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Damage survey and collapse mechanisms due to seismicity in Gothic Churches around Catalonia region and Mallorca

Pinar Abacilar

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ADVANCED MASTERS IN STRUCTURAL ANALYSIS OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

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UNIVERSITAT POLITÈCNICA DE CATALUNYA

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Year: 2010

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.

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Date: 21st of July of 2010

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To my parents…

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ABSTRACT

The impacts of the seismic actions in historical centres have started to be an important concern in the last decades especially following the devastating earthquakes caused damage on the cultural heritage around Europe (mainly in seismic regions like Italy, Greece and so on). These recent events which caused great amount of human, cultural heritage and economic losses made researchers pay more attention on the results of these seismic actions and how to prevent these types of damage. Analyzing the behaviour of how these phenomena occurs can answer the questions on how the damage could be prevented. These ideas made contributions on invention of the collapse mechanisms improved especially during the last decades. By the improvement of these collapse mechanisms and systemizing the possible failure types in abacuses regarding the seismic actions, it became possible to understand the real behaviour of the structures. This knowledge helps during construction processes of the structures and guides in defining the maintenance and intervention techniques along the whole life of the structure.

Although Catalonia region is not among the high seismic zones in Europe, there have been frequent earthquakes which sometimes made damage resulting with deaths and heavy decays on the structures. Analyzing the effects of these seismic actions which mainly focus on the period of the 14th century is very important in terms of defining the possible risks of these structures and avoiding further decay. Considering these aspects, the study consists of the case studies around Catalonia region with the same type of typology. The case studies generally have similar construction dates and they are major samples of their periods. The framework of the study does not only consist of analyzing the damage due to seismic actions but the whole structural problems of these cases in order to understand what further damage can occur in case of a future earthquake. By defining the damage that the structures already have, the correlation between this damage and the possible failure mechanisms regarding future possible seismic actions were set.

Cathedral of Barcelona, Santa Maria Del Mar, Santa Maria Del Pi, Cathedral of Mallorca and Cathedral of Girona were evaluated in the framework of this study. After defining the general characteristics and analyzing the damage the structures has, the possible collapse mechanisms were improved with the relation of these types of mentioned damage. As a result of the expected failure mechanisms, some interventions techniques and recommendations regarding the improvement of this study in the future were highlighted.

The importance of the historical structures is not a questionable and the seismic actions play an important role in their decay. Since the impacts of these disasters are irreversible, it is inevitable to have proper knowledge on the possible results in order to avoid losing this cultural heritage on which all people have responsibilities.

RESUMEN

Los impactos de las acciones sísmicas en centros históricos, ha comenzado a ser un tema importante es las últimas décadas, debido especialmente a los terremotos devastadores que han causado muchos daños en el patrimonio cultural en Europa (como Italia, Grecia). Estos acontecimientos recientes, los cuales han causado un gran número de pérdidas humanas, perdidas en el patrimonio cultural y sobretodo pérdidas económicas, obliga a los investigadores prestar más atención a los resultados de las acciones sísmicas de estas acciones y como prever los daños que causan. Analizando el comportamiento de cómo ocurren esos fenómenos, se puede contestar la pregunta de cómo se pueden prevenir todos esos daños. Éstas ideas contribuyeron en la intervención de la mejora de mecanismos de colapso, especialmente en las últimas décadas. Con la mejora de éstos mecanismos de colapso y la sistematización de posibles tipos de fallo respecto a las acciones sísmicas, hace posible entender el comportamiento real de éstas estructuras. Éste conocimiento ayuda y guía durante el proceso constructivo de las estructuras a definir las técnicas de mantenimiento y de intervención a lo largo de toda la vida de la estructura. Aunque la región de Catalunya, no está entre una de las zonas con alto índice sísmico de Europa, frecuentemente ha tenido terremotos los cuales algunas veces ocasionaron daños dando como resultado muertes y problemas en las estructuras de los edificios. Analizando los efectos de éstas acciones sísmicas, las cuales principalmente tuvieron lugar a lo largo del siglo XV. Es importante en éstos términos la definición de los posibles riesgos de éstas estructuras y evitar más problemas. Considerando éstos aspectos, el estudio consiste en diferentes casos aunque comparten la tipología, y que están ubicados en la región de Catalunya. Los casos de estudio, generalmente tiene una época de construcción bastante similar y también se trata de las mejores muestras en esos periodos. El marco de estudio no sólo consiste en analizar el daño producido por las acciones sísmicas, si no también todos los problemas estructurales de esos casos, a fin de entender que daños pueden ocurrir en caso de un futuro movimiento sísmico. Al definir los daños que tienen estas estructuras, la correlación entre estos daños y los posibles mecanismos de fallida, y así establecer una relación con las posibles acciones sísmicas. La Catedral de Barcelona, la Iglesia de Santa María del Mar, la Iglesia de Santa María del Pi, la Catedral de Mallorca y la Catedral de Girona, han sido evaluadas dentro de éste marco de estudio. Después de definir las características generales y analizando los daños que tienen sus estructuras actualmente, los posibles mecanismos de colapso se mejoraron en relación a estos daños mencionados. Como resultado de los esperados mecanismos de rotura, algunas intervenciones técnicas y recomendaciones esperan la mejora con éste estudio, y en el futuro tendrán relieve. La importancia de las estructuras históricas no es cuestionable ni las acciones sísmicas juegan un role importante en su decadencia. Desde los impactos de estos desastres son irreversibles, es inevitable tener un conocimiento de los posibles resultados a fin de evitar de perder éste patrimonio cultural con el cual la gente tiene responsabilidades. Estos impactos son por lo general en zonas sísmicas que no tienen una alta sismicidad causando problemas en las estructuras aún con terremotos moderados.

ÖZET

Mayorka ve Katalunya Bölgesi'ndeki Gotik Kiliselerde Hasar Analizi ve Depremden Ötürü Yıkılma Mekanizmaları

Sismik faaliyetlerin tarihi merkezlerdeki etkileri son yıllarda özellikle yıkıcı depremlerin Avrupa'daki kültürel miras üzerinde pekçok hasara neden olması ardından önemli hale gelmiştir (özellikle İtalya, Yunanistan ve benzeri sismik bölgelerde). İnsani, ekonomik ve kültürel miras kayıplarına neden olan bu son olaylar araştırmacıları sismik faaliyetlerin sonuçlarına ve bu tür hasarların önlenmesine daha fazla eğilmelerine neden olmuştur. Bu tür fenomenlerin nasıl gerçekleştiğinin analiz edilmesi bu hasarların nasıl önleneceğine yönelik soruları cevaplayabilir. Bu düşünceler özellikle son yıllarda "yıkılma mekanizmaları'nın" ortaya çıkışına katkıda bulunmuştur. Bu "yıkılma mekanizmaları'nın" geliştirilmesi ve sismik faaliyerler göz önüne alınarak olası çöküş tiplerinin düzenlenmesi sayesinde yapıların gerçek davranışını anlayabilmek mümkün olmuştur. Bu bilgi yapıların kontrüksiyon aşamasında yardımcı olmakta ve yapının tüm yaşamı boyunda bakım ile müdahale tekniklerinin belirlenmesine rehberlik etmektedir.

Katalonya bölgesi Avrupa'da yüksek sismik özellikteki bölgeler arasında olmamasına rağmen, bazen ölümler ve yapılarda ağır hasarla sonuçlanan depremler sık sık olmuştur. Bu yapıların olası risklerinin belirlenmesi ve daha fazla hasarın engellenmesi açısından genellikle 14. Yüzyılda yoğunlaşan bu sismik faaliyelerin etkilerinin analizi çok önemlidir. Bu özellikler gözönünde tutularak çalışma; Katalonya bölgesinde aynı tipolojiye sahip örnek çalışmaları içermektedir. Bu örnek çalışmalar genellikle benzer yapım tarihlerine sahiptir ve yapıldıkları dönemin öncü örnekleridir. Çalışmanın çerçevesi yalnızca sismik faaliyetler nedeniyle gerçekleşmiş hasarların analizini değil ayrıca gelecekte olası bir deprem durumunda hangi tür hasarların oluşabileceğini anlamak için bu örneklerin tüm yapısal sorunlarını da içermektedir. Bu yapıların sahip oldukları hasarların belirlenmesiyle bu hasarlar ile gelecekteki sismik faaliyetler durumunda olası "yıkılma mekanizmaları" arasında bağıntı kurulmuştur.

Barselona Katedrali, Santa Maria Del Mar, Santa Maria Del Pi, Mayorka Katedrali ve Girona Katedrali bu çalışma kapsamında değerlendirilmiştir. Yapıların sahip olduğu genel karakteristikler ve hasarlar analiz edildikten sonra bahsedilen hasarlarla ilişkili olarak olası yıkılma mekanizmaları geliştirilmiştir. Beklenen yıkılma mekanizmalarının bir sonucu olarak bazı müdahale teknikleri ve bu çalışmanın gelecekte geliştirilmesi adına önerilerin altı çizilmiştir.

Tarihi yapıların önemi sorgulanamaz ve sismik faaliyetlerin bu yapıların hasar görmesinde önemli etkileri bulunmaktadır. Bu tür afetlerin etkilerinin geri dönüşümü olmadığından, üzerinde tüm insanların sorumluluğunun bulunduğu kültürel mirasın kaybolmasını engellemek amacıyla bu olayların olası sonuçları üzerine en düzgün şekilde bilgi sahibi olmak kaçınılmazdır.

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1. INTRODUCTION

The value of the historical constructions is a globally accepted fact and conservation of these structures is among the missions of people who work in this field. Apart from human based reasons which cause damage on the cultural heritage and historical monuments, the natural disasters are among the most destructive events both threatening the human life and the structures. Throughout the history, the historical centres have suffered from the earthquakes many times. Better understanding on the impacts of the earthquakes is very important in terms of preparedness of the structures for the future disasters.

There are various components that have influences on understanding the real behaviour of the structures. Some of these components can be summarized as the reliable historical information, geometrical and material characteristics, soil types, structural modifications and previous alterations and so on. These components should be evaluated together in order to help in interpreting how the structure can behave under lateral loads following a seismic action.

1.1 Goals and Objectives of the Study

The study is composed of general and specific objectives. The *general objectives* that dominate the total structure of the study are;

- To define the existing damage related to the past earthquakes and with the recognition of all the existing damage, foreseeing the effects of future earthquakes;
- To highlight the importance of the seismicity not only in high seismic zones but also zones with moderate seismicity.

The *specific objectives* of the study are as follows;

- To show the damage patterns and identify the possible reasons of the most common damage visible on the historical structures;
- To carry out a comparative study regarding damage types and reasons in the structures belong to same periods and constructed in or around the same region;
- To analyze the data obtained from the historical research and visual inspection and compare the same types of structures in terms of level of the damage;
- To relate the existing damage with the effects of the past earthquakes;
- To draw a general frame work on the most possible collapse mechanisms due to earthquake using the historical information and previous researches;
- To identify the most possible collapse mechanisms due to earthquake for the case studies;
- To identify the vulnerability of the historical structures using the case studies;

- To define the general recommendations and interventions to avoid possible damage in the structures in terms of seismic actions;
- To construct a base for future studies regarding the structural analysis of these buildings;

The decisions and evaluations are based on the visual inspection and the historical information obtained by the previous works on the case studies. To highlight the importance of the damage on understanding the structural behaviour is among the objectives.

1.2 Contents of the Document

The study starts with the general information about the seismic facts and the history of the Catalonia region. The fault lines under which Catalonia is influenced, the historical earthquakes that caused damage around the region were evaluated. The earthquakes occurred around the centuries when the case studies detailed in this study were constructed were detailed such as the earthquake of 1373, the earthquake series of 1427, one of the most mentioned historical earthquake of 1428 and finally the earthquake of 1448. The impacts of these historical earthquakes on the structures that compose the content of this study were also added in this chapter.

