SEISMIC RETROFITTING ASSESSMENT OF HISTORICAL CHURCHES

The reconstruction of The Basilica of Santa Maria di Collemaggio after the 2009 L'Aquila earthquake

ANGELIKA HEDENSTRÖM

The faculty of economics, society and technology

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Supervisor: Patrik Nedar and Zahra Shadravan
Examiner: Bozena Guziana
Date: 2019-01-25
E-mail: ahm15006@student.mdh.se
ABSTRACT

This study summarizes previous research to evaluate and verify the results of the extensive restoration of The Basilica of Santa Maria di Collemaggio after the 2009 L’Aquila earthquake. In addition, it aims at identifying the vulnerability factors and challenges in preserving these buildings. The research is based on scientific reports in the field as well as a on site study of a selected church and two reference churches. After the 2009 L’Aquila earthquake most part of the city was destroyed, including a big part of the cultural heritage. The Basilica of Santa Maria di Collemaggio that is considered an important symbol for the city of L’Aquila suffered severe damages during the 2009 L’Aquila Earthquake, including shear damages in the façade, crushing of nave pillars, and a total collapse of the transept, probably caused by the failure of the two main pillars. An extensive rehabilitation work begun to restore The Basilica of Santa Maria di Collemaggio, directed by Italian universities, ENI and the municipality of L’Aquila. To not conflict with the cultural heritage, new technology was combined with traditional seismic retrofit action. In the case of The Basilica of Santa Maria di Collemaggio many damages occurred on weak elements that previously had been damages and rebuilt. This underlines the importance of correct seismic retrofit actions and verification of the effect of the implementation. In the rehabilitation work parts of the church was completely rebuilt, among which the transept and the main pillars meanwhile other parts of the church was repaired or exchanged. Further enhancements were made, including modern technology such as installing a structural health monitoring system. In previous research the system has been used to make synthetic test to for evaluating the work. The results from those tests suggests that the rehabilitation project has been successfully completed and that the global seismic resistance of the Basilica has been improved. The present study concludes that incorrect performed seismic retrofit can have devastating result on the structural health of the building. Modern technology such as structural health monitoring system can be used for a more accurate analysis of the building. It also concludes that structural building evaluations are crucial in order to avoid repeating previous mistakes and to validate safety, sustainable interventions and correct implementation for seismic retrofitting. However, if the interventions will affect invasively and if the building will resist stronger earthquakes in the future can still not be said.

Keywords: L’Aquila, earthquake, reconstruction, church, Basilica, Santa Maria di Collemaggio, Collemaggio, historical, heritage, preservation, seismic, retrofit, SMH
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Västerås in January 2020

Angelika Hedenström
SUMMARY

This study summarizes previous research to evaluate and verify the results of the extensive restoration of The Basilica of Santa Maria di Collemaggio after the 2009 L’Aquila earthquake. In addition, it aims at identifying the vulnerability factors and challenges in preserving these buildings. The research is based on scientific reports in the field as well as a on sight study of a selected church and two reference churches.

Seismic events can cause both extensive material damage and losses of human lives. Historical masonry churches are particularly vulnerable due to the building geometry, lack of horizontal stiffness and poor material properties. This study investigates the restoration and retrofit actions done in during the restoration of The Basilica of Santa Maria di Collemaggio in L’Aquila. The studying a Basilica and two reference churches and scientific reports this research investigates the causes, damages and rebuilding techniques used for restoring historic churches after earthquakes. In addition, it aims at identifying the vulnerability factors and challenges in preserving these buildings.

The 6th of April 2009, an Mw 6.25 earthquake struck the Abruzzo region in central Italy. One of the affected churches was The Basilica of Santa Maria di Collemaggio that is considered an important symbol for the city of L’Aquila. It suffered severe damages during the 2009 L’Aquila Earthquake, including shear damages in the façade, crushing of nave pillars, and a total collapse of the transept, probably caused by the failure of the two main pillars.

An extensive rehabilitation work begun to restore The Basilica of Santa Maria di Collemaggio, directed by Italian universities, ENI and the municipality of L’Aquila. To not conflict with the cultural heritage, new technology was combined with traditional seismic retrofit action. New material such as carbon fibre reinforced polymer was introduced to strengthen the existing structure. In the case of SMC many damages occurred on weak elements that previously had been damages and rebuilt. This underlines the importance of correct seismic retrofit actions.

In the rehabilitation work parts of the church was completely rebuilt, among which the transept and the main pillars. The previous pillar construction with poor filling material was exchanged with a hollow reinforced concrete beam, covered with the recovered stones from the previous pillars. Also, the walls and roof structure were strengthened with steel frames and wires.

Further enhancements were made, and a structural health monitoring system was installed in 2017. It aims at providing data for understanding the earthquake response of the basilica, as well as enhancing the planning of maintenance. In the research that has been a base for this investigation synthetic tests were made to follow up on the seismic response after the restoration. These tests suggest that the rehabilitation project has been successfully completed and that the global seismic resistance of the Basilica has been improved.

The structural health monitoring can be a useful and cost-efficient tool for further research and enhance the understanding the building behaviour under seismic events, the structural health and need for maintenance. The results from tests in previous research suggests that
the rehabilitation project has been successfully completed and that the global seismic resistance of the Basilica has been improved.

In the comparison with two reference churches it was seen that SMC suffered much severe damage during the earthquake, and it was not only limited to the most common damages. The damages of the reference churches however, corresponded to the most common damages on macro elements. One of the important factors that might have affected this was the difference in size and open spans among the churches.

