The vertical cracks could also be caused by the compression either in naturally weak parts of the stone, or in areas that lost compressive strength due to the extreme temperature of the fire (and likely a combination of the two).

10.2 Multi-block Vertical Cracks

The vertical cracks that on the center of the pier faces that extend through multiple blocks and pass through the mortar joints (see Figure 9) were usually observed on consecutive faces of a pier. They all occurred around the same elevation - approximately at the mid height of the pier and were found on piers 1, 2 ,3, 6, and 7. Because these cracks were found on piers that suffered only minimal fire damage and because they occur at such a height on the pier it is not likely that they are a result of fire. It is possible that these cracks existed before the fire of 1936. They could be a result of one of the previous earthquakes that the church experienced in 1373 or 1428.

10.3 Horizontal cracks in base

The horizontal cracks that occur in the bases of piers 3 and 5 are difficult to explain. Because they occur in only two locations, and one is in a new stone, they are likely to be local defects in the stone. It is an unusual crack pattern for compression elements like the piers. However, because the pier are compression elements, these cracks are not of concern structurally.

10.4 Spalling

Spalling is a systematic damage observed on the piers and is likely due to thermal shock. When exposed to fire or an extreme heat source, the exterior or exposed surface of stone will experience a temperature change while the interior of the stone will remain unchanged or heat at a much slower rate. The resulting thermal gradient between the exterior and interior creates thermal stresses that cause spalling and other damages. Edges are especially prone to spalling because the heat can work from both sides, thus creating a steeper thermal gradient. This was evident on the piers, as much of the spalls occur on the edges. Spalling that has occurred after the fire event can be due to salt crystallization behind the soot covering. This process can expel the outer layer of stone.

10.5 Sheeting

Sheeting, which was found on the faces of the piers, is also likely due to thermal shock. On flat surfaces, the thermal gradient is likely to be the same across the surface of a localized area. This causes the stone to break in even planes or layers, which explains why sheeting occurs on the flat pier faces. Sheeting that has occurred after the fire event can be due to salt crystallization behind the soot covering. This process can expel the outer layer of stone.

10.6 Mortar Loss

Many factors can contribute to mortar loss during a fire event. Mortar is a porous material and will heat much faster than the stone. At high temperatures, the mortar will lose water which contributes to its destruction, eventually it will transform to powder, disintegrate, emptying the joint. The differential properties between the stone and mortar can also cause damage, as the stone experiences thermal expansion, the weaker mortar will be compressed and in some cases expelled

10.7 Color change

Reddening, yellowing, and darkening were observed on the piers of Santa Maria del Mar. Different minerals undergo color changes at various temperatures. The increase in redness is due to the oxidation of iron minerals as they transform into hematite at high temperatures beginning at 250-300°C. Studies have shown Montjuïc stone to contain iron rich minerals (Navarro & Gimeno, 2016), which explains its pinkening. Stones also tend to shift toward the yellow spectrum at high temperatures (Hajpál, 2002) although the exact mineral(s) transformation responsible for this is not always known. The darkening of color can be attributed to both mineral transformations and soot and combustion product accumulation.

10.8 Pitted Texture

The pitted texture is liked the visible result of rapid granular disintegration, the phenomenon in which the grains of the stone become loose and fall out. Rapid granular disintegration can be a response to salt crystallization. Oils and waxes from the fire introduce new chemicals into the stone and coat its surface, reducing its permeability. The combination of these processes leads to salt crystallization behind the less/impermeable surface coating. This can cause spalling of the surface material which leaves exposed a weaker surface that is more susceptible to further salt crystallization and decay – thus creating a dangerous cycle. Cleaning of the soot accumulation can also lead to rapid granular disintegration because it exposes the stone likely damaged by the salts.

10.9 Speckled/textured staining

Speckled staining can be the result of sporadic soot and combustion product accumulation. Flames are somewhat random and do not necessarily affect a surface evenly. It could also be atrributed to mineral transformation. Because minerals are dispersed throughout the stone, not always in an even manner, as they change phases and colors, some parts of the stone can be more affected than others.

10.10 Soot Accumulation

During the combustion process, byproducts of a fire such as fumes, smoke, oils, and ashes are released into the air. They accumulate not only on the surfaces exposed to the flames, but also on other surfaces in the vicinity of the fire.

10.11 Damage to Repairs

10.11.1 Cracking of Portland cement repair

Much of the small cracking observed in the Portland cement repairs is likely the result of shrinkage as the material dried. Cracks can be a result of incompatibility with the surrounding sandstone. The cracks along the borders of the repairs are likely due to inadequate boding and separation. Compression in the pier can also contribute to the cracking.

10.11.2 Spall of Repair Material

Spalling of the portalnd cement repair material is likely to do with compatability issues between the portand cement and sandstone. The incompatibility and ineffectiveness of these repairs are due to a combination of factors. The two materials have different Young's Moduli and thermal expansion behavior. The shrinkage of the Portland cement can cause separation from the stone and the lower porosity of the cement can cause salt to crystalize at the boundary of the two materials which will later act to expel the repair.

10.11.3 Horizontal Cracks in Portland cement repairs

The most probable explanation for the horizontal cracks in the Portland cement repairs is shrinkage during the drying process and potentially other factors resulting from the incompatibility between the cement and the sandstone. The piers are compression members so the cracks should not be a result of structural insufficiency.

10.11.4 Crusting of Portland cement repair

Crusting of the Portland cement repair can be due to salt crystallization behind the soot covering. Because the Portland cement is less porous than the sandstone, moisture and salts can become trapped at the border of the two materials. When the salts crystalize, the process can expel the outer layer of stone. Other incompatibility issues such as differential thermal properties and shrinkage can contribute to crusting.

10.11.5 Exposed corroded iron elements

In areas where some of the repair material has spalled off, it is visible that iron elements were used to bond the Portland cement to the sandstone. With time and moisture, the iron has begun the corrosion process which causes expansion and creates rust. Iron can expand to over six times its original volume. This will have damaging effects on the surrounding sandstone, adding expansion stresses.

10.12 Other Damages

10.12.1 Vertical Cracks Below Fixtures

The cracks that appear below the fixtures mounted on the piers could be caused by the mounting of the object, the later stress concentration due to a rigid insertion of fixture, or by the corrosion of the mounting element. While the candle holders could have been present during the fire, the fans and electrical installations were not, so the cracks occurring due to these are post-fire damages.

10.12.2 Exposed brick and iron mounts for fixtures

Brick additions with iron connection elements were found on many piers, they were likely an intervention to allow mounting an object to the pier. Today, the iron elements are corroding due to exposure to air and moisture.

11. RECOMMENDATIONS FOR FURTHER RESEARCH

After the inspection and damage evaluation, there still exist many unknowns about the true condition of the piers that need to be further evaluated in order to best design interventions for the preservation and stability of the piers. Recommended tests, the results they can provide, and their pros and cons are described below.

11.1 Evaluate the Current Strength of Stone

As previously described, fire and extreme temperatures can have damaging effects on the mineralogical and macro level of stone and masonry. In order to understand the remaining compressive strength of the Montjuïc stone in the pier of Santa Maria del Mar, there are a variety or combination of tests that can be performed.

11.1.1 Cores in Lab

One way to test the true current compressive strength of the stone is to core samples and take them to the lab for uniaxial compression tests. At least six cores should be tested so that the sample size is sufficiently large. These samples should come from various locations in the pier to reduce the impact of local stone irregularities. The benefit of this test is that it will provide direct results of the compressive strength. The drawbacks are that it is destructive especially if many cores must be taken and expensive. One way to minimize the destruction and number of cores needed is to evaluate only the worst case "damaged" stones. This will provide the "worst case" compressive strength among the stones - a value that will provide a strength estimate on the safe side. Even so, due to the destructive nature of this test, it will be best to try other non-destructive methods first in order to avoid further damage to the piers if possible.

11.1.2 Lab experiment with Montjuïc Stone

Another way to directly test the compressive strength of Montjuïc stone exposed to extreme temperatures is to design a laboratory test replicating the fire event and then preform uniaxial compression tests. Ideally samples of real Montjuïc stone should be used, however the quarry is closed, so if samples cannot be obtained from the municipal reserve then a very similar alternative such as Postaer can be used instead. Methods described in (Gomez-Heras et al., 2009) such as oven heating, or direct flame, or laser can be used, however, in this case it would be best to try to replicate as close as possible temperature and conditions of the actual 1936 fire. It can be hypothesized that the fire produced a temperature of approximately 500°C, as this is the approximate maximum temperature of the flames of wood fires (Myers, 2016). Benefits to this method is that it will closely approximate the strength of the stone in the pier because the experiment will use the actual stone type (or one very similar) and closely replicate the fire temperature. The results can be applied with more accuracy to the pier than that of previous studies which used different stone types that were heated to pre-determined temperature intervals. The cons are that is can be expensive, time consuming, there is a minimal amount of Montjuïc stone available, and despite their best efforts, lab experiments will have inherent differences from a real fire event.

11.1.3 Extrapolation of results obtained from similar stones

The easiest, least expensive, and completely non-destructive method to estimate the post-fire compressive strength is to extrapolate the results from previous studies on stones similar to the Montjuïc stone. In the laboratory study on seven German and three Hungarian sandstone types (Hajpàl & Török, 2005). Postaer stone has the closest properties to Montjuïc stone (see Table 6). At a temperature of 600°C it lost 32% of its compressive strength (Hajpàl & Török, 2005). Considering that studies (Navarro & Gimeno, 2016; Olivera, 2000) have shown healthy Montjuïc sandstone to have a compressive strength of upwards of 60 MPa, extrapolating these results would hypothesize a compressive strength of at least 36 MPa in the damaged stone. This value is likely higher because it is very doubtful that the fire caused the stone to reach 600°C. Cons to this method are that labs do not replicate true fire events and that the stones and heating temperatures have some variations from the conditions in Santa Maria del Mar. However, it is recommended to begin the compressive strength analysis with this step. The addition of other test could be used if more accuracy is deemed necessary.

11.1.4 Penetrometer test

A penetrometer is a spring based device that measures the resistance of a material to the insertion of a steel needle. It can be used to show how compressive strength varies among damaged and healthy stones by testing stones with various states of damage. The benefits of this test are that it is easy, inexpensive, and fast to carry out. Limitation include that it is only a measurement of the surface of the stone and might not be indicative of the stone as a whole. It is recommended as an easy second step and can be combined with one of the previous methods described, which determines the worst case compressive strength, to understand the true strength of the piers as a whole and how much strength was lost in the damaged sections.