After the second part consisting the general information about seismicity in Catalonia, the chapter describing the detailed information on the case studies was explained. Santa Maria Del mar, Santa Maria Del Pi, Barcelona Cathedral, Girona Cathedral and Mallorca Cathedral are the samples that constitute the main body of this work. Each case study starts with the general information about the structure, explains the historical information obtained from books, internet and previous studies and researches. The previous restoration works, the processes the structures have undergone and construction stages were explained depending on the information obtained. For each case, the damage survey depending on the visual inspection and photographic documentation were undertaken. The most important structural damage and problems were mapped for the cathedrals. The possible reasons of these types of damage were analyzed in a comparative way.

The fourth part is dedicated into the general information about what failure mechanism and vulnerability means. The improvement of the concept of collapse mechanisms and the definitions of the most common mechanisms were explained in detail. The last part of this chapter consists of the special studies on the collapse mechanisms and abacuses of the specific structures – churches.

After giving information on why and how the collapse mechanisms could occur, the evaluation of each case was done. Considering the damage, the most possible collapse mechanisms were defined. After defining the failure types, basic modelling of these mechanisms was implemented in each cathedral. Barcelona and Girona Cathedrals were not used for modelling since the damage patterns don’t compromise with any collapse possibility. These examples were compared with the other cathedrals in order to define the differences in terms of structural point of view.

The last chapter focused on the interpretation of the expected mechanisms and recommendations about what can be done in order to avoid these types of failures.

2. SEISMICITY IN CATALONIA

2.1 Introduction

Although Catalonia is considered as a low to moderate seismic area, it has been under the influence of various earthquakes that caused some destruction in history especially during 14th and 15th centuries.

Catalonia is located in the northeast part of Iberian part; the northern part of the plate was defined and limited by Pyrenean range. This zone is divided into three units; western, central and eastern Pyrenees.

Catalonia is under the influence of the seismic network of Eastern Pyrenees. The instrumental data shows low seismicity with magnitudes up to 4.5 in a period of about 50 years and the historical seismicity reports the occurrence of two intensity VI-VIII earthquakes that caused damage in the zone in a period of 1000 years (Masana, 1996).

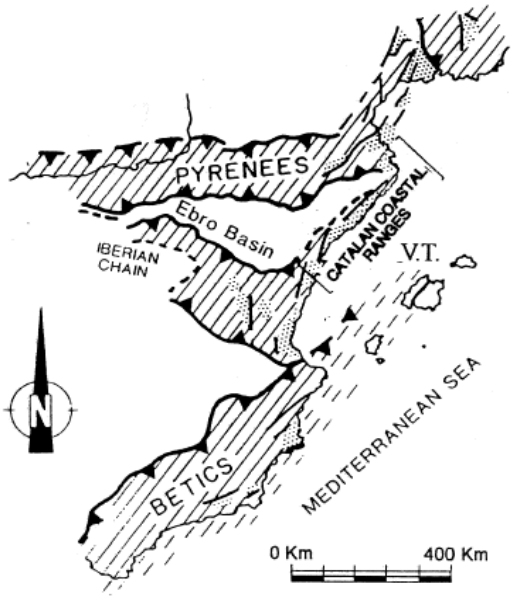


Figure 1 – Map of Iberian Peninsula depicting Catalan Coastal Ranges (Masana, 1996)

2.2 Geological Information of Catalonia

The works on the preparation of the catalogues about the historical earthquakes made it possible to have detailed information on the seismic history of the region. It is possible to find comprehensive information especially based on the earthquakes that happened around XIV and XV centuries.

The work of Fontser`e and Iglesi´es (1971) constitutes the first reliable compilation of seismic activity in Catalonia. Their study provides the basis for any study of historical seismicity in Catalonia (Lambert, J., Olivera, C., Redondo,E., Riera-Melis, A. and Roca, A. 2008). Thanks to these studies, some authors and researchers like Cadiot (1979) and Banda and Correig (1984) focused on the specific earthquakes.

The first mentioned strong ground motion is the one occurred in the year of 1373. The epicentre of the earthquake is Central Pyrenees with an intensity of VII-IX (Mercali Scale). *Next, a long sequence of earthquakes with epicentral intensities up to VIII occurred in the north eastern region in 1427 following a NW – SE oriented band that corresponds to a known fault system. The 2nd of February, 1428, an earthquake of epicentral intensity IX, the largest event ever known in the region in historical times, occurred in the Eastern Pyrenees; a few documents mention that in July–August 1428 some aftershocks still took place but their vague descriptions do not allow to individualize or to quantify none of these aftershocks. Twenty years later, a smaller earthquake (I_0 = VII–VIII) occurred in 1448 at a distance of about 34 km away (N-NE) from the town of Barcelona* (Lambert, J., Olivera, C., Redondo,E., Riera-Melis, A. and Roca, A. 2008).

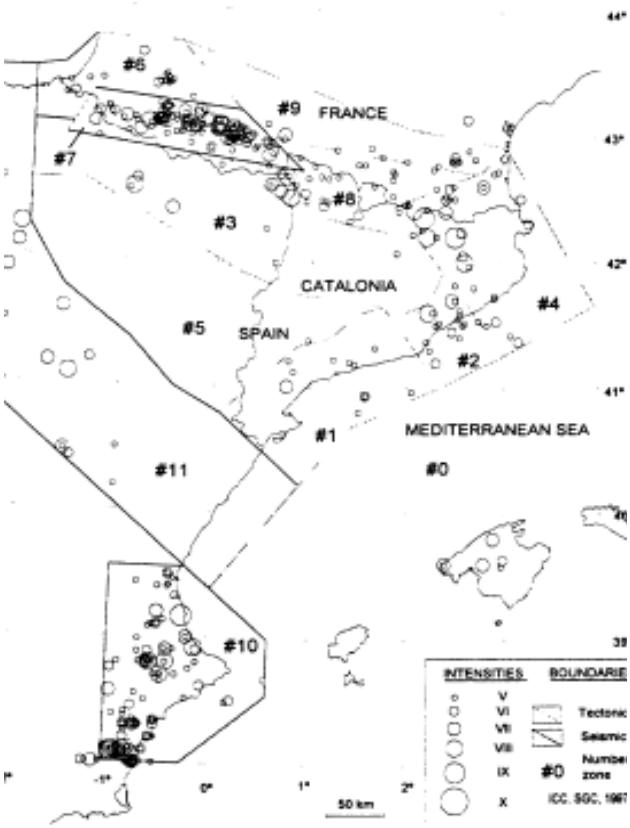


Figure 2 – Seismic Zonation of Catalonia (Fleta, J., Goula, X., Roca, A., Secanell, R., Susagna, T. 2000)

The relation of the soil type and surface geology with the seismic intensity is very important for zoning of an area in terms of seismicity. The other studies regarding on the geotechnical characterization for the regional assessment of seismic risk in Catalonia made it possible to categorize the soil types of the region. The results showed that the area is composed of four major types of soil types considering the simple surface geology characteristics.

The investigations showed the following results;

(R): Rocky, unweathered rock and hard; shear wave velocity higher than 800 m/s; very good mechanical characteristics. Fresh rock.

(A): Granular. Compact material; and cohesive hard clay or marl: shear wave velocity between 800-400 m/s: good to very good mechanical characteristics. Compact sands and gravels, highly consolidated stiff clays.

(B): Weathered of fractured rock: granular" semi-compact material: cohesive" semi-compact material and soft chalk: shear wave velocity between 400-150 m/s: average mechanical characteristics. Relatively compact sands and gravels mean stiff marls and clays.

(C): Granular" non-cohesive material; cohesive soft clay. Mud and weathered chalk: shear wave velocity lesser than 150 m/s: poor mechanical characteristics. Soft sands or gravels and clays" altered gypsum and mud (Estruch, I., Fleta, J. and Goula, X. 2003).

Cities	R (%)	A (%)	B (%)	C (%)	AREA Km2
Badalona	2.7	3.1	53.8	40.3	10.41
Barcelona	18.6	4.2	47.4	29.7	100.5
Girona	4.6	0.0	92.9	2.5	4.49
Hospitalet	0.0	2.8	33.9	63.3	11.94
Lleida	0.0	75.0	7.2	17.7	10.06
Mataró	33.3	44.7	0.0	22.0	6.54
Olot	64.3	17.3	10.3	8.1	4.75
Sabadell	2.9	82.1	2.1	12.9	15.87
Sta.Coloma	41.9	1.7	40.3	16.1	4.25
Tarragona	5.3	0.0	48.9	45.8	4.81
Terrassa	32.9	46.8	0.0	20.4	17.68
Vielha	35.4	0.0	0.0	64.6	1.87

Table 1 – The distribution of the soil types in percentages in Catalan Cities (Estruch, I., Fleta, J. and Goula, X. 2003)

The table above shows the percentages of the soil types of in the Catalan cities. The results of the study indicate that the majority of the soil type is in type B which is fractured rock in the widest city of Catalonia, Barcelona. The important outcome is that 29.7 percent of the soil is in C type which is the granular type composed of the soft clay. Although the area is not in a high seismic zone, the percentage of the soft soil is not very small in the overall results. The general soil condition is more balanced in Girona comparing to Barcelona. The majority of the soil type is in B class (fractured rock).

2.3 Historical Seismic Events in Catalonia

As it has been indicated in the beginning of the chapter, Catalonia is a low to moderate seismic region but still it has encountered seismic activities which caused some destruction throughout its history.

The major earthquakes that have still been the main source of the studies and are still being evaluated to define the possible results of the seismicity in Catalonia will be summarized within the framework of this part of the work.

In the studies of IGC (Institut Geologic de Catalunya), 1373 (Ribagorça) and 1427-1428 earthquakes (at la Selva, la Garrotxa, la Cerdanya and el Ripollès areas) are mentioned as the two well documented damaging earthquakes in late medieval periods (www.igc.cat).

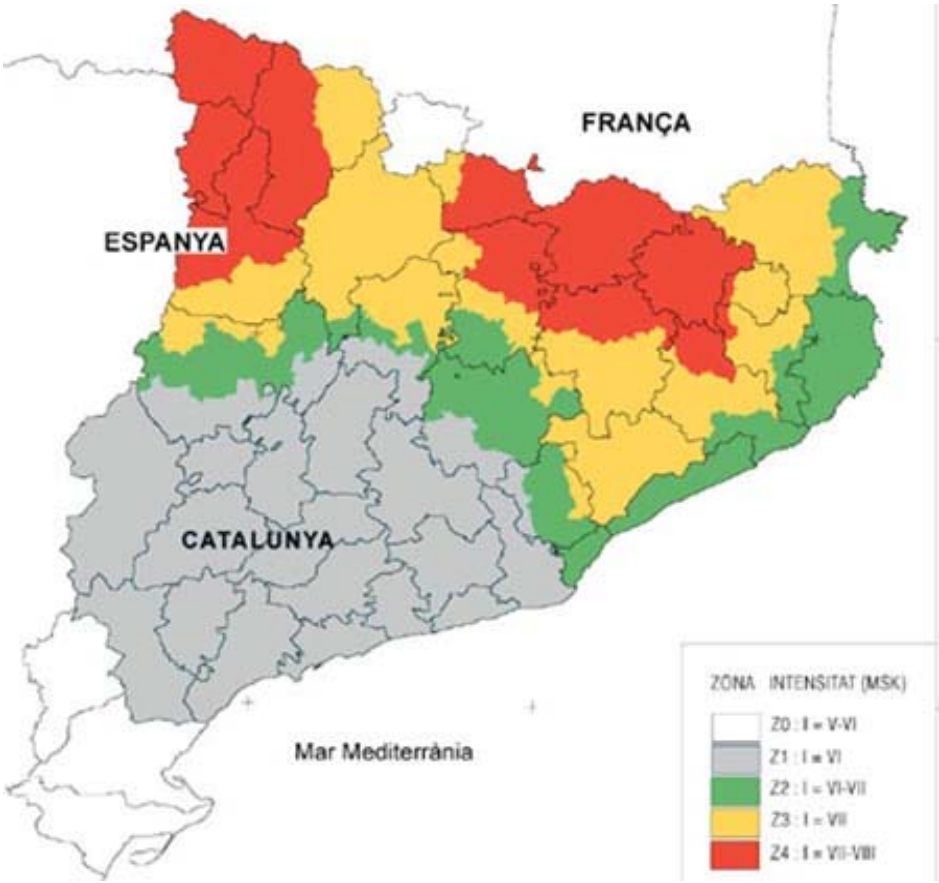


Figure 3 – Seismic Vulnerability of Catalonia Region (www.igc.cat)

Before giving more detailed information about these major earthquakes, it is important to give a list of the recorded earthquakes that happened in Catalonia between the 13th and the beginning of 20th centuries. The intensities are indicated in Mercali scale.