The present study concludes that incorrect performed seismic retrofit can have devastating result on the structural health of the building. Modern technology such as structural health monitoring system can be used for a more accurate analysis of the building. It also concludes that structural building evaluations are crucial in order to avoid repeating previous mistakes and to validate safety, sustainable interventions and correct implementation for seismic retrofitting.

However, if the interventions will affect invasively and if the building will resist stronger earthquakes in the future can still not be said.

**Keywords:** L’Aquila, earthquake, reconstruction, church, Basilica, Santa Maria di Collemaggio, Collemaggio, historical, heritage, preservation, seismic, retrofit, SHM
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ABBREVIATIONS

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<th>Description</th>
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<tbody>
<tr>
<td>CFRP</td>
<td>Carbon fibre reinforced polymer</td>
</tr>
<tr>
<td>CLT</td>
<td>Cross laminated timber</td>
</tr>
<tr>
<td>FRP</td>
<td>Fibre reinforced polymer</td>
</tr>
<tr>
<td>SS</td>
<td>San Silvestro</td>
</tr>
<tr>
<td>SMC</td>
<td>The Basilica of Santa Maria di Collemaggio</td>
</tr>
<tr>
<td>SPC</td>
<td>San Pietro di Coppito</td>
</tr>
<tr>
<td>SHM</td>
<td>Structural health monitoring</td>
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<tr>
<td>RC</td>
<td>Reinforced concrete</td>
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DEFINITIONS

<table>
<thead>
<tr>
<th>Definition</th>
<th>Description</th>
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<tbody>
<tr>
<td>Earthquake focus</td>
<td>The point where an earthquake originates (USGS)</td>
</tr>
<tr>
<td>Earthquake epicentre</td>
<td>The point on the earth's surface directly above the origin of an earthquake (Cambridge dictionary)</td>
</tr>
<tr>
<td>Macro element</td>
<td>A large element (Cambridge dictionary)</td>
</tr>
<tr>
<td></td>
<td>In this research the macro elements are referred to a limited part of a building, for example a belfry or an apse</td>
</tr>
<tr>
<td>Seismic retrofitting</td>
<td>The modification of an existing structure, aiming to make it more resistant to seismic activity, ground motion, or soil failure due to earthquakes (definitions.net)</td>
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1 INTRODUCTION

Seismic events can cause both extensive material damage and losses of human lives. Today, modern building technology can limit the extent of damage due to seismic activities. For historical buildings, this technology was not available by the time of construction. Hence, historical buildings are subject to significant damage when subjected to the forces generated by an earthquake. Yet, historical buildings are of great value to the local community as well as a heritage of mankind. Therefore, damaged historical buildings are often repaired and rebuilt. This study evaluates the repairing methods and how these methods correlate to the building technology developed to limit damage at subsequent earthquakes.

1.1 Background

The Earth is a complex and dynamic system that evolves continuously. As a result, the lithospheric plates are continuously moving and grinding towards each other. These movement may result in massive seismic events such as earthquakes, an unexpected violent shaking of the ground. Italy is included in a seismic area as the African plate is approaching the Eurasian plate, according to the Italian Civil Protection (u.y).

The 6th of April 2009, at 03:33 am an Mw 6.25 earthquake struck the region of Abruzzo in central Italy, close to the city L'Aquila. The epicentre was located only 5 km southwest from the city and 9 km under the ground surface. It was recorded by 58 accelerometric stations. According to Akinci, Malagnini and Sabetta (2009) that makes the earthquake one of Italy's most well recorded earthquakes with a normal fault mechanism.

According to De Matteis, Criber and Brando (2016) the earthquake caused approximately 300 deaths and over 1500 injuries. The estimation of unusable buildings after the earthquake is approximately 18000 buildings. The earthquake caused severe damages or collapses in major parts of the historic centre in the city of L'Aquila, including many historic churches.

Further the authors conclude that historical heritage is the building that suffer most damage during an earthquake. According to them, the majority of the monumental buildings that were destroyed in the 2009 L'Aquila earthquake were masonry churches. In the damage assessment after the earthquake only 344 of the 1018 investigated churches were considered safe to use.

Da Porto, Silva, Costa and Modena (2012) estimates ratio of unsafe churches in the city to 65%. Several of these suffered a total or partial collapse. Due to the high vulnerability, masonry churches are one of the building types that suffers the more damage and fatalities during seismic events. Additionally, it is one of the building types that is the most technically challenging to rebuild and protect, according to De Matteis et al. (2016).
A big part of the cultural heritage and monumental buildings are churches, according to the previous authors. L’Aquila has a richness of churches due to its historical religious importance. For the same reason the city is called the city of 99 churches and is one of the few cities outside the Vatican City with a pope. After the death of Pope Celestine V in 1294 he was buried in The Basilica Santa Maria di Collemaggio in L’Aquila, one of the most important churches of the city. The city is also hosting the jubilee La Festa della Perdonanza Celestiniana to celebrate the coronation of the pope, according to the committee of the jubilee, Comitato Perdonanza Celestiniana (2019).

After the 2009 L’Aquila earthquake several researches has been made on The Basilica of Santa Maria di Collemaggio, mostly damage assessments and vulnerability assessments. These researches have been a useful base for studying the basilica and for assessing the reconstruction of the basilica. However, some of the research shows that some interventions might have been directly destructive on the building. Cimellaro, De Stefano and Reinhorn (2011) claims that is the case with the Basilica of Santa Maria di Collemaggio. This statement underlines the need of investigating the retrofit interventions and verifying their impact on the building to avoid further damage.