11.2 Depth of Multi-Block Cracks

Perhaps the most important testing needed for the design of interventions is to determine the depth of the multi-block vertical cracks. The best, and recommended method for measuring this is with a sonic tomography test.

11.2.1 Sonic Tomography

Sonic tomography involves the use of several accelerometers to measure the waves propagating as a result of a series of single emissions in order to provide an “internal view” of a cross-section. It can provide very accurate results of the crack depth and stone condition but is very expensive and time consuming to carry out due to the need for many accelerometers and measurements.

11.2.2 Sonic and Ultrasonic Tests

If it is not possible to carry out a sonic tomography test, a Sonic or Ultrasonic Pulse Velocity (UPV) test can be tried as an alternative. These work by measuring the time taken to pass a sonic or ultrasonic wave through an object in order to understand the quality of its interior. UPV is typically better used for finding the depth of a crack in a single stone because it is has a shorter wavelength and is very sensitive to the irregularities of stone and masonry such as the mortar joints. Sonic waves have a longer wavelength and therefore can be applicable to composite materials on a macroscopic level. Since these test are easy to carry out, they can be tried as a first option to see what information can be obtained. One difficulty in this situation is the height of the cracks on the piers; it will present a challenge when preforming tests.

11.3 Depth of Single Block Cracks

In order to determine if reinforcement is needed for the cracks that appear in a single stone, the depth of the crack must be measured. The best method for this is a sonic test or Ultrasonic Pulse Velocity test (UPV) as described above.

11.4 Location of Iron Elements

Because of the risk iron poses to stone due to corrosion and expansion, the location of all of the iron additions in the piers must be found. The best and easiest method to do this is with the use of a magnetometer, a device that detects magnetic fields and therefore iron materials. Georadar can also determine the location of iron. It is a more expensive and complex test, however, if it is already being used for another purpose, such as determining the replacement depth, the results can also be used for iron detection and eliminate the need for an additional test.

11.5 Determine the Depth of the Replacement

From visual observation alone, it is impossible to know the depth of the patched spalls. It is also unknown if the apparent replacement stones are deep or only superficial. The boding mechanisms of these additions and the degree to which they are contributing the structural section is also unknown. Because it is important to understand the extent of the damage that these additions hide and the remaining structural section and capacity of the piers, the depth of these interventions must be determined. There are a variety of methods that can be used for this analysis.

11.5.1 Thermography Tests

A thermographic camera can be used to perform a passive thermography test. This means that the analysis is done with in-situ conditions and that the stone is not heated first. The camera will use infrared radiation to produce images of the piers. If the depths of the replacements are very shallow, they will be evident in the thermographic images. It is likely that this test is not sufficient, however, because it is cheap, fast, and easy, it should be performed as a first step to see what information can be obtained.

11.5.2 Georadar

Radar is valuable tool which detects changes in electromagnetic properties [columns] and can be used as a method for obtaining accurate thicknesses as well as mapping arrangement of the masonry (Ballard, 2007). Georadar, or GPR, is a radio echo-sounding system. In voids, radio waves from the radar pass through – but at three times the speed at which they travel through stone (Ballard, 2007). GPR produces high quality images and is lightweight and portable. However, it measures changes in electromagnetic properties which cannot be used to infer mechanical parameters.

11.5.3 Sonic Tomography

The best, and recommended method for measuring replacement depth is with a sonic tomography test. Sonic tomography involves the use of several accelerometers to measure the waves propagating as a result of a series of single emissions in order to provide an “internal view” of a cross-section. It can provide very accurate results of the pier composition and condition but is very expensive and time consuming to carry out due to the need for many accelerometers and measurements.

11.13 Sonic Test

Sonic test (as described in section 10.2.2) can also aid in determining the depth of replacement materials because sonic waves have a longer wavelength and therefore can be applicable to composite materials on a macroscopic level. Therefore, it can be used to understand the approximate thicknesses of the different materials.

11.6 General Recommendations

Because of their ease and cost efficiency, it is recommended that the first tests carried out are the thermos-vision test to see if the depth of repairs can be seen and the penetrometer test to understand the difference between the healthy and deteriorated stone. A magnetometer should also be used on the entirety of all of the piers to detect all of the iron elements. Once these results have been processed, if more information is needed, which is likely, further investigations can be carried out.

Because of the accuracy and amount of information a sonic tomography test can provide, it should be highly considered and preformed if possible, at least in critical locations. It will provide information on depth of the cracks and repairs, the most important factors in determining the condition of the piers.

In the case that sonic tomography can't be carried out, a combination of georadar, and UPV can be used to attempt to characterize the depth of the cracks and replacements.

12. RECOMMENDATIONS FOR REPAIR

12.1 Removal

12.1.1 Portland Cement Repairs

It is recommended that all Portland cement repairs are removed from the piers, this includes patches and mortar repointing. This is because of the incompatibility of the sandstone and the Portland cement, the danger it poses to visitors as the cement threatens to fall out, and the damage the Portland cement can cause in the sandstone. These repairs are also concealing the true state of damage. The incompatibility and ineffectiveness of these repairs are due to a combination of factors. The two materials have different Young's Moduli and thermal expansion behavior. The shrinkage of the Portland cement can cause separation from the stone and the lower porosity of the cement can cause salt to crystalize at the boundary of the two materials which will later act to expel the repair. It can be seen that at least in some places, iron elements were used to bond the cement to the stone. Removing the cement will expose any other iron elements which could be rusting and causing damage.

12.1.2 Iron Elements

Once detected during the investigation stage and exposed after the Portland cement removal. All iron elements should be removed from the piers. The rusting and expansion of the iron, up to six times its original volume, will continue to damage the sandstone until it is removed. If the remaining holes are small the can be left as is, or if a patch is needed structural hydraulic lime mortar can be used as a fill.

12.1.3 Fixtures

All of the fixtures mounted to the columns should be removed. This includes fans, lights, electrical cords, and announcement boards. These elements have been shown to damage and create cracks the sandstone. It is also possible and likely that iron elements have been used in the mounting - further contributing to stone damage.

12.1.4 Replacement Stones

Depending on the results from the investigations of the depth of the replacement stones and their bonding mechanism, the need for their removal can be determined. If it is found that these stones are well bonded to the surface of the sandstone and that no iron elements were used, it could be possible to leave these interventions in place. If this is the case, it would be best to remove a small sample to verify these conditions. However, if iron is detected, or insufficient bonding is suspected, these interventions should be removed and replaced.

12.2 Repair

12.2.1 Vertical Cracks

If determined to be deep and of structural concern, the vertical cracks, both those in a single stone and those that extend through multiple stones, should be fixed with high strength rods. Optimal materials include titanium and glass fiber. The rods can be inserted by drilling horizontally through the crack and fixed in place with miro-lime mortar. Two rods per stone should be sufficient, three if the crack is very long. In the multi-block cracks, when the crack occurs in the center of the stone in line with the mortar joints, rods might not be necessary because the stone sections are still very large and can provide resistance independently. This intervention is needed on piers 2, 6, and 7, requiring approximately 40 bars. The repair drawings can be found in Appendix B.

12.2.2 Spalls and Sheeting

After all repair removal, if the spalls and sheeting damages are only superficial, it will be best to leave the piers as is. This will provide a visual legacy of the building's history and eliminate the need and cost of further repairs. If some of the spalls are deep and concerning, they can be repaired. Options include filling with a structural hydraulic lime mortar with pozzolan additions or a mechanically, chemically, and visually compatible sandstone. If a stone is added, the exposed surface of the spall should be cut back to a flat plane in a healthy part of the stone. This will ensure a replacement stone can be cut to fit the area and that there will be a smooth bonding surface. For either option a high strength titanium or glass fiber rod should be used to anchor the repair, and in the case of stone replacement, it should be bonded with micro-lime mortar.

12.2.3 Replacement Stone

If it is determined that the existing replacement stones should be removed and replaced due to iron elements or inadequate bonding, a compatible sandstone should be cut to fit and bonded with a titanium or glass fiber rod anchored in micro-lime mortar. If it is necessary, the exposed surface of the pier should be cut to a flat healthy plane to provide a good bonding surface.

12.2.4 Mortar Repointing

Where a significant amount of mortar is missing and in the locations where the Portland cement repointing is removed, the piers should be repointed. A hydraulic lime repointing mortar with pozzolan additions should be used to repair the integrity of the piers.

12.2.5 Horizontal Cracks

Because the piers are compression members, the horizontal cracks are a strange phenomenon. They are likely superficial defects of the stone and may not need to be repaired. However, further testing (such as an ultrasonic test) to understand their depth is recommended to verify that no intervention is needed.

13. CONCLUSIONS

A summary of the conclusions from the study of the effect of fire on the stone masonry piers of Santa Maria del Mar is as follows:

- Damages observed in the piers of Santa Maria del Mar due to fire include spalling, sheeting, cracking, granular disintegration, color change, and soot accumulation. Of these, the most prominent and likely consequential are spalling and sheeting.

- Of the piers in the nave, the ones closest to the choir suffered the most damages. This is likely because the fire was concentrated near the choir. The rear two piers suffered almost no damages.

- The piers of the choir have an extensive amount of replacement stones. These make the piers appear in good condition. However, they indicate that these piers suffered a lot of damage and could be concealing their true state. The depth of these repairs and their bonding mechanisms are not known and further evaluations should be performed to better understand the true state of these piers.

- The multi-block vertical cracks which were found on many faces of the piers were not likely caused by the fire. They do not occur in some of the most damaged piers, are present in the least damaged piers, and occur at an elevation likely above direct exposure with the fire.

- The single and multi-block cracks in the piers that are result of fire could be dangerous for the strength of the piers and should be investigated into more detail

- The Portland cement interventions have not been effective mostly due to incompatibility and bonding. They are falling out, spalling, sheeting, and breaking. This has exposed that iron elements were used to bond them to the sandstone. These are now corroding.

- Further tests should be performed to understand the depth of the cracks, the depth of the replacements, and the remaining strength of the stone.

- The first step in a repair plan should be to remove all Portland cement repairs and iron elements.