Date	The area effected	Intensity (Mercali Scale)
1224- 16 November	BARCELONA- GIRONA	IV
1370- 21 February	BARCELONA	VI
1373- 21 February	CATALONIA	VIII
1373- 2 March	BARCELONA	VIII

1373- 3 March	BARCELONA	VII
1373- 8 March	BARCELONA	IV
1373- 11 March	CATALONIA	-
1373- 3 May	BARCELONA	V
1373- 22 May	BARCELONA	II
1373- 23 May	BARCELONA	II
1373- 24 May	CATALONIA	II
1376- 1 February	CATALONIA	V
1396- 2 May	GIRONA	-
1397- 28 May	GIRONA	IV
1404- 2 March	-	VIII
1410- 30 March	BARCELONA	VIII
1410- 27 July	GIRONA	-
1410- 5 August	BARCELONA	II
1410- 25 December	BARCELONA	-
1424- 4 March	CATALONIA	-
1425- 9 February	BARCELONA	-
1426- 3 March	CATALONIA	VII
1427- 1 March	CATALONIA	-
1427- 2 March	BARCELONA-GIRONA	IV
1427- 4 March	BARCELONA	-
1427- 14 March	BARCELONA	VI
1427- 19 March	BARCELONA	V
1427- 21 March	BARCELONA	V
1427- 22 March	BARCELONA	V
1427- 22 April	BARCELONA	V
1428- 2 February	BARCELONA	VIII-IX
1431- 24 April	CATALONIA	VI
1431- 24 July	CATALONIA	-
1435- 6 November	BARCELONA	-
1437- 6 December	BARCELONA	IV
1436- 6 November	CATALONIA	-
1439- 1 August	BARCELONA	-
1443- 24 March	BARCELONA	-
1448- 11 October	BARCELONA	-
1458- 26 June	BARCELONA	-
1464- 28 November	BARCELONA	-

1466- 9/10 February	CATALONIA	II
1471- 18 December	BARCELONA	-
1511- 23 February	BARCELONA	IV
1511- 23 December	BARCELONA	III
1525- 4 July	BARCELONA	VI
1525- 6 July	BARCELONA	II
1551- 23/25 December	CATALONIA	-
1572- 27 January	BARCELONA	II
1605- 20/21 December	BARCELONA	VI
1605- 25 December	BARCELONA	-
1628- 5 April	BARCELONA	V
1633- 2 June	BARCELONA	-
1660- 18/19/26 March	Palma de MALLORCA	VII
1660- 21 June	BARCELONA	VIII
1703- 6 January	BARCELONA	IV
1721- 24 March	Selva de MALLORCA	VII
1749- 22 February	MALLORCA	-
1753- 4 November	GIRONA	II
1763- 2 July	Santa Maria de MALLORCA	III
1771- 3 October	BARCELONA	V
1771- 7 November	BARCELONA	V
1773- 7/8 December	Palma de MALLORCA	V-VI
1783- 14 March	Inca MALLORCA	III
1798- 2 February	GIRONA	-
1835- 16 June	Palma de MALLORCA	V
1835- 14 October	MALLORCA	VIII
1852- 31 September	MALLORCA	V
1853- 6 January	BARCELONA-GIRONA	VII
1853- 27 January	BARCELONA	-
1854- 26 July	BARCELONA	VII
1854- 6 December	BARCELONA	I
1857- 7 August	BARCELONA	-
1859- 18/19 March	Palma de MALLORCA	-
1868- 11 May	BARCELONA	III
1870- 15 January	BARCELONA	IV
1873- 26 November	BARCELONA	IV
1875- 7 June	BARCELONA	VI

1875- 26 November	BARCELONA	-
1876- July	Palma de MALLORCA	-
1878- 10 August	BARCELONA	II
1880-1881	MALLORCA	-
1887- 6 May	Palma de MALLORCA	III
1887- 7/8 September	Palma de MALLORCA	IV
1901- 27 or 30 December	GIRONA	IV
1902- 22 May	BARCELONA	II
1903- 13 July	BARCELONA	II

Table 2 – The records on the historical earthquakes in Catalonia between 13th and 20th centuries (Recopilacid de Dades Sismiques de les Terres Catalanes entre 1100 i. 1906)

2.3.1 Seismic series of 1373

The one of the first proper records regarding the ancient earthquakes start with the series of seismic events happened in 1373. In that year, there is 10 seismic records starting from 21, february and going on until 24, May with the intensities changing in the range of II-VIII. These seismic events especially had an influence on Barcelona and Catalonia in general. The one which is mentioned the most in the reports is the seismic event occurred on 3rd of March in 1373. The epicentre of this event is Ribagorça.

These seismic series are important since they give a start on defining and evaluating the seismic hazard in the region. Some contradictions were under discussion regarding these seismic actions. The first mistake was about the epicentre of these events. Although it was thought that the epicentre was Olot where is located in the southern slope of the Eastern Pyrenees, the final conclusion was that it actually was in 200 km to the west in the county of Ribagorça (southern slope of the Central Pyrenees).). *On the other hand, two earthquakes catalogued with intensities IX and VIII were considered to be false, suggesting the occurrence of one large earthquake with an epicentral intensity of VIII-IX (MSK)(* Lambert, J., Olivera, C., Redondo,E., Riera-Melis, A. and Roca, A. 2008)

2.3.2 Seismic series of 1427

Although the seismic event that occurred in 1428 was greater than the one in 1427, it is important to highlight that there are eight recorded seismic events in that year. The seismic actions start from the date of 1 March and last on 22 April. Some references consider the seismic occurrences last until the end of May.

The most information regarding the level of damage it has caused can be available on the events occurred on 19th March and 15th May in 1427. The epicentre of the first event is believed to be in Amer and the following is in Olot and Vall d'en Bas.

The influences on Barcelona was also very visible and the area was shaken during almost two months' period with series of earthquakes changing in the range of IV-VI mainly with intensities of V.

The historical information reached up to now indicates that all the buildings in Olot region was destroyed in this earthquake.

2.3.3 2 February, 1428

A heavy earthquake with an intensity of VIII hit the area of Barcelona on the date of 2, February in 1428. The earthquake caused destruction in a high degree in Catalonia and in France. It is recorded that this event resulted with a lot of losses regarding the people.
The epicentre of the earthquake is Camprodon and Puigcerda.
The earthquake was felt over a wide area from Pryenees to Barcelona with a very wide radius and the effects are indicated as very devastating causing over a thousand of people to die.

2.3.4 25 May, 1448

This earthquake is among the most mentioned medieval seismic events which are recorded that had an impact on Catalonia.
The earthquake had the biggest impact in Barcelona and although there is not a certain agreement on the intensity of the earthquakes, there are several studies regarding the definition and general information about this seismic action. The overall results of these studies about this earthquake can be summarized as in the following;

General geographical coordinates	Sources	Description of the earthquake	Time- Duration	Global evaluation and/or description of the effects
In Barcelona and in all the Principality of Catalonia	*Dietari*	Very big	After midnight on Friday 24th, as it changed to Saturday, it was between 12 p.m. and 1 a.m.	It caused enormous damage to a great number of possessions, both in the city of Barcelona and outside it; it caused a lot of damage all over Principality, causing many deaths and destroying a great deal of property
In the city of Barcelona and in all the Principality of Catalonia	*Jornades*	Very big	Around midnight	It caused great damage to a lot of possessions, both in the city of Barcelona and outside it, it demolished a lot of *masies* (farmhouses) and it caused great damage all over Catalonia
In the city of Perpinya and in all the land of the Rosse1l6	*Livre Vert*	Very big	It was during the first hour after midnight- It lasted the length of one Lord's Prayer and an Ave Maria, or even more	People were very afraid, not without reason
They are not indicated; it is only specified that in the city of Vic there was no damage or death	*Acords*	Terrifying, very big	Around midnight	It demolished a lot of hamlets, houses, monasteries and other churches, and when they fell down a lot of people died; it knocked down a lot of churches, houses and *mas os* (farmhouses), and many people died in them

In the city of Girona, in Barcelona and in the Valles	*Revista*	Very big	Between 12 p.m. and 1 a.m.	More than 108 people died under the ruins of the demolished houses

Table 3 – The comparison of the information of different sources about 1448 earthquake

2.4 Historical Seismic Events in Mallorca

The seismicity of the biggest Balearic Island is low. The studies show that the instrumental records indicated that the current seismicity is superficial (smaller than 10 km depth) and low in magnitude (Mb smaller than 4) (Carrasco, P., Goy, J., Hernandez, G., Zazo, C. and Silva, P.G.2001).

Mallorca is the biggest segment that emerged from the mainland constituting the external zones of Betic Cordillera (east Spain).

The Spanish Seismic data bank shows only 21 earthquakes between the years of 1654 to 1996. Unfortunately, there is no information regarding the previous periods than 1654. *Only three major seismic events (intensity of VII) have been reported: in 1660, 1721 and 1851. The last event, known as the 1851 Palma earthquake (VIII MSK), can be described as a seismic sequence of at least 7 months' duration, initiated by the main shock on 15 May 1851, terminating on 12 December 1851 as documented by contemporary reports (www.igc.cat).*

The biggest seismic event happened in 1851 and lasted along seven months. The previous moderate earthquakes known before this date is in between 1827 and 1835 before 16 and 24 years before the main earthquake. The maximum intensities were VI at Sineu and Palma.

The ground motion in the main shock in 1851 was VII-VIII. It was felt over a polygonal area. Sóller, Valldemossa and Banyalbu far in the Northwest and Palma, S'Arenal and Sencelles in the Southeast define an area approximately 497 km^2 effected by the seismic event. The shaking was felt mostly along the coast line causing moderate damage to buildings. Many towers and the cupolas of the churches collapsed in Palma area including the western wall of the Cathedral (www.igc.cat)

13 earthquakes were felt after the main shock and only after twenty days of the earthquake, an aftershock with an intensity of VI destroyed most of the previously damaged buildings causing the total collapse of Sant Marçal church at Marratxí and moderate ground failures (Pujó, 1851).

Date	Time	Description	Intensity (MSK)
1851-05-15	01:47:00	Main shock (see text): severe damage to buildings and moderate ground collapses	VIII (IGN)
1851-05-15	05:00:00	Noticeably felt, strong seismic tremor	> VI
1851-05-18	20:30:00	Only felt by some people	III-II
1851-05-21	14:30:00	Only felt, seismic tremor.	III-II
1851-05-22	04:00:00	Noticeably, panic at Palma	V-IV
1851-06-07	18:00:00	Panic at Palma and total destruction of St. Marçal church at Marratxí (Sa Cabaneta)	VI (IGN)
1851-06-28	00:00:00	Light shaking	< III
1851-08-28	00:00:00	Only felt by some people	
1851-08-31	00:00:00	Only felt by some people	
1851-09-16	00:00:00	Only felt by some people	
1851-09-17	00:00:00	Only felt by some people	
1851-09-28	00:00:00	Only felt by some people	
1851-11-09	00:00:00	Only felt by some people	
1851-12-22	00:00:00	Only felt by some people	
		Only felt by some people	
1852-05-11	00:00:00	Light shaking felt at Palma bay	III
1852-06-04	00:00:00	Only felt by some people	II-III
1852-06-10	00:00:00	Noticeably felt	III
1852-08-31	00:00:00	Strong shaking at Palma. Panic. Most people leave houses	V (IGN)

Table 4 – The records on the earthquake series in 1851- 1852 (Carrasco, P., Goy, J., Hernandez, G., Zazo, C. and Silva, P.G.2001)

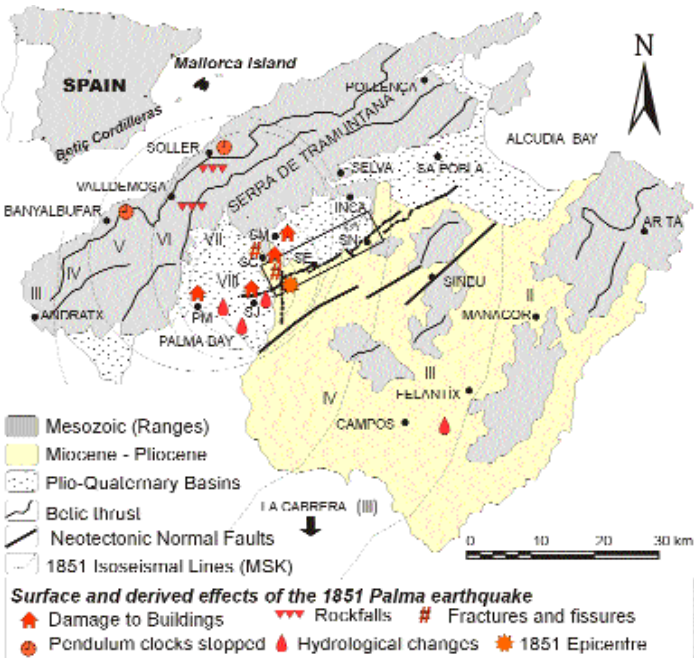


Figure 4 – Geological information on Mallorca based on the relation with the earthquake of 1851 (www.igc.cat)

2.5 Damage on Historical Structures due to Seismic Actions

Santa Maria Del Mar

- 1373 and 1428;

The collapse of rose window and upper part of the tower are among the main damage that the structure has encountered.