1.2 Purpose

This research studies medieval churches damaged in earthquakes in L’Aquila. The research goal is to summarise previous research, evaluate and verify the results of the extensive restoration of The Basilica of Santa Maria di Collemaggio after the 2009 L’Aquila earthquake.

The study also aims at identifying the challenges of preserving cultural heritages in seismic active regions. Additionally, the research aims to identify the factors that makes these buildings relatively vulnerable for earthquakes.

1.3 Research questions

1. Why are historic churches more vulnerable to earthquakes than other buildings?
2. What are the challenges in preserving or rebuilding historical churches damaged in earthquakes?
3. Which damages occurred on The Basilica of Santa Maria di Collemaggio?
4. What building methods are used in rebuilding The Basilica of Santa Maria di Collemaggio?

1.4 Research limitations

The research will investigate the subject with focus on building technology. Therefore, no consideration will be taken towards aspects such as political, social or economic aspects.
2 METHODOLOGY

2.1 Case study

The study includes a case study of the reconstruction of The Basilica of Santa Maria di Collemaggio (SMC) in L'Aquila. The study is based on previous research and complementary sight visits. The case study is also compared with reference objects in the same city.

2.2 Reference objects

In addition to the case study two more churches have been selected as reference objects, the San Pietro di Coppito church (SPC) and the San Silvestro church (SS). The aim of the reference objects is to compare the occurred damages and the building techniques used for restoring the buildings. The churches have been selected based on the differences and similarities with the case study. All churches are placed in L'Aquila and were damaged during the 2009 L'Aquila earthquake. They vary in size and layout, but the main structure is built with local, traditional building techniques. They are built in Romanesque style with traditional sack masonry walls.

The reference churches suffered much lighter damage in compare to The Basilica of Santa Maria di Collemaggio and many of the damages that occurred matched with the most common damages on macro elements as described in figure 1.

2.2.1 San Silvestro

During the visit of the SS church very few damages were noticed and were concentrated to the belfry and main façade, and a high amount of steel ties could be seen on the upper left corner.

On the inside of the church all the damages were restored, and no cracks could bee seen on the apse.

2.2.2 San Pietro di Coppito

The SPC church experienced a collapse of the bell tower, façade cracks and damage on the roof of the apse.

The church was closed for public visitors at the time of the visit and only external damages had been restored and signs of old damages like big cracks and variations in the masonry were observed. Some anti-seismic interventions were visible as steel elements in the façade, among bolts and ties.
One of the bigger damages on the church occurred on the bell tower. The upper part had been rebuilt which was showing with a contrast between the masonry and the smooth plaster.

2.3 Sight visits

Sight visits have been made on the case study object and the two reference objects. The visits were all made in September 2019. The main goal of the visits was to study and document damages, implemented building techniques and result of the rehabilitation work.

2.4 Literature study

The literature study is composed by previous research such as scientific articles, books and information collected from educational websites provided by authorities or organisations involved in seismic building techniques. The main source has been scientific databases found via Google Scholar, such as Research gate, ScienceDirect and Scopus.

Seismic events and damages caused by earthquake has been widely researched in seismic active areas. The damage on cultural heritage has also been a hot topic in Italy, since the country is hosting a big part of the cultural building heritage, including UNESCO world heritages.

The cause of the collapse of The Basilica of Santa Maria di Collemaggio after the 2009 Earthquake has been investigated from several research groups. Among many, Cimellaro et al. (2011) and Antonacci et al. (2010) and Zucca et al. (2018) are some of the researchers that has investigated the case and many co-existing factors have been pointed out. For instance, Cimellaro et al. (2011) mean that extensive damages have lately been seen on cultural heritage churches due to the incorrectly performed retrofit inventions.
3 THEORETICAL FRAMEWORK

This chapter will cover the necessity and challenges of cultural heritage preservation and seismic retrofitting. Additionally, it will explain the vulnerability factors of historical masonry churches.

3.1 Risks and seismic building response

Marshak (2016) states that the destruction from an earthquake depends on many factors. Among them, the terrain, the distance between the urban environments and the earthquake epicentre and focus depth. Also, the building type, quality of the buildings and foundation circumstances makes a big difference in whether the forces will damage the building or not. Regarding the loss of human life another important factor is if people are being indoors or outdoors at the time of the event. Being inside a building during an earthquake is a bigger hazard then being outdoors.

According to Milani, Shehu and Valete (2017) the high vulnerability of masonry churches has been known for decades. The factors have been concluded as the lack of stiff horizontal elements enhancing the box behaviour, the geometry of the elements and the low tensile strength of the masonry, making the construction vulnerable to out-of-plane loads.