14. REFERENCES

Ballard, G. (2007). What Lies Beneath: non-destructive investigation of masonry defects. Historic Churches, 2007

Caballé, F., González, J., Giráldez, P., Roca, P., González, R., Domenge, J., & Vendrell, M. (2008). Construction process, damage and structural analysis. Two case studies. Structural Analysis of Historic Construction: Preserving Safety and Significance, 643-651.

Chakrabarti B., Yates T., Lewry A. (1995). “Effect of Fire Damage on Natural Stonework in Buildings,” Construction and Building Materials, vol. 10, no. 7, pp. 539–544.

Gómez-Heras, M., Mccabe, S., Smith, B. J., & Fort, R. (2009). Impacts of Fire on Stone-Built Heritage. Journal of Architectural Conservation, 15(2), 47-58.

Gómez M., (2005), Procesos y formas de deterioro térmico en piedra natural del patrimonio arquitectónico. Doctoral Thesis Universidad Complutense de Madrid

Hajpál M. (2002). Changes in Sandstone of Historical Monumnets Exposed to Fire or High Temperature. Fire Technology, 38, 373–382

Kompaníková Z., Gómez Heras M., Michnová J., Durmeková T., Vlcko J. (2014), Sandstone alterations triggered by fire-related temperatures. Enivron Earth Sci. 72: 2569-2581

McManus N. (2007). Where there is Fire there is Soot and Smoke. Cleaning & Restoration. Restoration Industry Association. May 2007

Mazziotti A. (2016). Structural Analysis of Historical Masonry Buildings. PhD Thesis. University of Naples Federico II

Murcia J. (2008). Seismic Analysis of Santa Maria del Mar Church in Barcelona. Master Thesis Technical University of Catalonia (UPC)

Myers F. (2016). Flame Temperatures in Wood Burning Fires: Hardwood vs. Softwood. The American Association for the Advancement of Science

Navarro A., Gimeno D. (2016). Montjuic Sandstone: mechanical properties, decay and treatment. Defensive Architecture of the Mediterranean XV to XVIII Centuries. Vol. IV

Oliveira D., Lourenço P., Roca P. (2000). On the Compressive Strength of Stacked Dry-Stone Masonry.

Roca P., Clapés J., Caselles O., Vendrell M., Giráldez P., Sánchez-Beitia S. (2008). Contribution of Inspection Techniques to the Assessment of Historical Structures. RILEM Symposium on On Site Assessment of Concrete, Masonry and Timber Structures - SACoMaTiS 2008. 621 – 632.

Roca P. (2017). SA1.14 Example: Study of Santa Maria del Mar Church in Barcelona. MSc SAHC Lecture Notes

Sasinska B. (2014). Fire Damaged Stone: The Effects of Heat, Flame, & Quenching. Thesis Presented to the Faculty of Architecture, Planning, and Preservation Columbia University

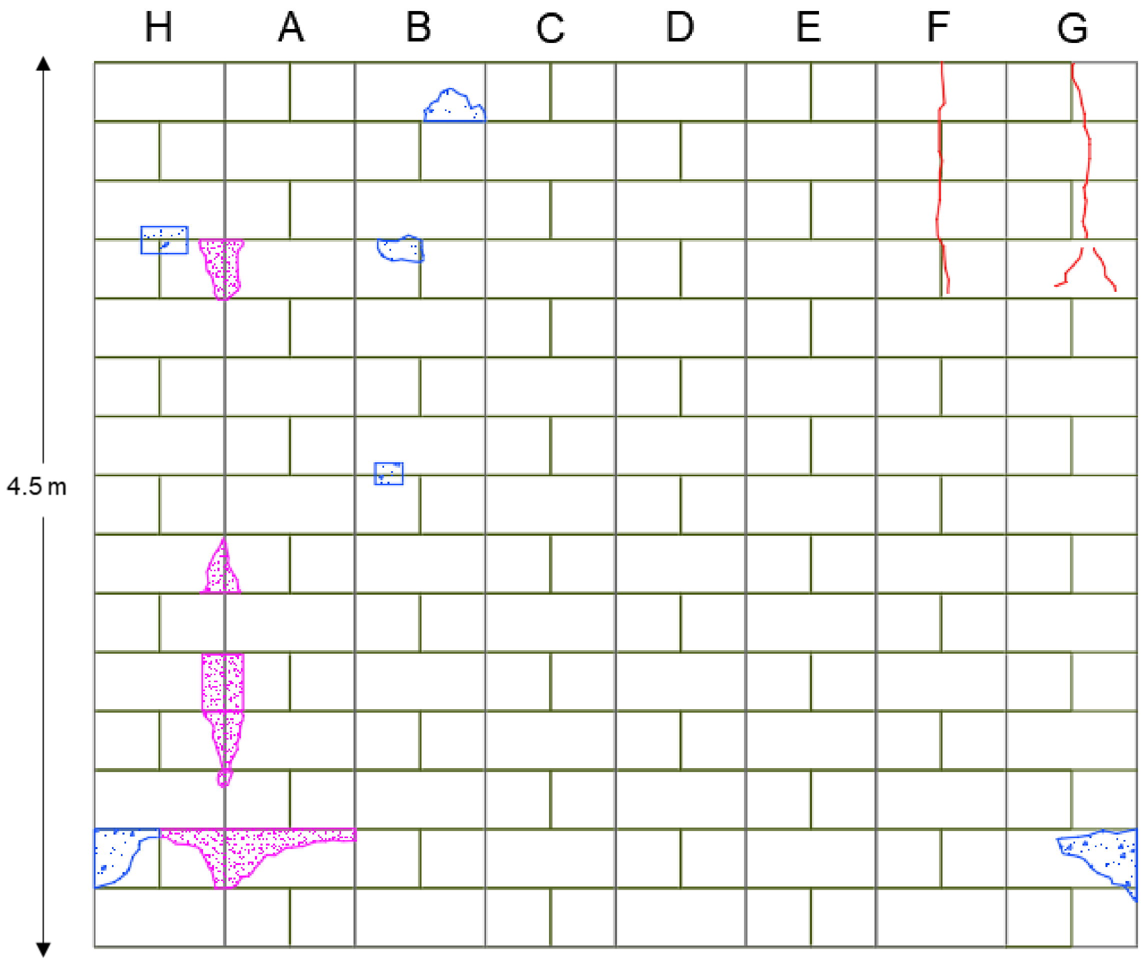
Török Á., Hajpál M. (2004). Mineralogical and Colour Changes of Quartz Sandstones by Heat, Environmental Geology Vol 46, 311-322

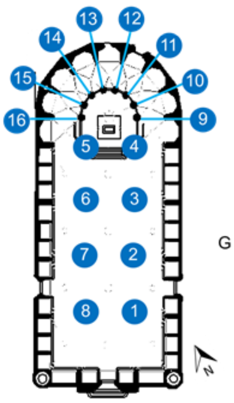
Török Á., Hajpál M. (2005). Effect of Temperature Changes on the Mineralogy and Physical Proper ties of Sandstones. A Laboratory Study. Restoration of Buildings and Monuments, Vol. 11, No 4. 1–8