The references mention about the death of 25 people due to the collapse of the rose window during the earthquake in 1428. The restoration of this part was done in 1459.

The results of the earthquake took place in 1428 can be evaluated together with the results of the one in 1427. These earthquakes are among the most mentioned and important ones which have an important impact on Barcelona in general.

The previous one occurred in 1373 occurred with an intensity of VII-IX in the epicentre Pyrenees. This earthquake caused the collapse of the upper part of the Eastern tower which was only been able to be restored in the 20th century.

Santa Maria Del Pi

- 1428;

The seismic action occurred in 1428 had an influence on the damage of Santa Maria Del Pi. Even though it is difficult to define which types of damage are correlated with this earthquake since the previous seismic series started in the year of 1427, it is known that the structure was affected by these occurrences.

Barcelona Cathedral

There is not a known damage due to any seismic actions in the structure throughout its history. Although the structure is located in a very close proximity to Santa Maria Del Mar and Santa Maria Del Pi, the results of the historical earthquakes are not similar with the other two cathedrals in Barcelona Cathedral.

Girona Cathedral

Although the construction was not able to be fully completed even until 18th century, the main parts like the cloister and the main body of the cathedral were already raised until the 12th century. The front façade and the tower were still half completed during the earthquake series that influenced Catalonia region around the 14th and 15th century. There is not any known damage due to any of these seismic actions.

Mallorca Cathedral

- 1660 and 1851;

Mallorca Cathedral has encountered some problems due to seismic actions in history. Some of these effects have successfully been reported. The first known influence was due to the earthquake occurred in 1660. The collapse of the two arcs close to the front façade occurred as a result of this earthquake. The leaning of the front façade was correlated with this seismic action in some reports prepared in these periods.

Another earthquake with an intensity of VI caused the collapse of the parts which were already deteriorated on the façade. The date of this seismic event is 1851.

But the accessed information about these earthquakes is sometimes confusing since some of the reports mention that this damage already existed before the seismic events.

3. FAILURE MECHANISMS AND VULNERABILITY

3.1 Introduction

Analyzing of the results of the seismic events has become very important throughout Europe especially in the countries which are located in high seismic zones. The great losses that thread the human life, the cultural heritage of the countries causing economic loss in high amounts are among the heavy costs of the earthquakes. In order to avoid these types of damage, it is very important to understand the real behaviour of the structures under seismic actions. This process gets harder especially when the concern is historical structures whose typologies are usually more complex, the construction techniques are not in use most of the time or they have already been damaged due to various natural disasters for over decades or even centuries. The definition of the failure mechanisms has started to be used commonly in the last decades. The origin why the failure mechanisms were started to be created was the need to simplify the complexity of the structural behaviour and deal with the possible collapses in the structures. The historical information, analyzing the structural damage carefully and comparing these with already defined collapse mechanisms are important processes in order to understand how a structure would fail.

Figure 5 – Collapse of exterior wall of S.Maria Assunta following an earthquake

Figure 6 – The cracks due to earthquake in the interior facades of S.Maria Assunta (Lagomarsino, S. 2006)

The previous studies showed that a relevant survey in order to inspect the internal composition of the masonry is the first process. The investigation and the classification with reference both to their constructive characteristics and to chemical, physical and mechanical properties are made in order to accomplish the first process with the help of onsite and laboratory tests. The qualitative identification of the damage process is strongly believed as a critical phase. Data on cracks, deformations, local or overall collapses are used to identify the damage process which would lead to mechanical model in

the latter steps. To this end a set of the most frequent collapse mechanisms are elaborated and clarified by means of an abacus of outlines. The final aim of the analysis would be the proposal of mechanical models able to interpret and forecast the observed damage modes (Binda, L., Gambarotta, L., Lagomarsino, S. and Modena, C.)

Figure 7 – Collapse of the upper part of the facade in S.Stefano Church in Umbria

Figure 8 – Damage on the upper part of the facade in S.Silvestro, Sellano (Lagomarsino, S. 2006)

Finally it is important to define basic things in order to analyze the seismic response of the structures. These hints can be summarized as the following;

- A proper knowledge of the traditional constructive techniques;
- The identification of the damage and collapse mechanisms activated by the earthquake;
- The check of the effectiveness of the most applied retrofitting techniques (Lagomarsino, S. 2006).

Figure 9 – Damage on the Bell Towers (S.Maria di Constantinopoli, S.Giovanni Battista, Cerreto di Spoleto (G. Augusti, G., Ciampoli, M. and Giovenale, P. 2005)

3.2 General Failure Mechanisms

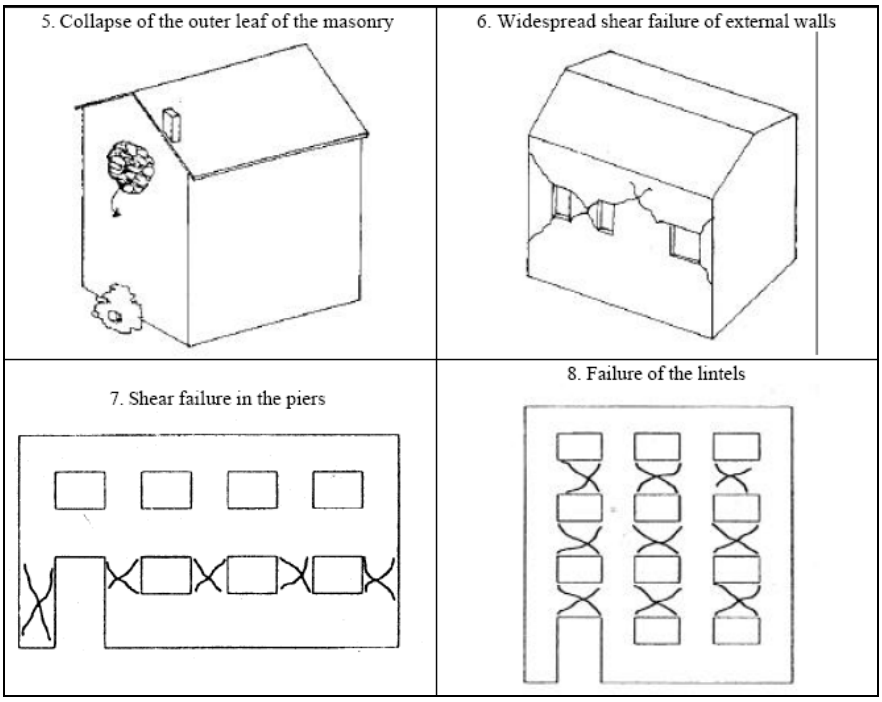
After the seismic events that demonstrated the need of the structural behaviour models, a wide classification was made considering the aspects that were highlighted above such as the morphology,

historical information and damage survey. Once these abacus collapse mechanism were formulated, it was widened through the consideration of different type of structures like churches or residential units. In order to simplify the complex buildings especially like churches, macroelements are considered for the collapse mechanisms.

Marcoelement means the portion of the building with homogeneous constructive characteristics and structural behaviour. It can coincide with a portion identifiable even under the architectural and functional point of view.

The macroelements interact each other's underlining lesions in correspondence of the contact zone (influence band). The influence bands are determined by lacking or missing connections or by damage effects (lesions).(Msc-SAHC SA3 Lecture Notes 2009-2010)

These possible macroelements for the churches can be like the bell tower, front facade, cloisters and so on.



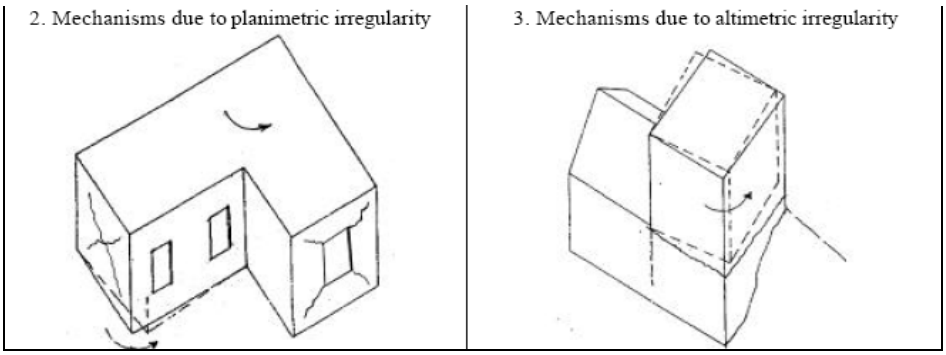


Figure 10 – Sketches that are in the abacus of the considered collapse mechanisms for the buildings (Msc-SAHC SA3 Lecture Notes 2009-2010)

After defining the macroelements, evaluation of the collapse probability of each of them and of the whole building for each macroelement is done. *First, the macroelements that define the structural organism of the building and characterize its dynamic response are individuated; then: the most significant collapse mechanisms (i) for each macroelement (j) are recognized; by means of limit analysis, nominal values of the seismic coefficients Cij (i.e. the ratios ag/g between ground and gravity accelerations corresponding to the activation of mechanism i in macroelement j), are obtained; the probability density functions fCij of the seismic coefficients Cij are defined: in the following application, each Cij has been assumed to be normally distributed, with mean value E[Cij] equal to the value calculated in step, and coefficient of variation (c.o.v.) estimated on the basis of the number and significance of the geometrical and mechanical parameters considered in step b) and of their uncertainties (G. Augusti, G., Ciampoli, M. and Giovenale, P. 2005);*

The following damage mechanisms are considered for the single cell:

1. Overturning of the front walls
2. Local overturning in the upper part of external walls
3. Overturning of a corner;
4. Hammering of beams or sliding between r.c. tie beams and the masonry;
5. Collapse of the outer leaf of the masonry;
6. Widespread shear failure of external walls;
7. Shear failure in the piers (weak floor mechanism);
8. Failure of the lintels (global overturning mechanism of the piers);
9. Cracks in presence of discontinuity in the masonry (closed openings, chimney pipes);
10. Shear failure mechanisms in the internal walls;
11. Failure of architraves in the internal walls;
12. Cracks and failure mechanisms in masonry vaults;
13. Damage and collapse of the staircases;
14. Unthreading of the beams and other damage in the floors;
15. Damage in the roof covering;

16. Overturning of standing out or overhang elements (balcony, eaves, chimney pot).

Once the survey of all the cells has been carried out, if a complex building aggregate is considered, the interaction mechanisms between the adjacent cells must be analysed, consisting of:

1. Hammering between adjoining buildings;

2. Mechanisms due to planimetric irregularity;

3. Mechanisms due to altimetric irregularity;

4. Hammering due to the offset between the levels of adjacent floors. (Msc-SAHC SA3 Lecture Notes 2009-2010)

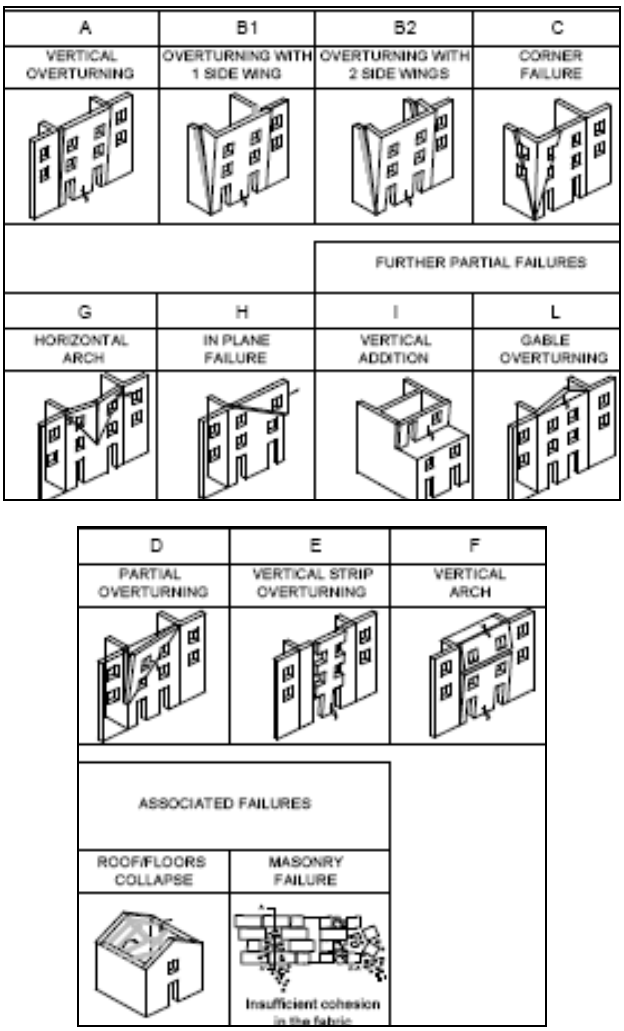


Figure 11 – Samples of Out of Plane Collapse Mechanism (D'Ayala, D. and Speranza, E. 2001)

In order to make a better understanding on collapse mechanisms, a detailed explanation about the most common failure types will be explained by using the information of Lecture Notes of "Seismic Behaviour and Structural Dynamics" (Msc- SAHC Master Programme- 2009-2010 Period);

The main recorded collapse modalities are:

1. Rotation out-of-plane of bearing masonry (lacking of orthogonal connection)

2. Rotation out-of-plane of the top part of the walls (beating of the roof)

3. Masonry disconnections, masonry expulsion (masonry typology and material quality)

4. In-plane mechanisms for shear stresses with diagonal cracks (presence of openings, thin walls)

The typical collapse mechanisms are determined, on the base of the observation of the collapse modalities of the existing buildings, collected in abacuses divided depending on different construction typologies (isolated buildings, array of buildings, churches)

The determined mechanisms are schematized with kinematic models, based on equilibrium conditions, which provide a collapse coefficient C=a/g for the elementary mechanism, i.e. the seismic mass multiplier that leads the element to failure.

Out of Plane and In Plane Actions

The main types of the out of plane mechanisms and in plane mechanisms can occur in different types. The most basic ones can be visualized as follows;

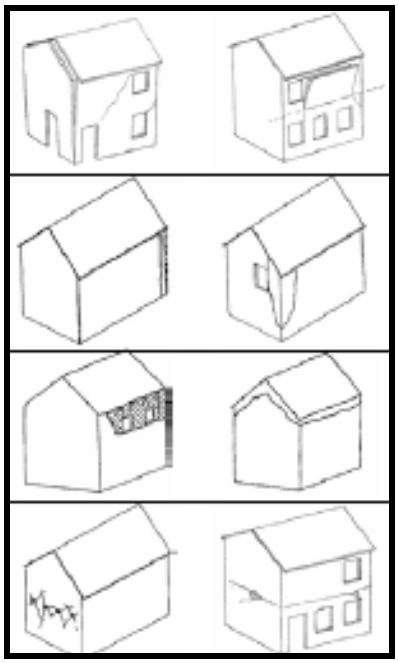


Figure 12 – Out of Plane Action- External Walls

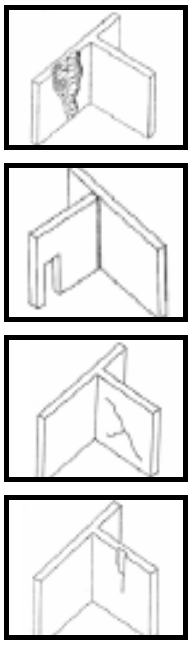


Figure 13 – Out of Plane Action- Internal Walls

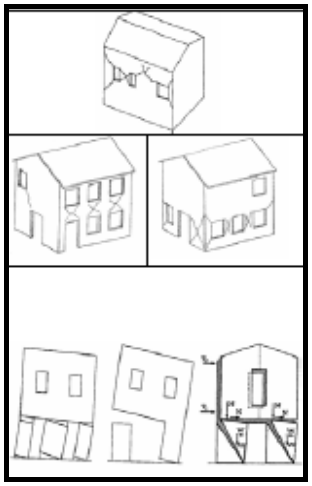


Figure 14 – In Plane Action

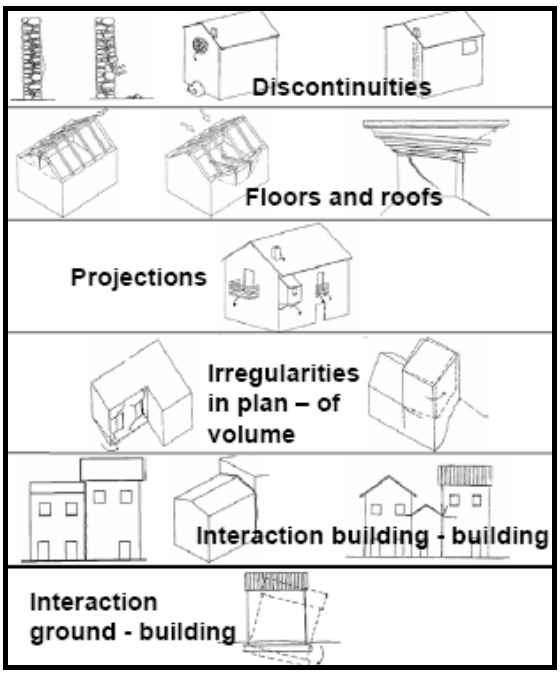


Figure 15 – Out of Plane versus In Plane Collapse Mechanisms

Out of Plane Mechanism occurs due to various reasons and considering the main reason, the type of the collapse occurs in different ways. The most common failure types are as follows;

1- When the cracks are inclined or vertical in floor bands where the openings are, the expected collapse can occur due to the overturning out of plane of portions of the building.

Figure 16 – Out of Plane Mechanism

2- When the concern is lack of connection between orthogonal walls or any kind of elements providing box behaviour, the total collapse of the facade may occur. This phenomenon is observed by the formation of a cylindrical hinge with horizontal axes in correspondence to the ground level of the foundations

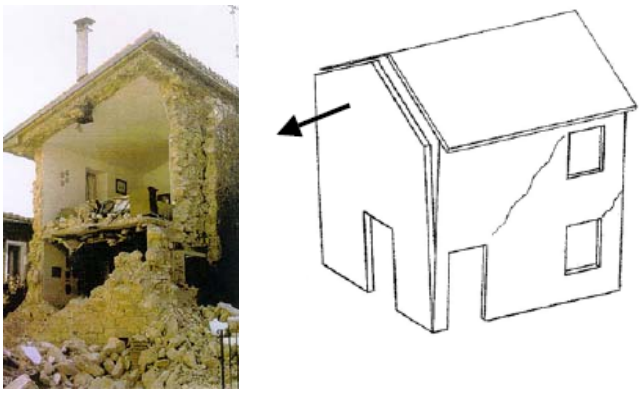


Figure 17 – Total collapse of the facade

3- When the connections between the external walls, anchoring of the floors to the perimeter walls are insufficient or the openings that are close to the edge of the perimeter walls are present, then the collapse of the corner of the structure may occur. This can be observed by the rotation out-of plane of the corner for the interaction of forces acting on the orthogonal walls.

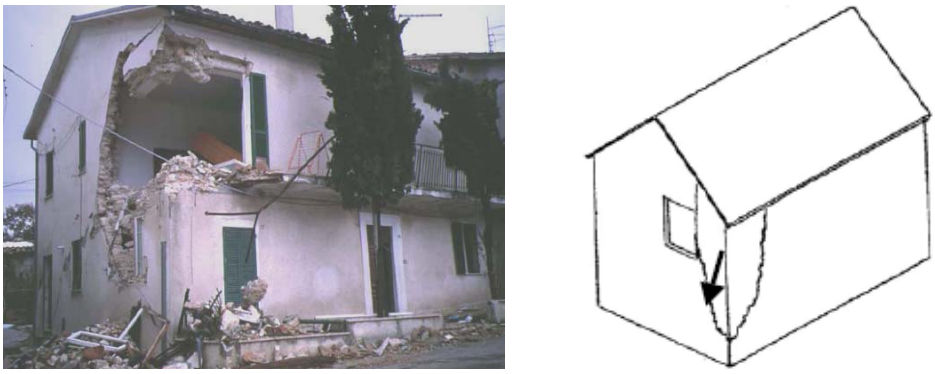


Figure 18 – Collapse of the corner of the facade

Out of Plane Mechanisms due to the Masonry Discontinuities

1- When the inner leaf of the masonry is not in good quality considering the construction characteristics and mechanical composition, the presence of voids in masonry, absence of diatonic walls, lack of adhesion and cohesion of the walls, local collapses may occur by ungluing between the masonry faces. Overturning out of plane of some parts of external of the masonry faces can be the concern.

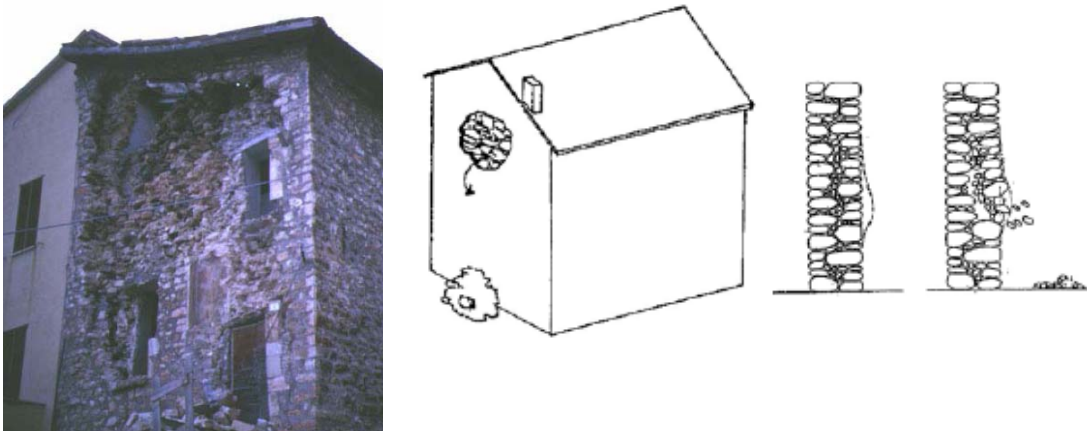


Figure 19 – Partial collapse ue to the irregularity of the masonry

Out of Plane Mechanisms due to the Roof

1- When the roof is not sufficiently connected to the masonry, local collapse in the top of the tympanum wall and isolated collapses of the cornice can due to happen. In this case, rotation out-of plane of part of the facade, due to the beating of the top of the beam on which the seismic action is concentrated.