3.2 Challenges in preservation of cultural heritage

Crespi, Franchi, Giordano, Scamardo and Ronc (2016) states that preserving cultural heritage in seismic regions can be challenging for many reasons. One reason is that it can be difficult to make the adequate assessments for needed enhancement of the building. Most cultural heritage buildings have a great variation of type, material and building techniques. As a result, masonry buildings can have great variations in response to the forces induced by an earthquake. In many cases relevant parameters are lacking for a precise assessment of existing buildings. For instance, the knowledge about the inner composition of the elements are often limited, as well as extensive geometrical surveys are often lacking. In addition, many cultural heritage buildings have undergone several modification or restoration over the past years. This highly effects the mechanical characteristics and properties of the building. Therefore, the ability of making correct deductions based on assumptions and standardized methods are limited. In order to make an accurate conclusion expensive in-situ tests are often required to collect the correct data, according to the authors. Also, Milani et al. (2017) mean that traditional static schemes cannot be applied on churches due to their complexity. Therefore, the Italian Guidelines of Cultural Heritage is likely the most complex codes for cultural heritage preservation.
3.3 Seismic retrofitting on historical building

With modern technology and understanding of seismic behaviours, modern buildings can resist greater seismic events than many cultural heritage buildings. In order to strengthen the already existing buildings, seismic retrofitting can be implemented. Seismic retrofitting is an engineering field focusing on strengthening existing structures to enhance the seismic resistance, according to Brighthub Engineering (u.y).

Interventions have however shown to be destructive if not implemented correctly. Cimellaro, De Stefano and Reinhorn (2011) mean that retrofitting has been implemented incorrectly on historical masonry buildings the last 50 years, causing increased forces and therefore increased damage. One example of destructive retrofitting is exchanging the wooden roof structures and floors with heavier concrete elements. This caused both higher additional weight and deformation due to bad connections between the new and pre-existing elements.

Milani et al. (2017) also states that there is a high demand in limiting the seismic vulnerability amongst cultural heritage after the past seismic catastrophise. To do so however, they claim it requires economical means and advanced technical solutions with enough strength, high execution speed and low invasiveness. One of the materials that seems to fulfil the requirements while upgrading the seismic response is reinforced carbon strips. The authors mean that composite materials such as fibre reinforced polymers (FRP) can therefore be an option for strengthening the vulnerable macro elements. According to their study the FRP is not only shown to be low invasive, but also very effective in preventing shear and bending mechanisms, as well as ensuring the box behaviour with correct implementation. The stiffness was not affected by the retrofit actions.

3.4 The mechanical influence of typology and macro elements of churches

As earlier mentioned, churches and cathedrals often have a complex geometry which affects the structural behaviour. According to Milani et al (2016) the failure of macro elements is typical for masonry churches. According to da Porto et. al. (2012) a very effective method to interpret the behaviours of the churches during seismic events is to divide the building into macro elements and study the elements separately. In this method, each architectural component is considered a macro element. The Italian Guidelines for Cultural Heritage (2011) uses 28 different macro elements to describe the most common failures on churches, as describes in figure 1. The specific failure mechanisms is composed by the acting forces or mechanism and the specific macro element on which they occurred. Using these 28 failure mechanism simplifies the damage assessment of the churches. It also highlights the most common vulnerabilities among the churches.

Another vulnerability correlation was found by in a survey made by De Matteis et al. (2016). They identified the correlation between the typological classification and the resulting damage index. According to the authors, this suggests that the most vulnerable churches are
those classified as hybrid churches, meaning churches where significant interventions have been made over time, affecting the homogeneity. It was found that the earlier the church was built, the more homogenous it tends to be. This has a significant effect on the damage, according to the authors.

Table 1: The correlation between the typology class and the damage index

<table>
<thead>
<tr>
<th>Church typology class according to building time</th>
<th>Damage index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medieval</td>
<td>0.95</td>
</tr>
<tr>
<td>Post medieval</td>
<td>1.1</td>
</tr>
<tr>
<td>Hybrid</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Figure 1 Classification of mechanisms for religious buildings (Form A-DC 2006. source: Guidelines for Cultural Heritage 2011 G.U. no. 47). Copyright De Matteis et al. Published with permission.
4 THE BASILICA OF SANTA MARIA DI COLLEMAGGIO

In this section The Basilica of Santa Maria di Collemaggio will be investigated with previous research and on-site documentation. The Basilica of Collemaggio is one of the biggest and most important churches in L’Aquila. During the 2009 earthquake it was heavily damaged and an extensive reconstruction work was required to restore the damages. The church has been selected as a case study for investigating the challenges and technical solutions of the rehabilitation work after the earthquake.

![Illustration of The Basilica of Santa Maria di Collemaggio](image)

*Figure 2 Illustration of The Basilica of Santa Maria di Collemaggio. Copyright 2019 Tiziano Perotto. Published with permission.*

4.1 History and cultural importance

The church has a three nave Latin cross basilica layout, also known as a typical Romanesque cathedral layout with a central nave with two lateral aisles, a transept traversing the nave and the apse at the other side. The central nave is a semi open space, with big arches between the seven masonry pillars, dividing the central nave from the lateral aisles. Two bigger masonry pillars are found at the end of the nave, supporting the triumphal arch and connecting the nave with the transept. Onwards these will be referred to as the main pillars.
The Basilica of Santa Maria di Collemaggio is the largest 13th century basilica in the Abruzzo region. The church was built in the will of pope Celestine V during the years 1287-1294 (Arcidiacono, Cimellaro and Ochsendorfc, 2015). It is considered the most typical and important piece of architecture in Abruzzo. In 1902 it was also declared as a national symbol (Arcidiocesi Metropolitana di L’Aquila, 2018). The authors Crespi et al. (2016, p.1) describe it as “...one of the outstanding architectural heritage in Abruzzo Region.”

The Basilica of Santa Maria di Collemaggio is a hybrid church with Aquilian sack masonry walls. The church has an extensive history of renovations and restorations, many of these due to the history of strong earthquakes. Crespi et al. (2016) suggest that many of these interventions resulted in some of the damages in latter seismic events.