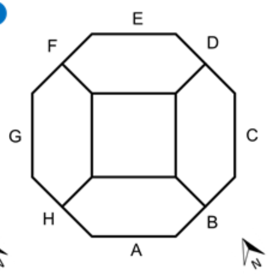
APPENDIX A

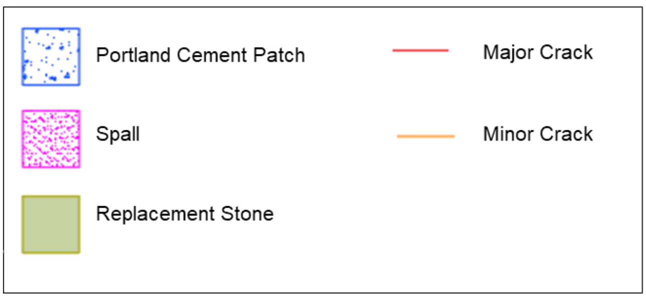
Damage maps

PEIR 1

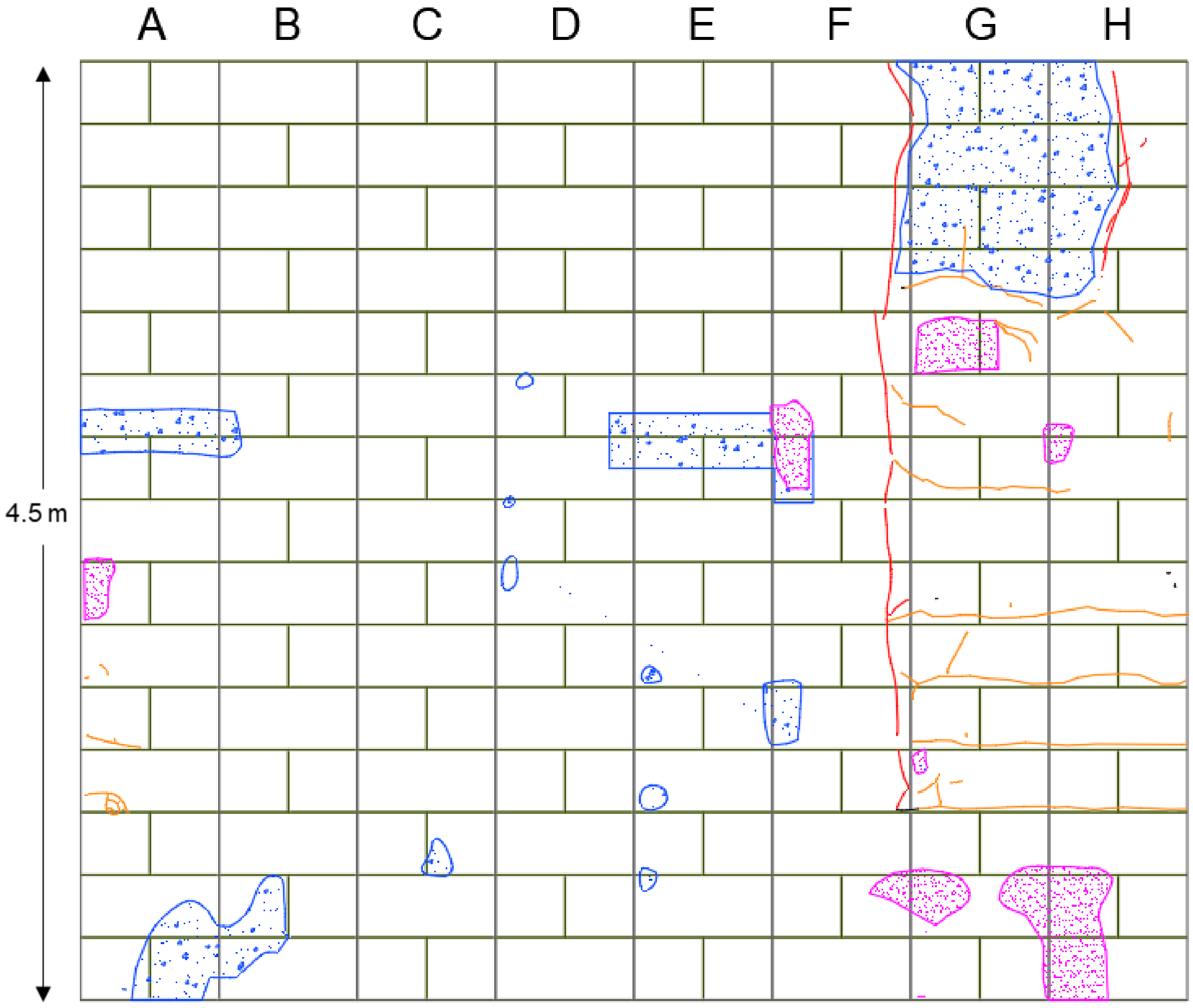


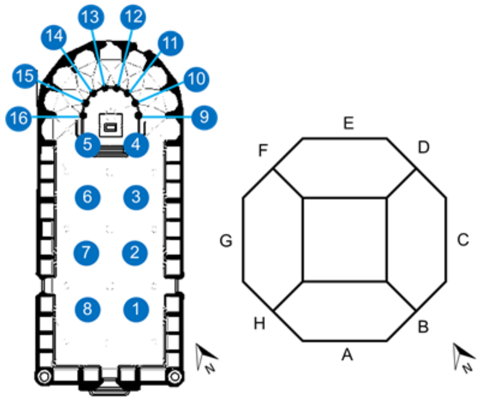


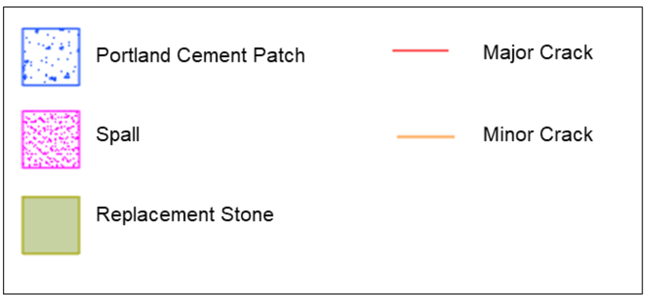




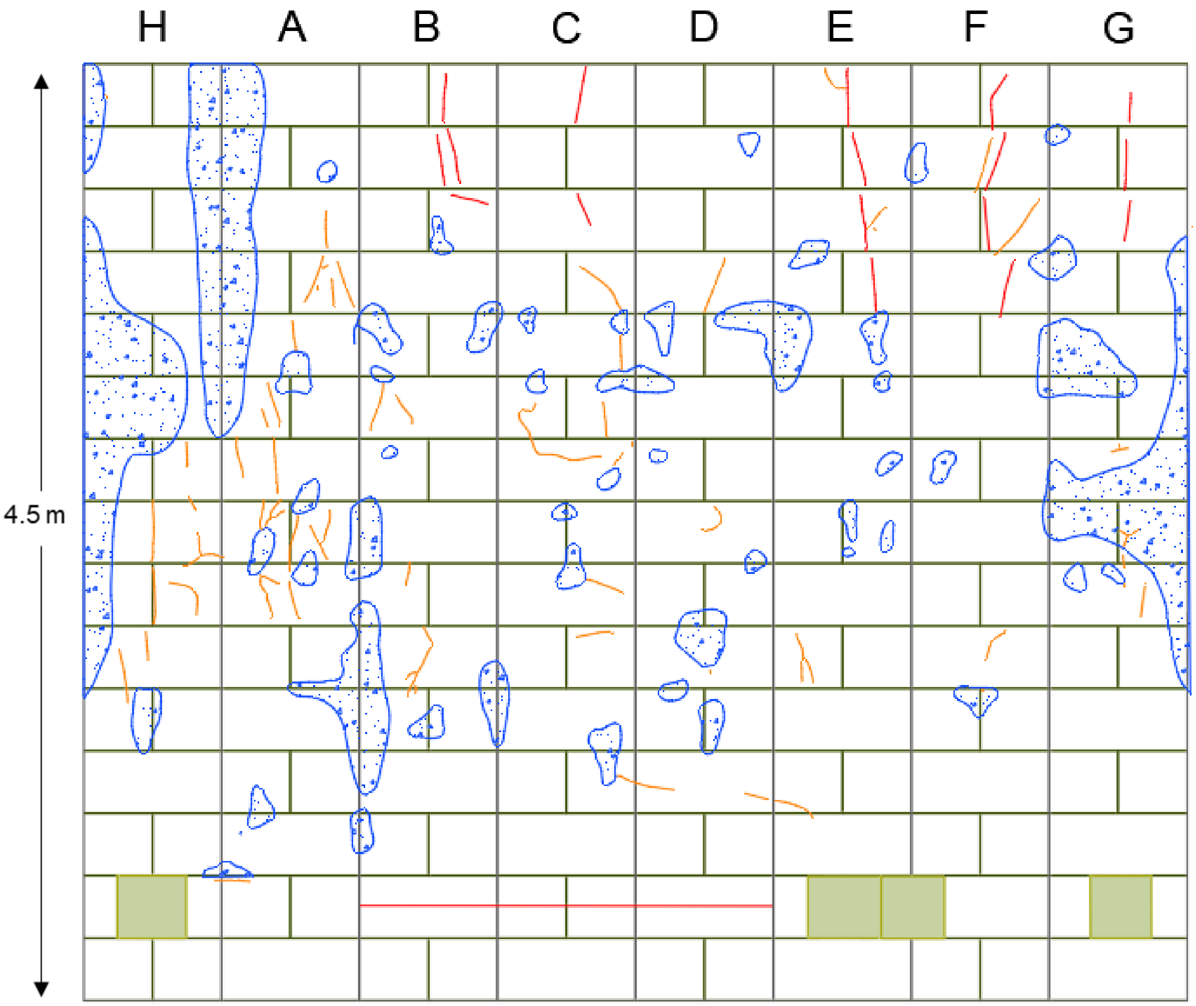
PEIR 2

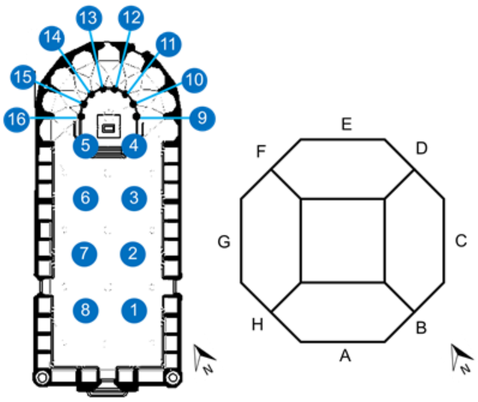

A
B
C
D
E
F
G
H
4.5 m

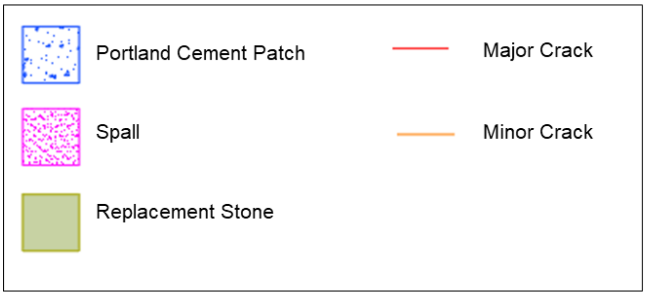

13
12
14
11
15
10
16
9
5
4
6
3
7
2
8
1
E
F
D
G
C
H
B
A


Portland Cement Patch
Major Crack
Spall
Minor Crack
Replacement Stone

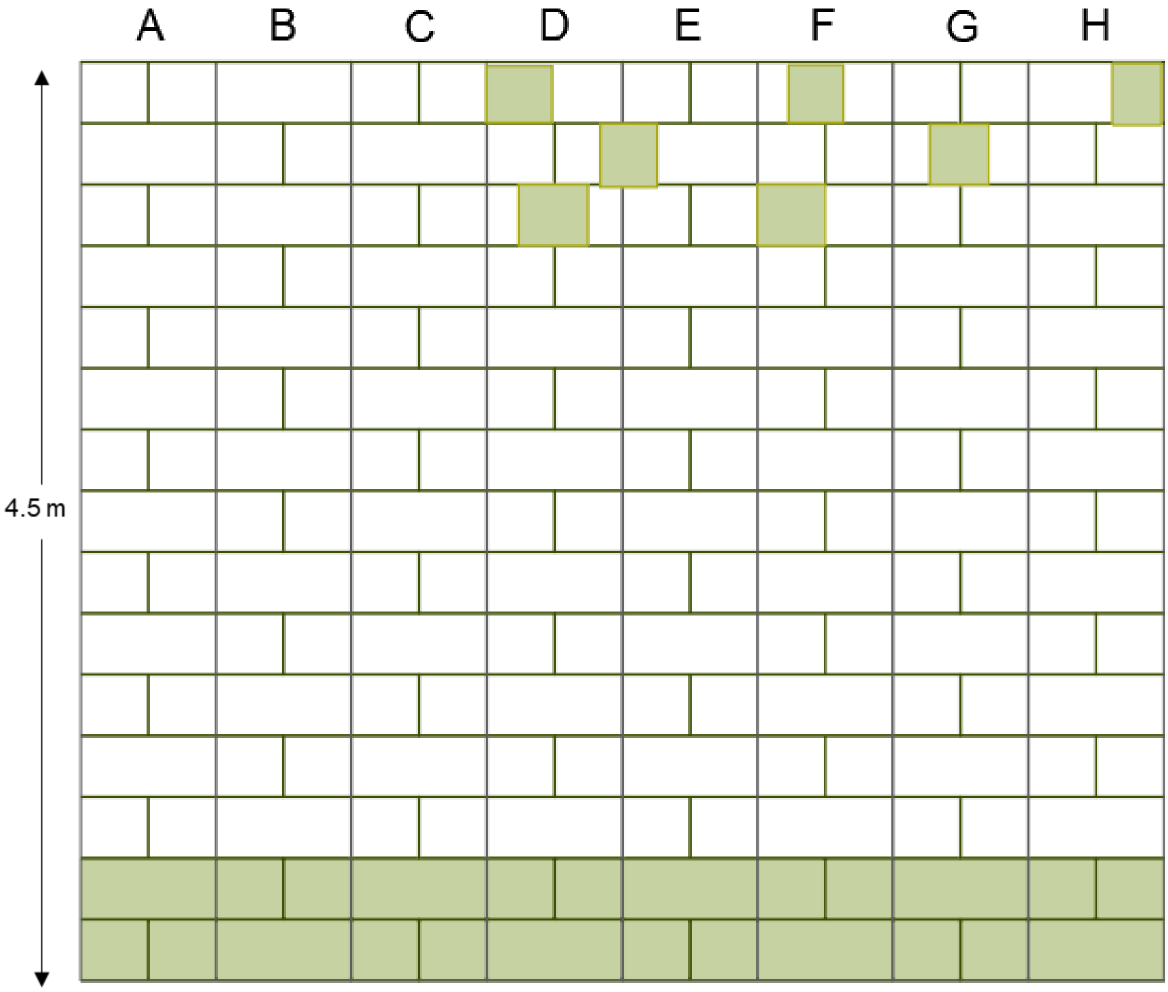
PEIR 3