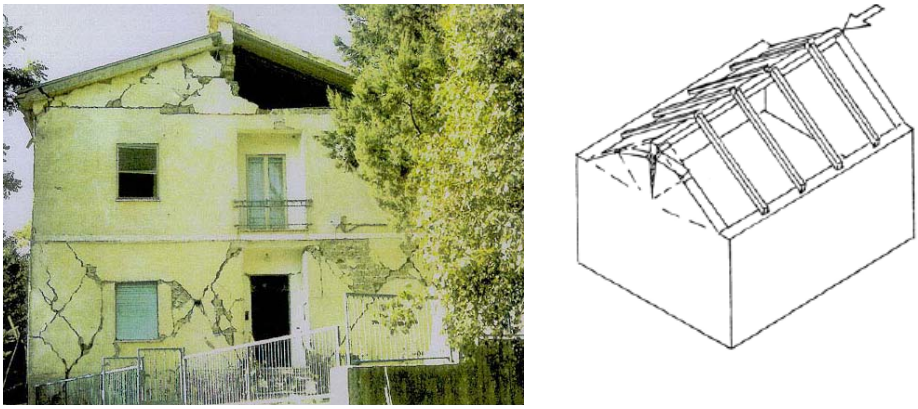


Figure 20 – Failure due to the stiff roof

In plane Mechanisms

1- Inclined or cross shaped are observed when a great concentration of stress is present or when the masonry in low quality with discontinuities. The mechanism shows itself with the shear failure of the whole facade.

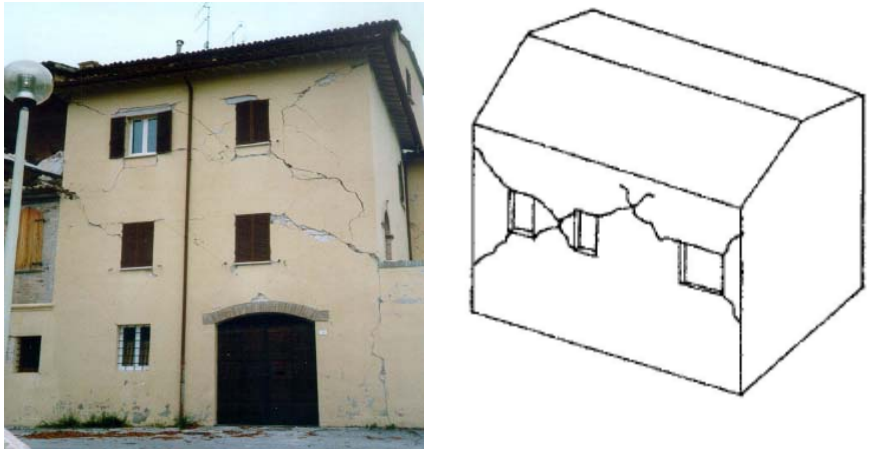


Figure 21 – In plane mechanism

2- When the lintels are weak or masonry band between the openings reduced in height and depth, crossed or diffused cracks in the area over the lintels of the openings are observed. Shear failure of the floor bands for the bending stress in the plane of the wall is observed.

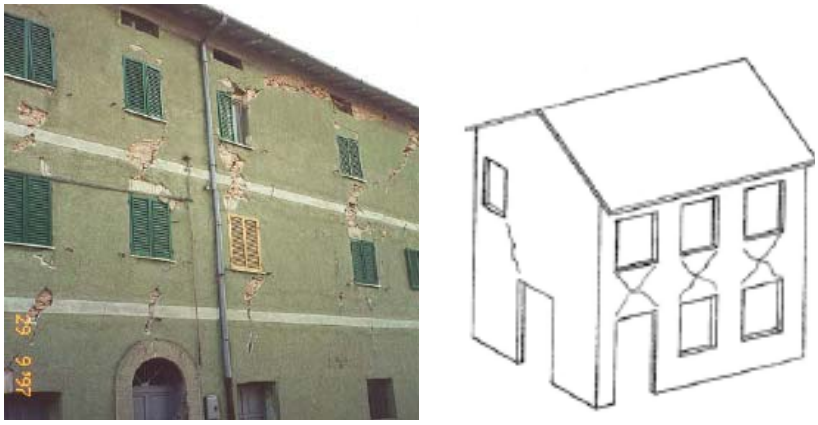


Figure 22 – Shear failure of the floor bands

3- When there are many openings on the facade or discontinuity and low quality in the masonry, lesions in the short walls may occur. This is due to the shear failure in the wall stressed in its place.

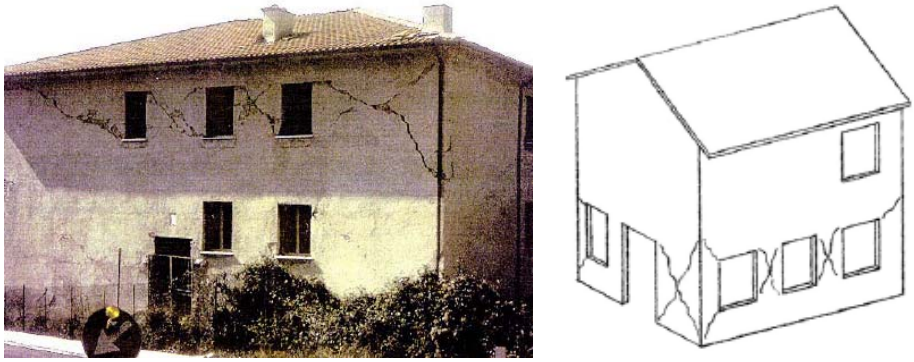


Figure 23 – Shear failure on the walls

4- When the problem is the openings excessive in dimensions or in amount, the walls become very slender leading the formation of nearly horizontal cracks or possible crushing of the edge of the masonry. The mechanism that is possible to observe is overturning of the masonry wall for rotation in their plane.

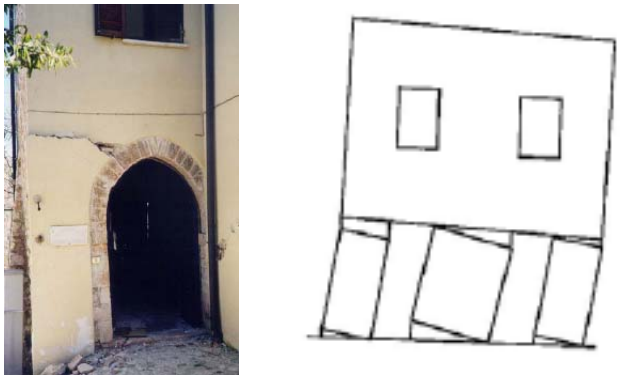


Figure 24 – In plane failure due to wide openings

Plan Irregularities

1- When the plan shape is irregular, different absorption of the seismic forces for the eccentricity of the mass centre with relation to the stiffness centre occurs. Shear failures on the walls of an extension of the plan is observed due to the rotation of the different parts of the plan relative to each other.

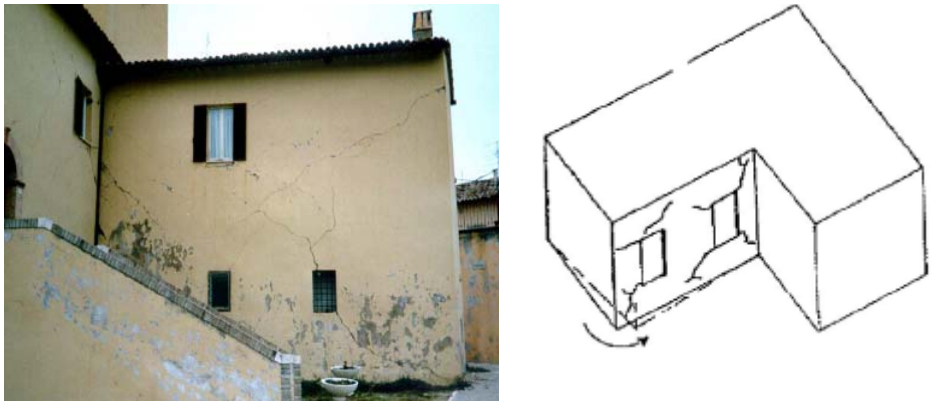


Figure 25 – Failure due to the irregularities in the plan

Settlement

1- Damage due to the settlement may have major reasons such as the excessive ground slope and non-homogeneity in the ground lift. Vertical cracks and slipping can be observed as a part of the out of plane rotations, slipping of one part or the whole of the building.

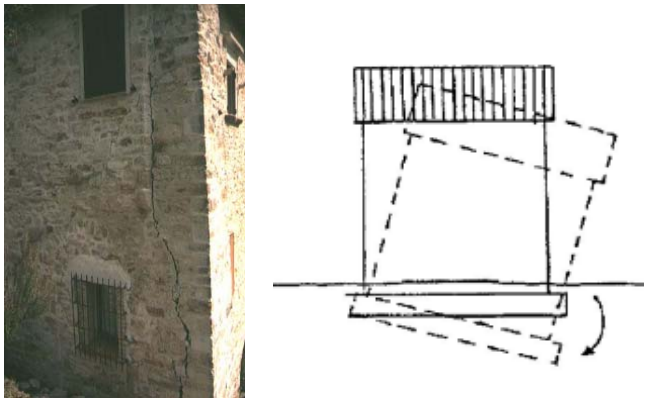


Figure 26 – Failure due to the settlement

3.3 Evaluation of the improvement of the approach in recent history

As it was indicated the first studies about the collapse mechanisms started after the heavy damage following the seismic actions. The beginning of the research projects specially based on churches and the structural behaviour of them was undertaken in Italy in 80s right after Friuli earthquake. The seismic facts showed that the churches were more vulnerable compared to palaces or any other kind or structures. Even in a low intensity earthquake, the churches are the structures which damage the most. The reports mention that In the case of Umbria and the Marches earthquake (1997), besides the Assisi Basilica, more than 2000 churches suffered significant damage in Italy (Lagomarsino, 2005).

One of the first projects was on behalf of GNDT (Earthquake Protection National Group). It has been focused on the analysis and collection of the damage patterns and collapse mechanisms in the church macro-elements, defined as the parts of the construction characterised by autonomous and unitary structural behaviour under seismic actions. As a result of a wide statistical analysis carried out on a significant sample of churches quite recurrent damage and collapse phenomenology have been recognised in the single macroelement of churches (Lagomarsino, 2005).

The systematic assessment and interpretation of the damage to churches which were due to the various earthquakes was achieved during the last 20 years from a structural point of view. *Churches have exhibited recurrent behaviour, under seismic actions, according to damage and collapse mechanisms of the different architectonic parts which behave almost independently.* As this was explained before, these parts are called as macroelements. The most typical examples of macroelements are the front façade, the triumphal arch, the vaults, the domes, the apse, the bell tower and the naves in a church.

In particular, the damage to more than 2000 churches after the Umbria and the Marches earthquake, in 1997, was assessed using a suitable form (Lagomarsino 1998), which considers 18 indicators, each representative of a possible collapse mechanism in a macroelement (façade; nave and transept; triumphal arch; dome and its base; apse) (D'Ayala, D. and Speranza, E. 2001).

The simplification of the structures by defining its macroelements and the advantages of the damage mechanisms are important since they allow the correlation of the cracks and deformations with a

particular kinematic collapse mechanism approach either occurred in a seismic event or possible to occur due to it.

This makes it possible to obtain a first interpretation of the structural behaviour of the structure and having the damage assessment is representative for a real preliminary diagnosis of the effects of the earthquake on the structure. In this sense light damage assessment is particularly interesting in those cracks, even if they do not compromise the structure; warn of the predisposition to the activation of the mechanism (Lagomarsino, 2006).

In this methodology, the knowledge on the various possible collapse mechanisms as much as it can regarding the deterioration or total collapse make it easier to define the possible damage prediction.

Apart from the mentioned studies regarding the churches, the extensive survey carried out by the authors together with other researchers in Umbria after the 1997 earthquake allowed to set up an abacus of failure mechanisms referred to different building typologies, and depending upon if the building had been repaired. The adopted diagnostic approach is based on the recognition of local and global collapse mechanisms traceable to in-plane or out-of-plane seismic action. The modelling of the structure behaviour and its safety assessment by macro-elements can highly benefit of the abacus, provided that the characteristics of the materials and the structure are known (L. Binda, G. Cardani, A. Saisi and M.R. Valluzzi, 2006).