In the 17th century an extensive renovation was made to transcend the church to Baroque style, as described by Gatulli, Antonacci and Vestroni (2013). After the 1703 earthquake the walls were lowered when rebuilding after they collapsed. In 1915 an earthquake only damaged the upper corner of the façade. After, improvements were made to improve the out-of-plane-stiffness and resistance. Reinforced concrete was introduced by two spurs along the longitudinal walls, together with a concrete grind and a one stone thick brick leaf was added in the façade.

In 1960 the transept was heavily damaged in another earthquake, according to Gatulli et al. (2013). It was after that demolished and a similar one was built in its place, using reinforced concrete. In 1970 a restoration work begun with the aim to restore the original, medieval appearance of the church. The longitudinal walls that had been lowered after a previous earthquake was now extended to original height by inserting elements of reinforced concrete at the top and bottom of the masonry. The bare columns and pointing arches were revealed by removing external material. Around the year 2000 further interventions were made to improve the seismic behaviour and decrease the vulnerability on the walls. To do so, a light
weight steel bracing system was placed under the roof and injections of grout was made into the walls. The authors mean that the purpose of the grout was to enhance the mechanical characteristics and the bracing system was made such that it would minimize the transfer of forces from the pillars to the walls, which at that point was considered the more vulnerable component of the church. Cimellaro et al. (2011) mean that the interventions made during this year was particularity destructive since it significantly increased the weight, leading to increased forces during the 2009 earthquake.

4.2 Causes and damages after the 2009 earthquake

The earthquake caused extensive damages to the church including a collapse of the transept, i.e. the dome, the two main pillars with connected roofing, the barrel vaults and the triumphal arch with connected roofing. Cimellaro et al. (2011) mean that the collapse most likely was cause by crushing of the pillars. They were believed to be strong, solid pillars but during the restoration the core was found to be filled with small, calcareous stones.

Antonacci et al. (2010) states that the collapsed was caused by several concurrent factors. In addition to the poor mechanical properties of the pillars caused by poor pillar material the strong forces from the nave walls participated in causing the lability of the entire triumphal arch. However, Zucca, Franchi, Crespi, Longarini and Ronca (2018) states that an observation of the implosion mechanisms suggests that the collapse of the transept was caused by the initial collapse of the pillars. In the observation they found the occurrence of evident stiffness differences between the pillars and the façade. This affected the nave structure by causing an eccentricity between the centre of stiffness and the centre of mass. This led to an increased force from the nave structure to the pillars, causing their structural failure.

Furthermore, Alaggio, Aloisio, Antonacci and Galeota (2019) confirms significant crack patterns in masonry macro elements. In particular, the lateral walls suffered damages due to out-of-plane mechanisms such as flexural behaviours and overturning of the façade. The authors also suggest that another cause of the façade damages was the lack of proper connections among the structural sections, creating significant cracks and detachments, among which between the wall and structural pillars.
Figure 4  Damages on SMC. Recreated from From Damage and performance evaluation of masonry churches in the 2009 L’Aquila earthquake. Copyright Brandonisio et al. (2013). Published with permission.

Figure 5
a) The collapsed transept  
b) The foundation of one of the collapsed main pillars  
c) Damage of the nave pillar to the right. From The new foundation system for the transept reconstruction of The Basilica di Collemaggio. Copyright 2018 Zucca et al. Published with permission

4.3 The rehabilitation project

After the collapse 2009 a large-scale rehabilitation work was needed, among which a new foundation system was required to rebuild the basilica (Zucca et al. 2018). Essential vertical structural elements such as the collapsed main pillars needed to be rebuilt with functioning connections to the pre-existing parts of the church.

The aim of the rehabilitation work was to strengthen the global structural properties by decreasing the local vulnerabilities and thereby diminishing the already mentioned collapse mechanisms and at the same time enhancing the historical value, according to Alaggio et al. (2019).

Furthermore, Alaggio et al. (2019) states that the entire structural rehabilitation work was made by a multinational oil and gas company by name ENI, directed by Italian Universities. The work included both modern retrofitting and traditional interventions in seismic
reconstruction for restoring damages parts. Furthermore, the authors describe how a mixture of both traditional materials and innovative composite materials such as CFRP (Carbon fibre reinforced polymer) was used in the reconstruction of the Basilica.

Eni (2017) explains in a press release on their website how the company contributed in the rehabilitation work with economical means, safety expertise, and their expertise of managing complex projects as well as the implementation of advances technologies. They claim that the project of restoring the basilica was completed on time thanks to the unique partnership with the Municipality of L’Aquila, Università degli Studi del L’Aquila, Politecnico di Milano, the Sapienza University of Rome, the Archaeological, Fine Arts and Landscape Superintendence for L’Aquila and the regional Superintendence for Architectural heritage and Landscape.

### 4.4 Structural rehabilitation and technique implementation

#### 4.4.1 Nave walls

In order to strengthen the nave walls and thereby improve the wall properties an internal steel reinforcement system was applied, according to Alaggio et al. (2019). The intervention involved inserting a mesh made of high strength steel wires into the walls as well as repointing the aged mortar. Traversing steel bars was used to anchor the mesh on both sides of the masonry wall. The foundation anchoring was done by using helical bars, anchoring the wires into grouted holes in the ground. Over the central nave the mesh was instead anchored over the pillar heads.