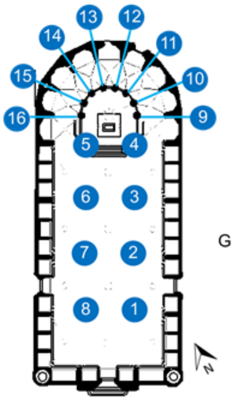

H
A
B
C
D
E
F
G
4.5 m

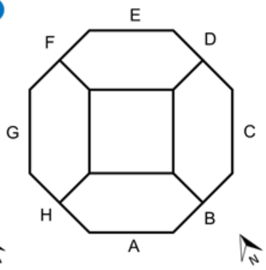

13
12
14
11
15
10
16
9
5
4
6
3
7
2
8
1
E
F
D
G
C
H
B
A

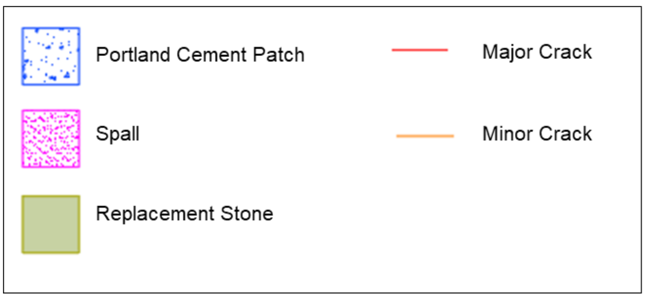

Portland Cement Patch
Major Crack
Spall
Minor Crack
Replacement Stone

PEIR 4

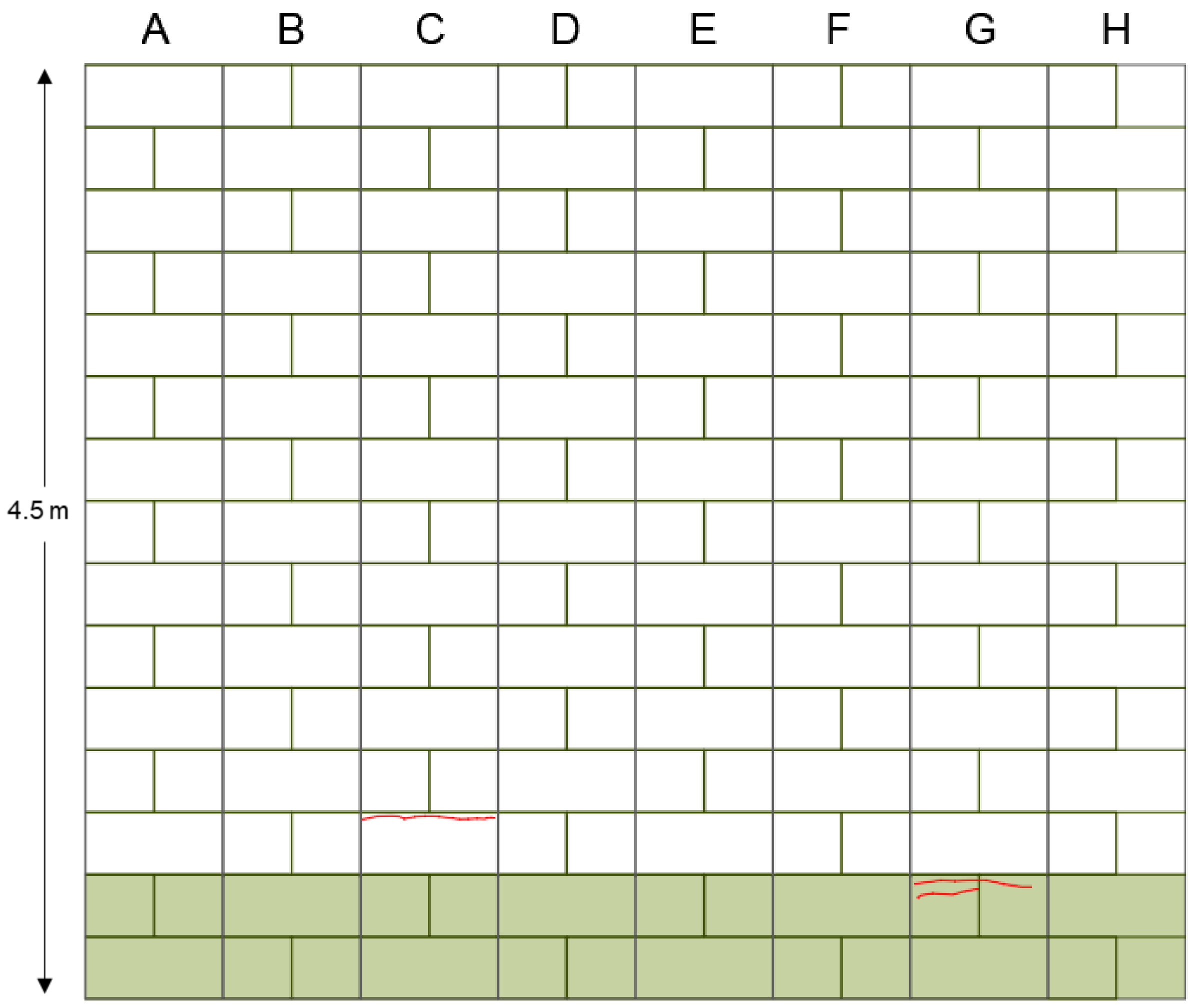

A
B
C
D
E
F
G
H
4.5 m

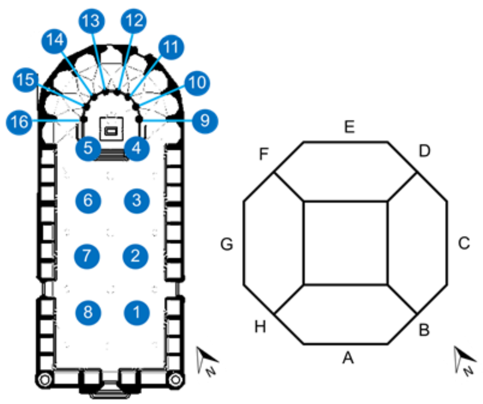

13
12
14
11
15
10
16
9
5
4
6
3
7
2
8
1
N

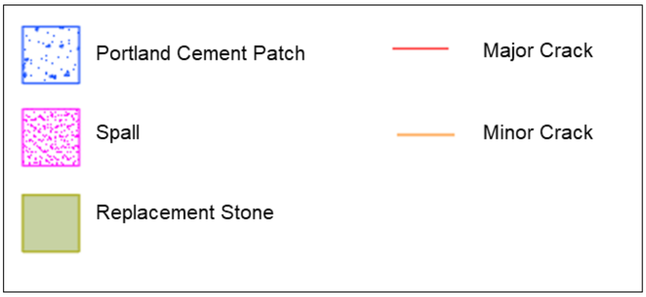

E
F
D
G
C
H
B
A
N


Portland Cement Patch
Major Crack
Spall
Minor Crack
Replacement Stone

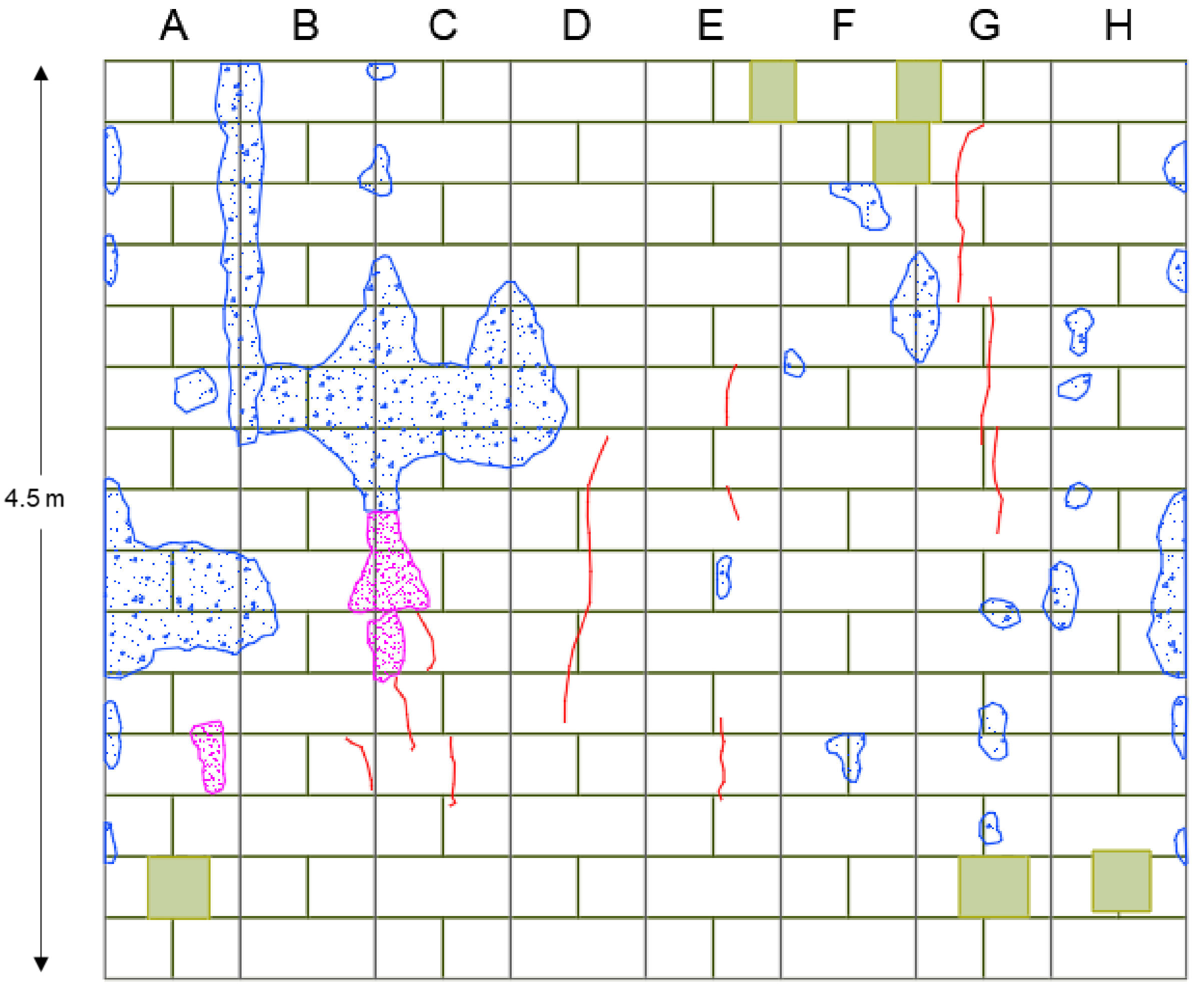