3.4 Abacus for the churches

After the explanation of the reasons why the studies about collapse mechanisms started to be applied on the churches, the examples will be explained.

As it has already been indicated that the masonry churches are more susceptible to damage and partial or total collapses under seismic actions, the special interest has been paid in the recent decades. *The high seismic vulnerability of historic churches can be ascribed both to the particular configuration of this type of buildings, often characterised by open plan, presence of slender walls, lack of effective connections among the structural elements, and to the mechanical properties of the masonry material, i.e. nearly no tension strength (Gatto, D., Mele, E.and Luca, A. 2001).*

The previously mentioned GNDT database presents a classification of damage by using the structural macroelements and associated mechanisms of collapse. *For the purpose of this study, five mechanisms were analysed with reference to the macroelement façade: global overturning of the façade, overturning of the upper part, in plane failure of associated with membrane behaviour (arch effect), flexural failure due to lateral behaviour, diagonal crack pattern associated with predominantly shear behaviour*. (D'Ayala, 2005)

Seismic damage survey of the churches in Umbria has the following steps in defining the collapse mechanisms;

1. Typological and dimensional data: contains information about the typology and the dimensions of the church, broken down into the different architectonic elements (hall, presbytery, apse, transept chapel, roof covering, dome, crypt, facade, bell tower, vestry); in particular attention is concentrated on

the determining structural elements with regard to the seismic response of the building (buttresses, chains etc.).

2. Damage to elements of artistic value: the presence of artistic assets is noted inside the church and possible damage produced by the earthquake is indicated, without mention of its value.

3. Damage index and vulnerability index: in this section 16 possible damage and collapse mechanisms and characteristics of the different macroelements to be found in churches are identified. These are schematically illustrated in the abacus of figure 1; for each mechanism the following are indicated (figure 2): a) the presence of a macroelement; b) the size of the damage (0: no damage; 1: light damage; 2: fully developed mechanism; 3: severe damage, near collapse); c) the intrinsic vulnerability of the building to that mechanism, through two indicators linked to specific construction weaknesses (G. Augusti, G., Ciampoli, M. and Giovenale, P., 2005)

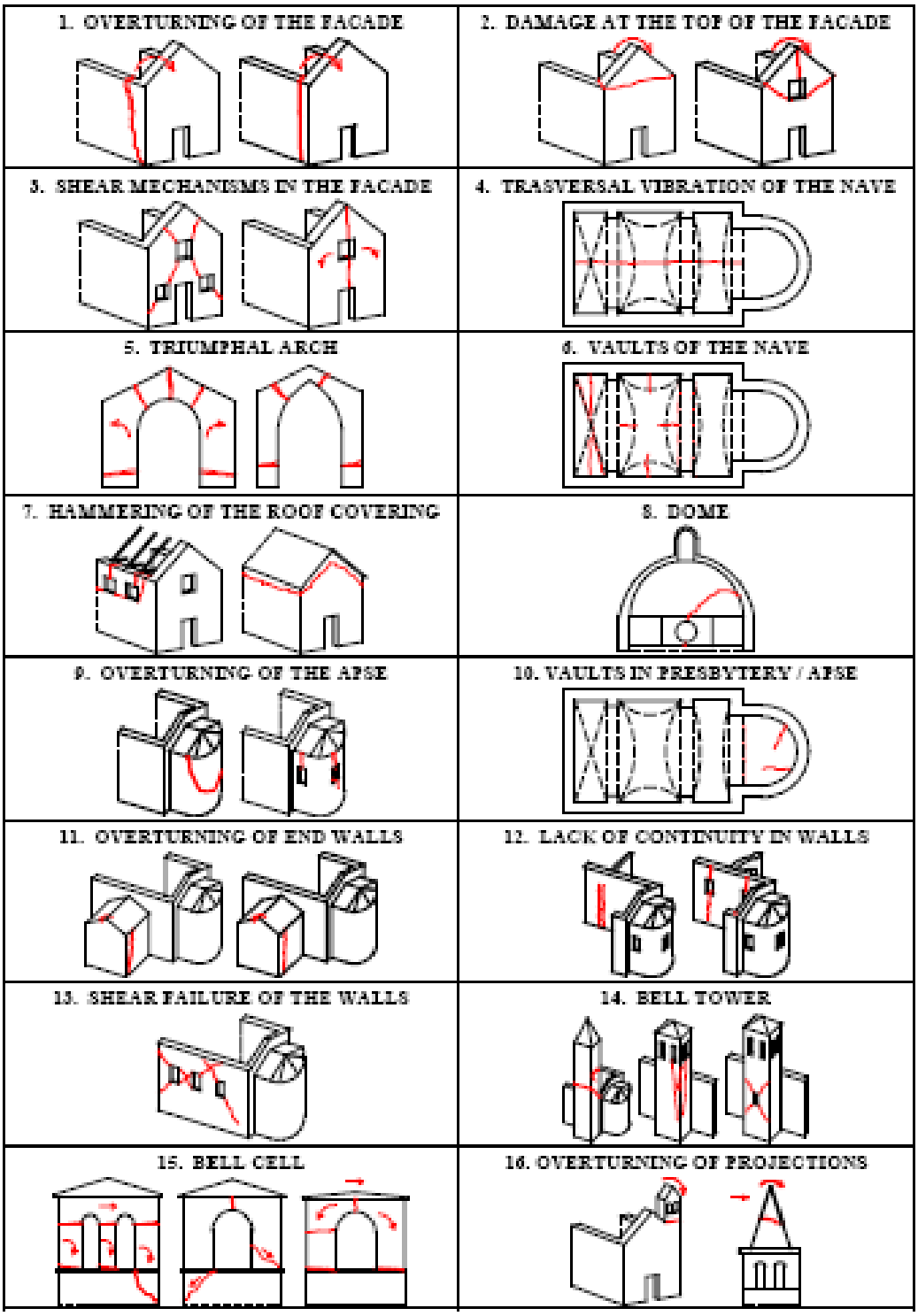


Figure 27 – Abacus of the damage mechanisms in the macroelements of the churches

1. OVERTURNING OF THE FACADE		**2. DAMAGE AT THE TOP OF THE FACADE**	
DETACHMENT OF THE FACADE FROM WALLS		CRACKS IN THE TOP PART OF THE FACADE	
Poor clamping between facade and nave walls Lack of longitudinal chains or efficient buttresses		Facade weakened by wide openings Lack of a connection with the roof covering	
3. SHEAR MECHANISMS IN THE FACADE		**4. TRANSVERSAL VIBRATION OF NAVE**	
SLOPING, VERTICAL AND ARCHED CRACKS		CRACKS IN ARCHES, DEFORMED WALLS	
Presence of many openings (also filled) Possibility of rotation of the side walls		Very thin side walls Lack of transversal chains or efficient buttresses	
5. TRIUMPHAL ARCH		**6. VAULTS OF THE NAVE**	
CRACKS IN KEY AND SPINE		CRACKS; DETACHMENT FROM ARCHES	
Arch of insufficient thickness or poor masonry Chains missing or badly placed; weak shear walls		Vaults lowered excessively or thin Presence of concentrated loads of roof covering	
7. HAMMERING IN THE ROOF COVERING		**8. DOME**	
BEAM SLIDING; DISCONNECTED TIE BEAMS		CRACKS IN: DOME, TAMBOUR, LANTERN	
Roof thrusting; roof covering rigid and heavy Lack of connection between tie beam and masonry		Tambour very high and with large openings Lack of hoops or external buttresses	
9. OVERTURNING OF THE APSE		**10. VAULTS IN PRESBYTERY / APSE**	
VERTICAL OR ARCHED CRACKS IN WALLS		CRACKS IN THE VAULT OR APSE BASIN	
Lack of hoops or chaining Weakening from many wall openings		Vaults lowered excessively or thin Presence of concentrated loads in roof covering	
11. OVERTURNING OF END WALLS		**12. LACK OF CONTINUITY IN WALLS**	
DETACHMENT OF END WALL		MOVEMENT OF JOINTS/DISCONNECTEDNESS	
Poor clamping between wall and orthogonal walls Lack of chains or efficient buttresses		Great difference of stiffness between two parts Lack of clamping or chains	
13. SHEAR FAILURE OF THE WALLS		**14. BELL TOWER**	
SHEAR CRACKS OR LOCAL DISCONTINUITY (OLD OPENINGS etc.)		CRACKS ON CONTACT WITH THE CHURCH; VERTICAL CRACKS; EXPULSION OF EDGE	
Masonry poor or of limited thickness Great weakening due to the presence of openings		Lack of connections with the church Masonry decayed, poor, of limited thickness	
15. BELL CELL		**16. OVERTURNING OF PROJECTIONS**	
CRACKED ARCHES; PIER ROTATION/SLIDING		PERMANENT ROTATION OR SLIDING	
Lack of chains or hoops; thin piers Roof covering heavy or thrusting		Lack of buttress or other connection Projection too thin	

Table 5 – The possible collapse mechanisms and the possible reasons in churches

4. PRELIMINARY RESEARCH ON CASE STUDIES

4.1 SANTA MARIA DEL MAR

4.1.1 Location

Santa Maria Del Mar stands in Barcelona's Ribera district. The basilica is a partly isolated building constructed on the Roman necropolis and is a leading example of Catalan Gothic.

The structure is attached to some annexes on the north direction but apart from these small additions, it is located alone in the area without any connection to the other buildings.

The area that the Catholic Church is located now can be called as the nucleus of the district or Vilanoca "del Mar" which is also known as Portal Major that has its prosperity thanks to its proximity to the port and the market across from the Castell Vell. Currently, Passeig del Born forms the centre of the neighbourhood into which the streets Carrer del Mar (Argenteria), Montcada and the waterfront houses in Ribera neighbourhood face towards. (Millan, A. 2003)

Figure 28 – General view of the location of St.Maria Del Mar (maps.google.com)

Figure 29 – General view of the building (Nieto, A. and Diaz, E., 2008)

4.1.2 Historical Information

The references about the construction indicate that the structure was planned to be built after the improvement of the Ribera area thanks to the closeness to the coast and becoming a popular and important place.

The design of the project was made by Berenguer de Montagut in 1324 and the construction of the structure started in the year 1329. The other architect contributed the work of the structure was Ramón Despuig but it is commonly indicated that porters of Ribera also helped during the construction period.

The construction process of the church is relatively short considering the period that it has been built and style of the structure. The total construction process took along 54 years starting in 1324 and finishing in 1383.

In the first phase of the construction the whole plan shape consisting buttresses, chapels, choir, façade and lateral walls were built.

Figure 30 – Old view of the front facade of St.Maria Del Mar (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

Figure 31 – The current state of the front facade of St.Maria Del Mar

An important turning point in the structure's life was the 1488 when the houses in the Santa Maria square were demolished in order to indicate the importance of the building. These buildings were again built as their original plan and in their initial places in the early 19th century (Nieto, A. and Diaz, E., 2008).

The second phase consists of the construction of the arches which were previously covered by timber roof at that period. The last phase was completed by the construction of the vaults.

The altar was changed with a new one by the request of the bishop in the late of 18th century. The work started in 1772 and the construction finalized in 1779.

4.1.3 Previous Studies

"Seismic Analysis of Santa Maria del Mar Church in Barcelona"-

By Juan Murcia Delso

The study focuses on the structural analysis of Santa Maria Del Mar Church considering the typical bay of the structure.

The work was prepared under the first edition of Msc-SAHC programme in the year of 2008.

The main content of the study consists of the following aspects;

- A structural analysis was carried out in this work
- Finite Element Analysis of the structure subjected to gravity load was done
- The seismic behaviour of the structure was studied by means of a static nonlinear pushover analysis
- The Capacity Spectrum Method was applied and the expected damage was analyzed

"Application of Capacity Spectrum Method to Medieval Constructions"

By Roberto Cuzzilla

The study consists of the evaluation of the Gothic Churches under seismic action using Capacity Spectrum Method as a tool.

Mallorca Cathedral, Santa Maria Del Mar and Santa Maria Del Pi were chosen for the work which was presented as the final project of Msc-SAHC programme in 2007-2008 period.