![Figure 6](image.jpg) The mesh structure on the longitudinal wall. From the S. Maria di Collemaggio basilica: from the vulnerability assessment to the first results of SHM. Copyright 2019 Alaggio et al. Published with permission.

#### 4.4.2 Main façade

To decrease the risk of overturning of the main façade stainless steel reinforcements was inserted into the façade, e.g. steel retaining ties and twisted steel reinforcements (Alaggio et al. 2019).
4.4.3 Pillars

For strengthening the octagonally masonry pillars along the nave reinforcing steel bars was used. The helical bars were inserted horizontally in drilled core holes (Alaggio et al. 2019).

After the collapse of the main pillars they needed to be completely rebuilt. Zucca et al. (2018) mean that since the 10 meters high pillars was meant to be an important resistance for seismic action, the new pillars needed to be designed differently from the previous ones in order to handle the torsional mechanisms. At the same time, they needed to meet the requirements from the Cultural Heritage Office. Therefore, the new pillars were therefore designed as hollow columns of reinforced concrete. The authors states that the RC column was covered with stone blocks that has been recovered from the previous pillars. The new
pillar core consisted of 40 Ø23 longitudinal rebars each, circularly placed in two lanes inside the hollow concrete pillar, as displayed in figure 10.

![Figure 9](image1.png) The steel frame of the new main pillars. From The new foundation system for the transept reconstruction of The Basilica di Collemaggio. Copyright 2018 Zucca et al. Published with permission.

### 4.4.4 Roof structures and vaults

Alaggio et al (2019) describes how previous roof structures was exchanged or modified to improve the stability. Previous concrete roofs over the transept, chapels and apse were exchanged for a lighter steel frame structure. An additional CLT panel was placed on the traditional timber trusses. Retaining steel ties were implemented to prevent out-of-plane-mechanisms of the apse. Over the vaults, strips of CFRP was places in a cross-pattern to strengthen the masonry vault structure.

![Figure 10](image2.png) The steel roof frame for the apse. From the S. Maria di Collemaggio basilica: from the vulnerability assessment to the first results of SHM. Copyright 2019 Alaggio et al. Published with permission.

### 4.4.5 Modern technology

After the 2009 earthquake numerous inventions have been done to enhance the safety and understanding of the basilica. For instance, an electronical monitoring system was installed in the basilica in 2011 to investigate the cause of the collapse. The system enhances the assessment for structural and maintenance purposes (Amoroso, Gaudiosi, Tallini, Di Giulio...
and Milana (2016). It includes accelerometer, inclinometer, crack meters and thermohygrometers. The system assists by providing valuable data for the conservation status as it compares the real time monitored data with previously collected data, as well as given environmental parameters, e.g. temperature and humidity. The municipality of L’Aquila (2017) states that the system provides valuable data that can be used in a broad perspective to different stakeholders. It can be used for further research, helping to understand the behaviour of complex basilica buildings during a seismic event. It also provides important information to other concerned institutions, such as the need of safety actions by the Civil Protection.

In addition to the monitory system, a geothermically plant was built to enhance a sustainable heating system for the basilica (Eni, 2017).

Figure 11 The placement of the SHM system. From the S. Maria di Collemaggio basilica: from the vulnerability assessment to the first results of SHM. Copyright 2019 Alaggio et al. Published with permission.

There is two ways of measurement in the SHM system, according to Alaggio et al. (2019). The first is Operations Condition Monitoring, and is a continuous measuring aiming to measure the effects of the daily use of the church. The second type of measurement starts when given acceleration threshold is exceeded, for instance during the occurrence of a seismic event. A real time alarm system has two thresholds, allowing two kinds of alarm actions depending on which one is triggered. The first results in recording the seismic event and the latter additionally sends an alarm message to the administrators of the SHM system, i.e. the University staff.

With the collected data from the SHM system Alaggio et al. (2019) investigated however the interventions after the 2009 earthquake had improved the structural performance of the basilica or not. The investigation was carried out as modal analyses of the church, both as a global model and macro element model. The research confirmed an improvement in the structural performance after the interventions. The authors also highlight that numerical models might not be reliable for a complex building structure as the basilica. They also point out the importance of continuous and long-term data collection in order to beneficially make structural- and safety assessment on this building type.
5 SITE OBSERVATIONS OF THE BASILICA OF SANTA MARIA DI COLLEMAGGIO

A field observation was done in September 2019. The author visited the basilica for making observations on both internal and external work. At the time of the visit the church had been open for public access for two years, and all the restoration work was completed.

During the sight visit many interventions were not visible, such as the inner materials of the pillars and the strengthening steel systems within the walls. However, some of the interventions were visible.

5.1 The façade

On the main façade no signs of the interventions were seen, se figure 17 in the appendix. Along the nave walls small irregular patterns of different stone types could be seen, but it was not clear if these patterns were caused by the insertion of the mesh or if they were signs of previous modifications on the nave walls. See figure 18-19 in the appendix.

5.2 The transept and nave

After the total collapse of the transept major interventions were needed in the rehabilitation project. The roof structure was rebuilt together with connections to the existing connection. For instance, big joints could be seen on the walls between the nave and the transept.

Apart from filled joint on the structural pillar between the transept and the nave, the different sections have also been made clear with different wall finishes, with white plaster in the transept and masonry stone along the nave. The plaster finish hints that the transept is not a part of the original structure.
Figure 12
a) The connection between the nave (left) and the transept (right)
b) The connection between the nave (in front) and the rebuilt transept (behind).