PEIR 5

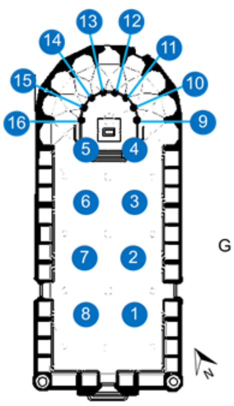

A
B
C
D
E
F
G
H
4.5 m

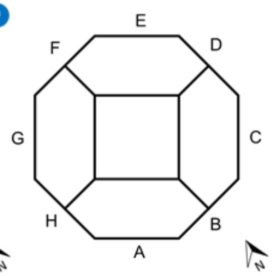

13
12
14
11
15
10
16
9
5
4
6
3
7
2
8
1
E
F
D
G
C
H
B
A

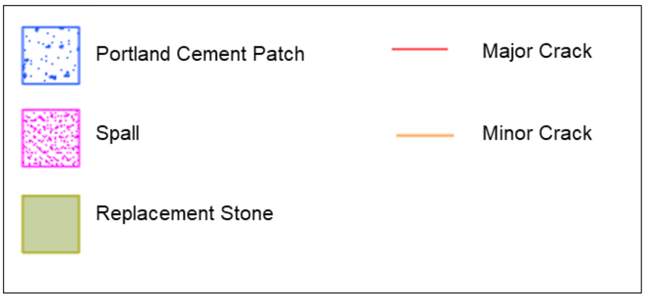

Portland Cement Patch
Major Crack
Spall
Minor Crack
Replacement Stone

PEIR 6

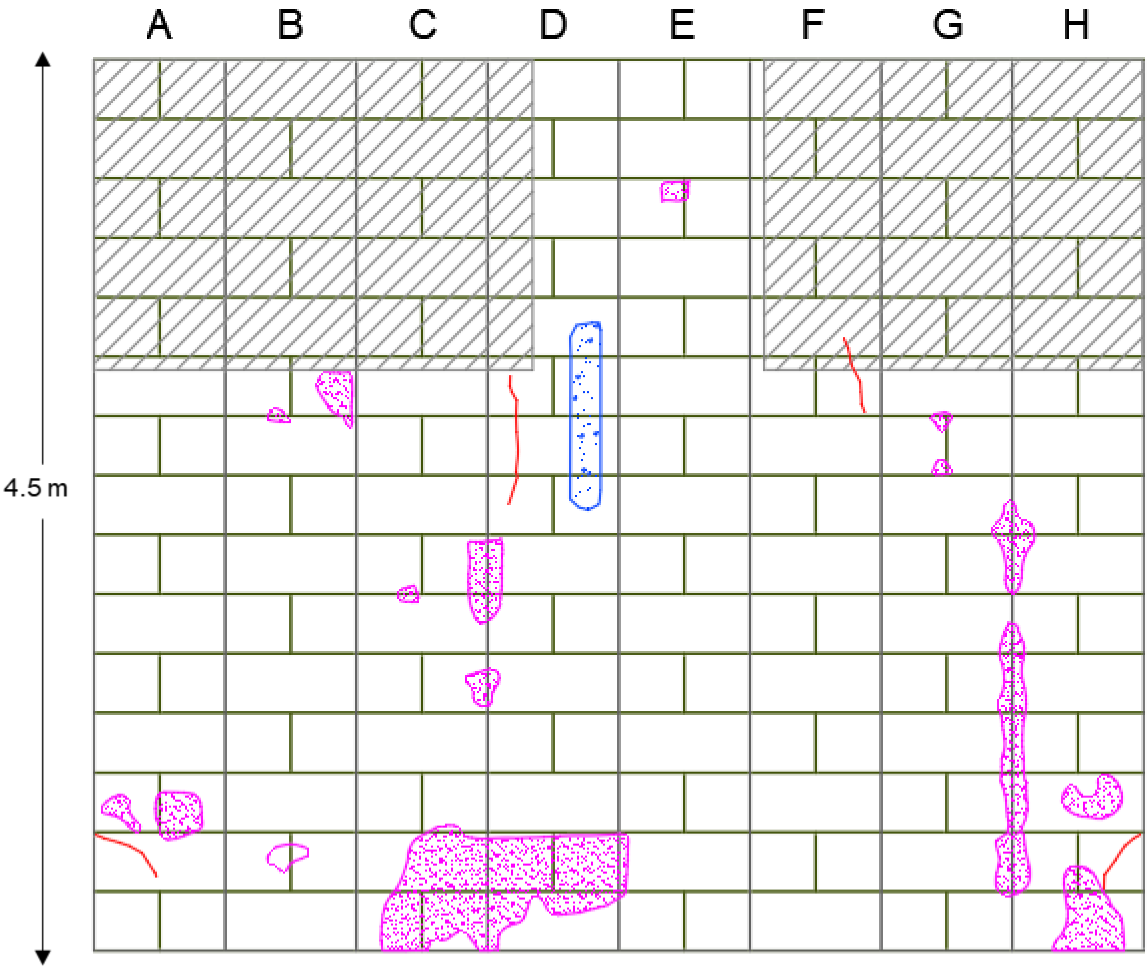

A
B
C
D
E
F
G
H
4.5 m

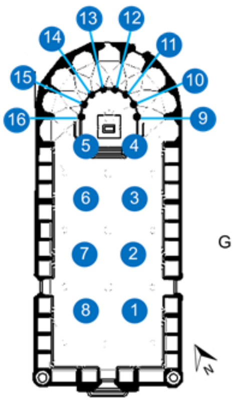

13
12
14
11
15
10
16
9
5
4
6
3
7
2
8
1

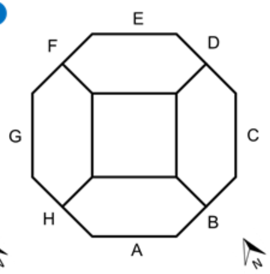

E
F
D
G
C
H
B
A

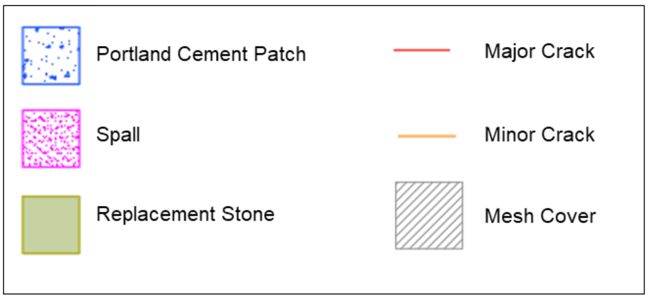

Portland Cement Patch
Major Crack
Spall
Minor Crack
Replacement Stone

PEIR 7

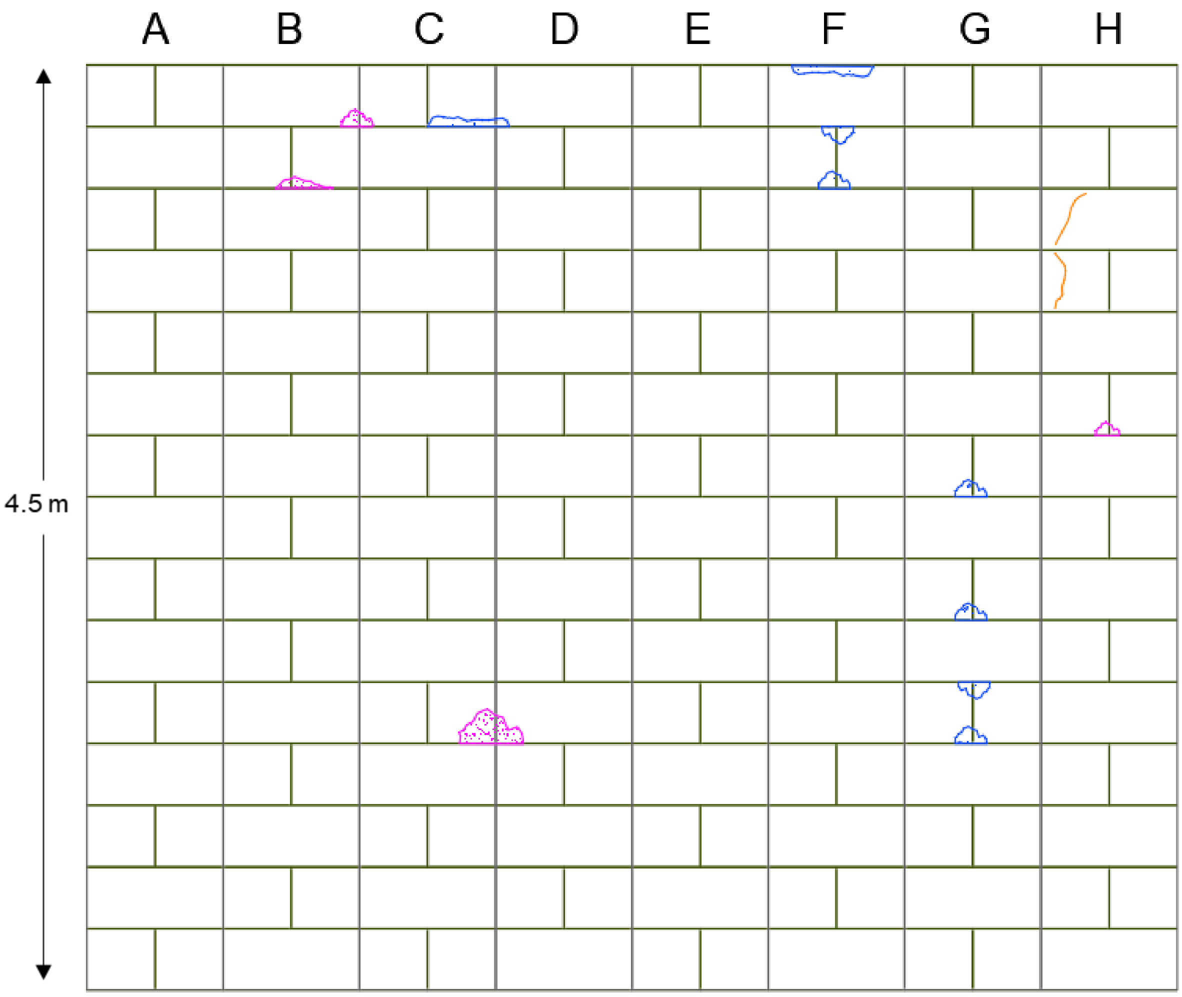

A
B
C
D
E
F
G
H
4.5 m

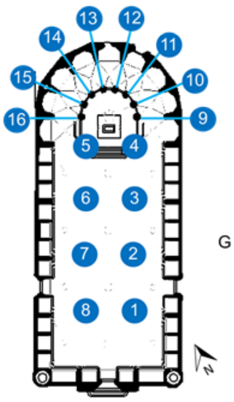

13
12
14
11
15
10
16
9
5
4
6
3
7
2
8
1

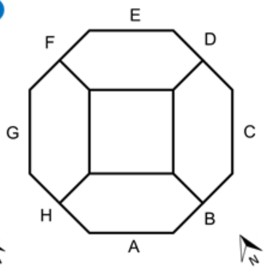

E
F
D
G
C
H
B
A

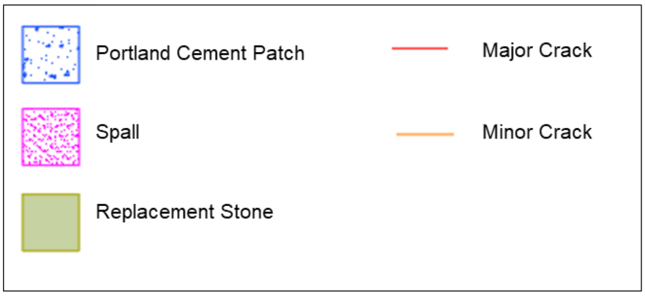

Portland Cement Patch
Major Crack
Spall
Minor Crack
Replacement Stone
Mesh Cover

PEIR 8

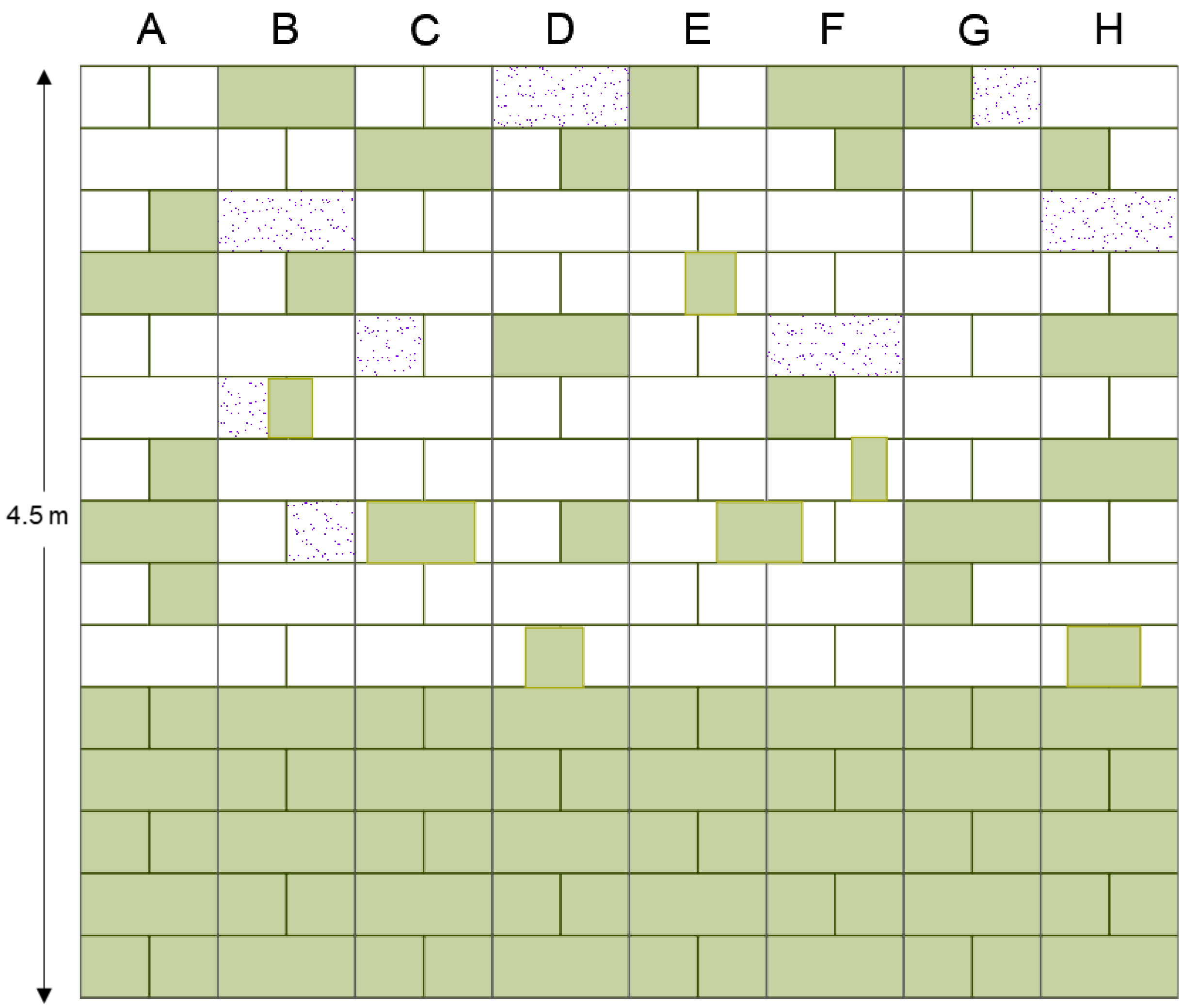

A
B
C
D
E
F
G
H
4.5 m

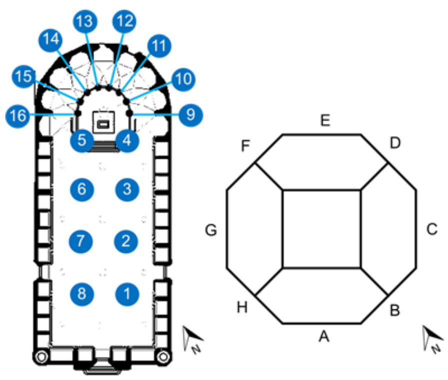

13
12
14
11
15
10
16
9
5
4
6
3
7
2
8
1

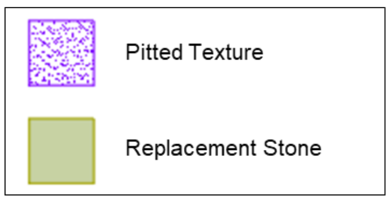

E
F
D
G
C
H
B
A