5.3 Pillars

The main pillars had been rebuilt with the same appearance of the previous pillars, meanwhile the nave pillars had been renovated. Some signs of reconstruction were observed on the nave pillars, like a mixture of old and new stones, see figure 20-22 in the appendix. The main pillars however, showed a homogenous and polished external layer which indicated the reconstruction of the entire pillar. See figure 25 in the appendix. Some connection details to the foundation were observed, such as wooden boards instead of stone blocks.
5.4 Roof structure

The wooden beams could be seen on the roof structures, but the steel reinforcement above was not evidently visible. Neither the carbon fibre strips were visible as they were placed over the vault stones.

1.1 Modern technology

Small sensors could be seen in several places in the Basilica, such as on several pillars, the façade walls and inside the vaults. See figure 21 and 24 in the appendix.

In addition to the monitory system a high number of decor lights was seen, among spotlights and façade lightning, see figure 23 in the appendix.
Figure 14 The triumphal arch and the two main pillars. The photo is taken from the transept towards the main façade. Over the arches and over the pillars heads receptors of the monitory system are visible.

6 REFERENCE OBJECTS

This chapter covers the reference churches, San Pietro di Coppito and San Silvestro. The SS church had been restored, but the restoration work was still carried out on the SPC church by the time of the research. Therefore, it was only accessible from outside.

Both churches were built in the 14th century with traditional Aquilian sack masonry walls, and partially in free stone.
6.1 San Silvestro

6.1.1 Background

The San Silvestro church is a medium sized three-nave church with a simple layout with polygonal chapels, according to Brandonisio et al. (2013). The entire roof of the nave is made of wooden trusses, and the zone of the apse is covered by masonry cross vault.

The same authors mean that this church suffered very light damage after the 2009 earthquake, limited to crack damages in the bell tower and vertically cracks in the corner of the main façade. These damages were caused by the inaction between the bell tower and partially by overturning mechanisms of the façade.

![Figure 15 The damages of San Silvestro. From Damage and performance evaluation of masonry churches in the 2009 L'Aquila earthquake. Copyright Brandonisio et al. (2013). Published with permission.](image)

6.1.2 Observations

During the visit of the church very few damages were noticed and were concentrated to the façade. The damages had been restored and metal ties could be seen on the upper left corner of the façade, see figure 26-27 in the appendix.

On the inside of the church all the damages were restored, and no cracks could be seen on the apse, see figure 28 in the appendix.

6.2 San Pietro di Coppito

6.2.1 Background

The church is significantly smaller than SMC and has a non-traditional layout with a big nave, almost the same size of the transept. Small side aisles can be found on the right side of
the nave. After the transept there is three apses with a bell tower to the right. Brandonisio et al. (2013) state that this is one of the rare bell towers in the city.

The entire roof structure of SPC is made of wooden trusses, apart from the apses, that has masonry cross vaults.

The 2009 earthquake caused a collapse of the bell tower that in turn caused damages on the roof over the apse. A partially overturning of the main façade and façade cracks also appeared, cause by the strong out-of-plane-mechanisms.

![Figure 16](image)

*Figure 16 The damages of San Pietro di Coppito. From Damage and performance evaluation of masonry churches in the 2009 L'Aquila earthquake. Copyright Brandonisio et al. (2013). Published with permission.*

### 6.2.2 Observations

During the time of the visit the church had not been restored and it was not accessible for the public. Therefore, only external observations were made. The external damages had however been restored and signs of old damages like big cracks and variations in the masonry, see figure 29-30 in the appendix. Some of these damages might have occurred before 2009. Some anti-seismic interventions were visible as steel elements in the façade, among bolts and ties up to 40 cm long. See figure 31 in the appendix.

One of the bigger damages on the church occurred on the bell tower. The upper part had been rebuilt and was showing with a contrast between the masonry and the smooth plaster, see figure 32 in the appendix.
7 DISCUSSION

The results of the research are here further discussed as well as the building enhancement and cultural heritage preservation.

7.1 A comparison between the churches

Thanks to the involvement of the Universities in the rehabilitation project the basilica has been an eligible case study. The objects of reference, however, has been used more as a visual comparison since the data and accessibility has been limited. For that reason, it would be more useful to compare the churches when there is more documentation and research. In that way even structural analyses and inner compounds of the elements could be taken in consideration. In the comparison it is evident that SMC has already been restored meanwhile many other churches, like the reference objects, are ongoing projects or yet to be renovated. This could be seen as a confirmation of the importance of the basilica towards the community. The differences in execution was also evident, as many of the interventions were hidden on the Basilica meanwhile large bolts and steel ties were clearly visible at the reference churches.

SMC suffered from extensive damage including a total collapse of the transept. Meanwhile, the reference churches suffered from less damages during the 2009 earthquake. Even though the damage of SPC is considered severe, it was mostly concentrated to the bell tower. This could be explained from the big difference in the building spans, putting higher requirements on the structural elements. The smaller churches had smaller spans and more elements endorsing the box-behaviour, meanwhile the Basilica had magnified elements and spans, and therefore more extensive damage could also be expected.

7.2 The impact of previous interventions

That the basilica was struck by earthquake several times could be hinted from the damages seen during the site visit. For instance, significant cracks were seen on a pillar between the transept and the nave, as well as cracks in the vaults. It was not clear whether this crack occurred during the 2009 earthquake or if the damage occurred before. This kind of cracks could be signs of the previous interventions.