Portland Cement Patch
Major Crack
Spall
Minor Crack
Replacement Stone

PEIRS 9-16 Represenative Example



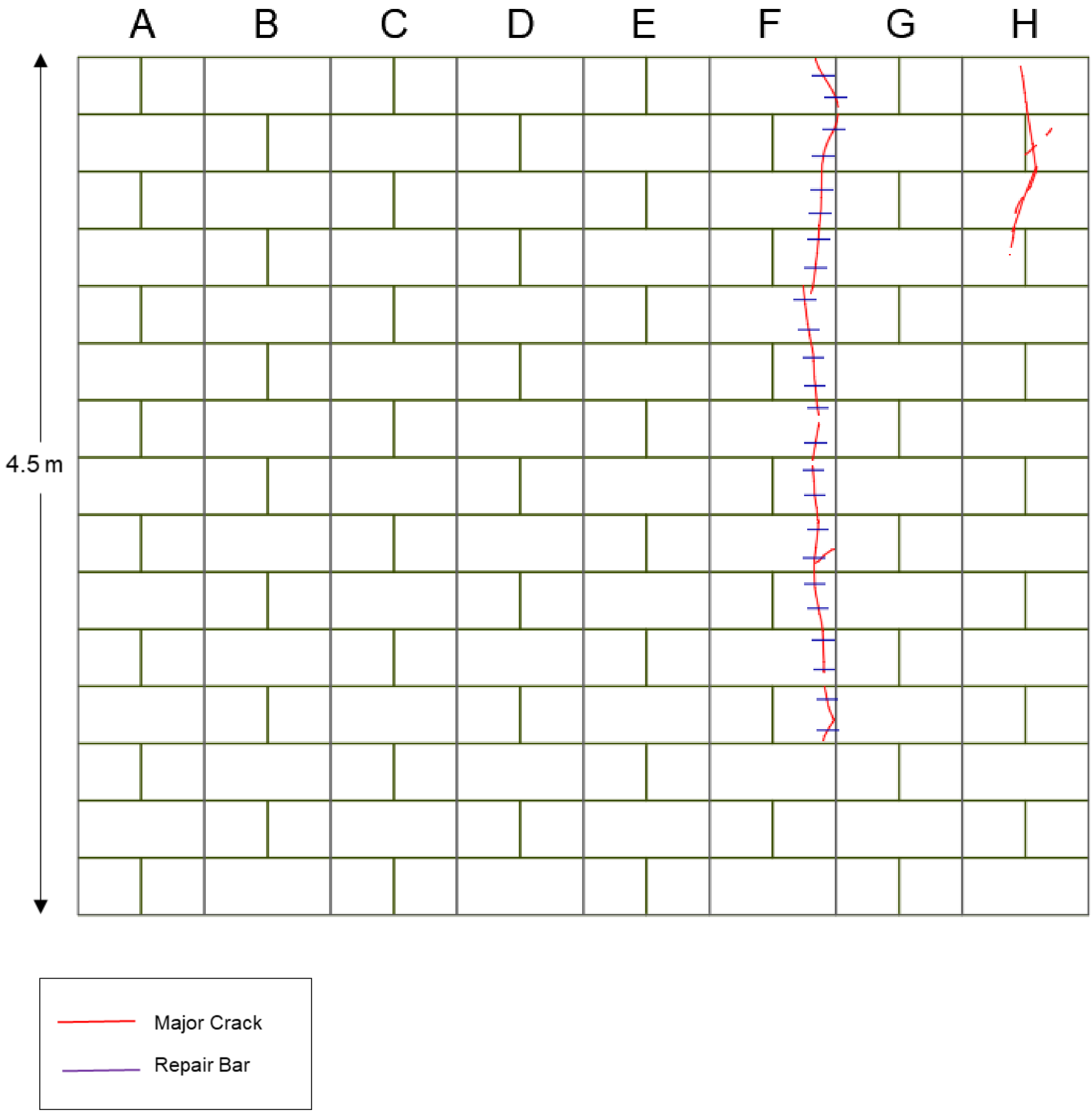




APPENDIX B

Repair proposal

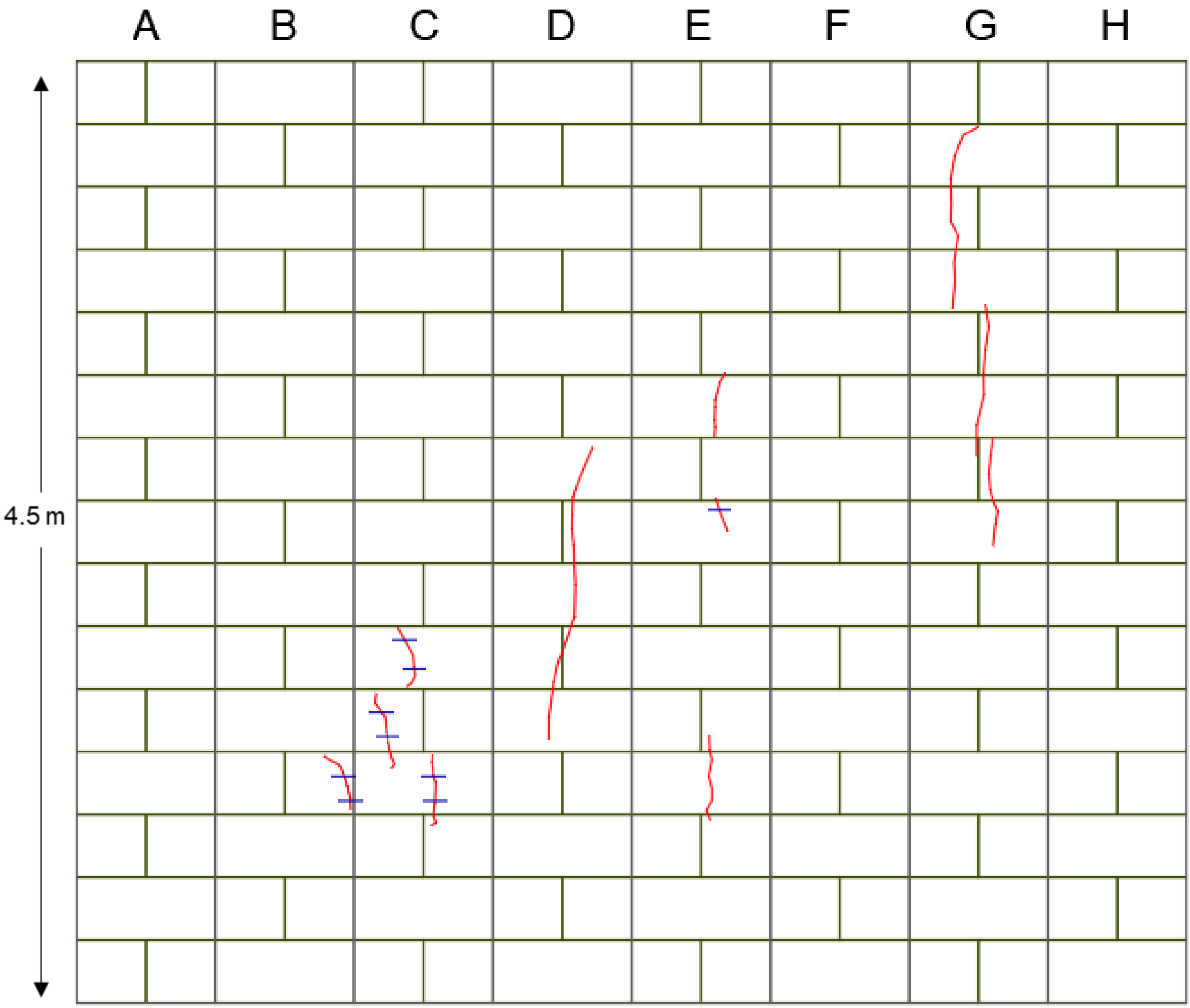
PEIR 2

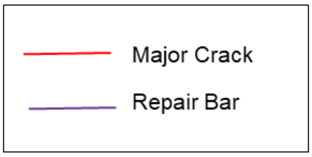


Stones needing repair: 12
Number of bars: 24

*Cracks in line with mortar joints may not need intervention

PEIR 6

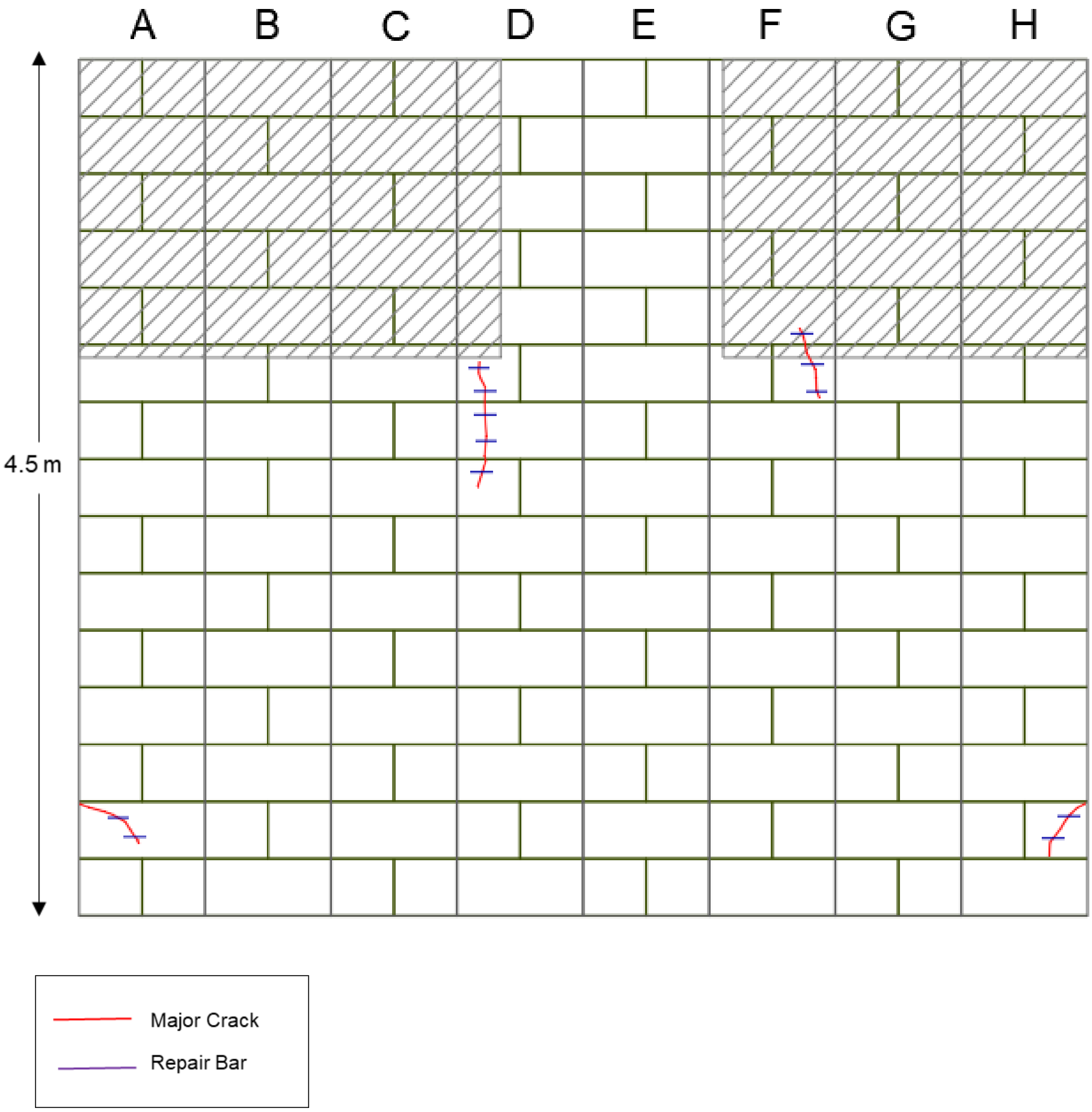




Stones needing repair: 4
Number of bars: 9

*Cracks in line with mortar joints may not need intervention

PEIR 7



Stones needing repair: 6
Number of bars: 12