As earlier mentioned, cultural heritage preservation can be challenging in seismic areas. The research emphasises the challenges in rebuilding and preserving these buildings. In the case of The Basilica of Santa Maria di Collemaggio many of the damage mechanisms might have been strongly affected by the previous interventions. This correlates with the statement of Cimellaro et al. (2011) that the wrong implementation of new building materials and retrofits can be devastating on the structure. This highlights the importance of correct intervention during the restoration. It also emphasizes the importance of functioning connections between the elements, not to mention the knowledge about the pre-existing building. The two
The human losses are as previously described depending on many factors. One crucial factor is however people are being inside the building at the time of the event. As the 2009 L’Aquila earthquake struck early in the morning the church was not open to visitors. Thanks to this, the damages were only material in this specific case.

7.3 The rehabilitation of The Basilica of Santa Maria di Collemaggio

The goal of the restoration was not limited to restoring but also improving the structural properties and well as architectural enhancement. The rehabilitation work of The Basilica of Santa Maria di Collemaggio suggests that structural improvements can be done on cultural heritage buildings without damaging the cultural value of the building. This also suggests that building rehabilitation can result as an overall building enhancement, including sustainability. In the case of The Basilica of Santa Maria di Collemaggio a geothermically plant was built during the rehabilitation work, which is used for the heating system of the basilica.

During the rebuilding process the new pillars were designed such that they would have their old appearance and at the same time meet the structural requirements. In the same way other inventions were designed so the structural restoration would not outcompete the architectural restoration. Also, the structural improvements in the wall were made such that the retrofitting action would be as hidden as possible, to ensure that it wouldn’t damage the cultural heritage of the basilica.

In the research it was found that the SHM system is an efficient and low-cost tool for assessing the structural health and need of maintenance. Additionally, it helps in providing valuable data for understanding a complex building structure.

In compare to earlier performed rehabilitation work the seismic resistance of the church has been tested before and after the restoration. In that way the SHM system plays a key role in structural validation and health monitoring. In that way a long-term diagnostic on the church will be possible, as well as preventing underperforming structural elements causing structural vulnerability. A careful and correct rehabilitation work and correct maintenance also prolongs the building life expectancy. This quality endorsement promotes a more sustainable building management as well as cultural preservation.

As earlier mentioned, the rehabilitation of the church was possible thanks to the municipality of L’Aquila, several Italian Universities and Eni, a multinational oil company. According to themselves Eni acted as a sponsor of the project, as well as providing project management skills with a high safety priority. Some might question the financial interest of a sponsoring multinational oil company as Eni. As described by Eni themselves, this is an altruistic act towards the people of L’Aquila, not aiming of making business profit. The focus of the project
is to give back the important symbol of the city to its inhabitants and thereby restore the normality and social functionality of the city.

Finally, today it seems that the restoration work of SMC was successfully completed. The architectural work has been approved by the concerned superintendence and synthetic tests indicated that The Basilica of Santa Maria di Collemaggio fulfils the structural requirements. However, since earthquakes are relatively unpredictable and only synthetic tests have been made, it is not known how the building will respond to an actual, and potentially stronger earthquake.

8 CONCLUSION

For cultural heritage preservation in seismic areas seismic retrofitting and seismic assessment are two of the crucial factors in order to make the correct decision for retrofit interventions. This is particularly important for churches and other complex building structures with higher seismic vulnerability. To ensure a correct restoration and technique implementation a validation of the restoration work is crucial for verifying safety and correct implementation knowledge.

This study found that the SHM system is an efficient and low-cost tool for assessing the structural health and need of maintenance. Additionally, it helps in providing valuable data for understanding a complex building structure and more reliable models on the structural behaviour of the building. In that way the system can also enhance the validation of the effects of the interventions. For further research, the SHM could also be an efficient and useful tool for safety assessment.

Finally, it appears that the restoration work of SMC was successfully completed, but however the interventions will affect invasively and if the building will resist stronger earthquakes in the future can still not be said.

9 FUTURE RESEARCH

Further research is needed to fully understand the response of cultural heritage buildings and suitable retrofit actions. For further research monitoring systems could be an efficient and useful tool for safety assessment in seismic regions.
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APPENDIX 1: ON SITE DOCUMENTATION FROM OF SMC

In this appendix figures from the site visit of The Basilica of Santa Maria di Collemaggio are displayed.

Figure 17 The main façade of The Basilica of Santa Maria di Collemaggio
Figure 18
The façade of the holy door wall, towards the main façade

Figure 19
The façade of the holy door wall, towards the end

Figure 20
Nave pillar with drilling holes

Figure 21
Nave pillar with monitory device
Figure 22
Different stone surfaces on one of the rebuilt pillars

Figure 23
The centre nave with the nave pillars

Figure 24
One of the vaults with a crack measuring device inside the vault crack

Figure 25
The right main pillar
APPENDIX 2: ON SITE DOCUMENTATION FROM OF SS

In this appendix figures from the site visit of San Silvestro are displayed.

Figure 26  Main façade of San Silvestro  Figure 27  Details of the main façade

Figure 28  The apse of San Silvestro
APPENDIX 3: ON SITE DOCUMENTATION FROM OF SPC

In this appendix figures from the site of San Pietro di Coppito visit are displayed.

Figure 29  Main façade of San Pietro di Coppito

Figure 30  Façade damages
Figure 30  Façade steel ties

Figure 31  The rebuilt bell tower