"The report on Santa Maria Del Mar regarding its construction and structural stability"

By Pere Roca, Francesc Caballé, Reinald Gonzàlez, Pilar Giràldez, Màrius Vendrell

A comprehensive report on Santa Maria Del Mar was prepared with the collaboration of different institutes including Technical University of Catalonia (UPC) in December, 2007.

The work consists of the detailed description of the structure, the construction phases and materials that were used, the historical information, the morphological data, structural analysis, seismic and dynamic analysis and damage.

4.1.4 Geometrical Characteristics

Santa Maria Del Mar which is quite often called as Cathedral of the Sea has a symmetrical rectangular plan shape with an orthogonal apse. The structure follows the general plan shape of a basilica without the transept.

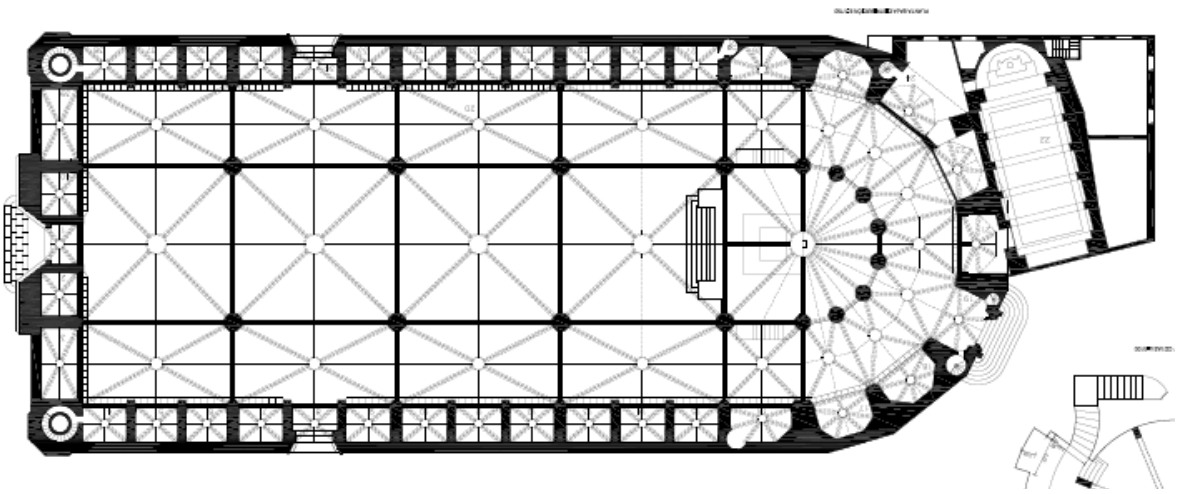


Figure 32 – The general plan lay-out of Santa Maria Del Mar (Nieto, A. and Diaz, E., 2008)

The design uses the module of 33cm. The structural components have a relation keeping this module as the base of the design and repeat it general in the structure.

The structure is composed of three naves two of which are rather smaller in the width comparing to main and central nave where the main entrance is faced to. The width of the central nave is approximately 13 meters (between the axis of two pillars) while the side naves are equal to each other with a width of while the side naves are equal to each other with a width of 6.50 meters.

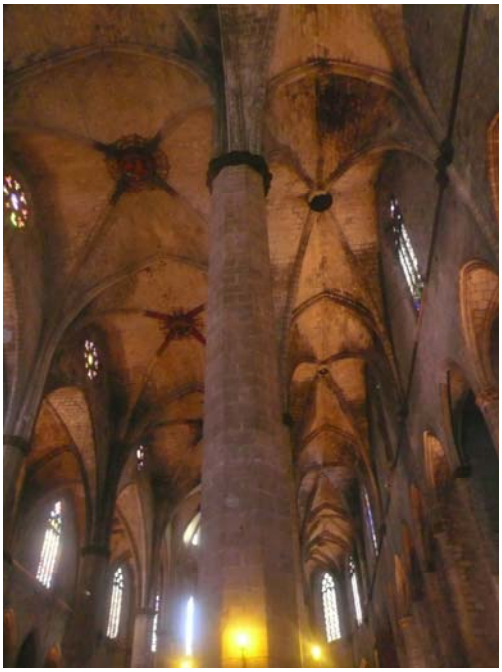


Figure 33 – General view of main and lateral naves

Figure 34 – General view of the main nave

Figure 35 – The view of main entrance

Figure 36 – The view of side entrance

Santa Maria Del Mar has four entrances two of which are from east and west facades located symmetrically, one is from the apse and one is from south constituting the main entrance. The big portal reaching up to 12 meters height over the main entrance is also enriched by a rose window with a diameter of 9 meters. The main entrance keeps its integrity and Gothic characteristics constituting an example rather different to the general Catalonian cathedrals.

The apse is an orthogonal shaped area facing towards seven different sides. Nine small chapels were located in the apse while the main three naves are surrounded by twelve chapels on each side.

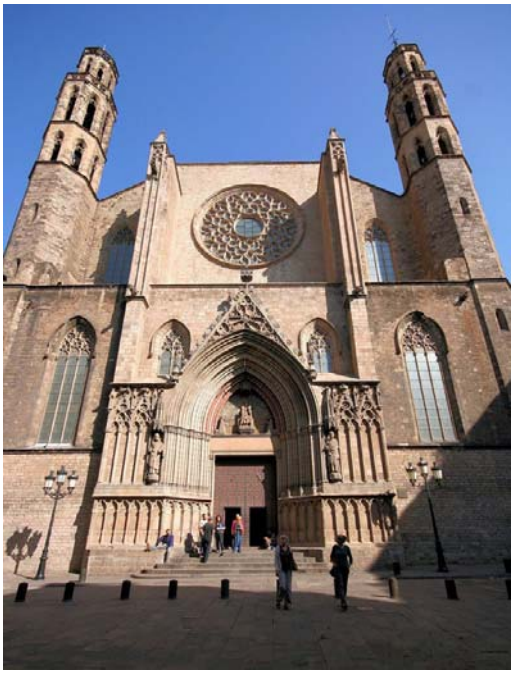


Figure 37 – The front facade

Figure 38 – The apse

Two bell towers are located on each side of the south facade having approximately 46 meters height.

Vertical Bearing Elements

The vertical elements in the structure are walls, columns and the buttresses.

The walls of the church were designed and constructed as three leaf masonry. The exterior and interior leaves are made of ashlar masonry and the infill is made of irregular rubble masonry. The sources refer that the stones used for the construction of the building were taken from the quarries of the Montjüic. The walls were built with stone blocks which were joined by using the lime mortar.

Figure 39 – The ashlar stone masonry

The typology of the bearing walls can be inspected visually without any need of an NDT thanks to the help of the previous damage occurred due to the bombing happened during the war both in 18th and 20th centuries. The exterior leaf of the wall has a thickness of one masonry block (approximately 18 ×13×17 cm) while the interior leaf of the wall has the same thickness. The rubble infill is thicker comparing to the exterior and interior leaves (a thickness of 55 cm).

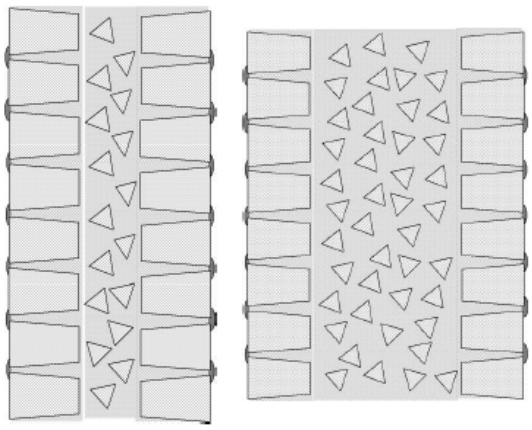


Figure 40 – The typology of the three leaf masonry wall (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

Figure 41 – The holes due to bombing revealing the morphology of the masonry wall

The walls extend in three main levels. In the first level, the lateral chapels were defined. It extends up to 16 meters of which 6 meters height is only the exterior walls without any opening apart from the entrances and 10 meters is designed with thirteen windows in longitudinal facade with the dimensions of 2.20 to 8.60 meters that are made of stained glasses which have an important contribution on the reputation of the structure. This level lasts with the roof of the small chapels. This roof was designed as a terrace.

The second level goes up to the height of 14 meters where the buttresses also extend to. This level also constitutes of the roof level of lateral naves.

The third and last level is the roof level of the central nave.

Figure 42 – The buttresses on the front facade

Figure 43 – The buttresses surrounding the apse

The naves are separated by slender orthogonal columns which has 155 cm in diameter. The main nave has four square areas defined by these columns in each corner with the total number of eight for the central nave.

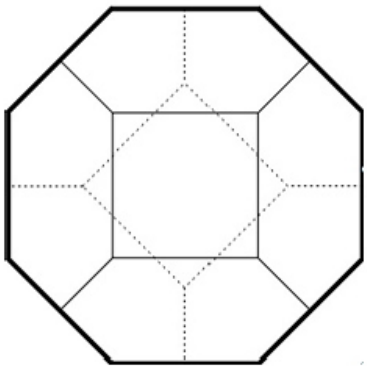


Figure 44 – The plan view of the columns of Santa Maria Del Mar

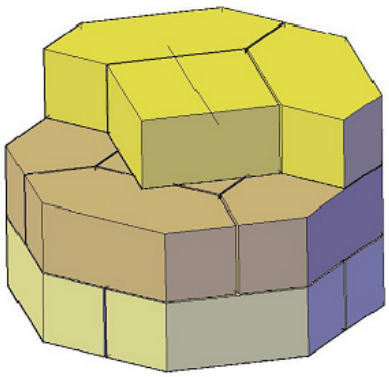


Figure 45 – The represantation of the columns' morphology in Santa Maria Del Mar (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

The studies that were undertaken by Universitat Politècnica de Catalunya, Universitat de Barcelona, Universidad del País Vasco, San Sebastián in Santa Maria Del Mar made it possible to get detailed information regarding the specific morphological characteristics of the columns, foundations and the walls of the structure. As a part of these inspections, seismic tomography was applied. This technique made it possible to understand the construction technique of the columns.

Each row of the column consists of five ashlar stone blocks. The one which is placed at the centre is a square one and surrounded by four hexagonal stones. The stability of the slender columns is achieved due to the technique of rotating the central square stone 45 degree in each row. The height of each stone row is 22 cm and the total height of the columns is 26 m.

The buttresses which have been constructed in the same style of the exterior walls extend to the level which can be categorised as the roof level of the lateral naves. They are built as 14 meters height hidden in the first level of the facade where the plan view is the widest due to the lateral chapels. They are visible in the second level around the lateral naves with the number of four in each side facades. In the front facade, two buttresses were located in each side of the portal. Last of all, eight buttresses were constructed around the apse making it possible to design little chapels between each of them.

Horizontal Bearing Elements

The horizontal bearing elements are the arches and vaults in the structure.

The studies regarding the construction process shows that the structural arrangement of the horizontal elements is different in Santa Maria Del Mar. The lateral vaults were constructed almost as high as the central vaults and they were positioned to receive the lateral thrust of the central vaults and carry it to the buttresses. In this way, the flying arches were not needed.

Figure 46 – Cross vaults of main and lateral naves

Figure 47 – Cross vaults of lateral naves

Different type of cross vaults was used in the structure. In the central nave, square cross vaults were designed which are supported by the arches on four sides at approximately 32 meters height. The rectangular cross vaults cover the areas over the lateral naves located on both sides of the central nave. As it was highlighted before, these cross vaults have almost the same height of the square ones with the height of 26 meters. The cross vaults over the apse were constructed in a similar shape of a palm.

Foundations

Geophysical techniques were applied by Universitat Politècnica de Catalunya, Universitat de Barcelona, Universidad del País Vasco, San Sebastián in order to analyze and obtain more information regarding the foundation and the soil type of where the structure is located.

GPR and similar techniques showed that some existing constructions lay below the ground level of Santa Maria Del Mar Church.

Figure 48 – The inspections showing the foundations (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

Figure 49 – The pre existing occurrences in the foundations

Roof

In the roof of the lateral naves, triangular shaped walls were designed with the channels to make the water drainage possible.

The main nave is inclined to four sides having the similar shape of the cross vaults and covered with tiles.

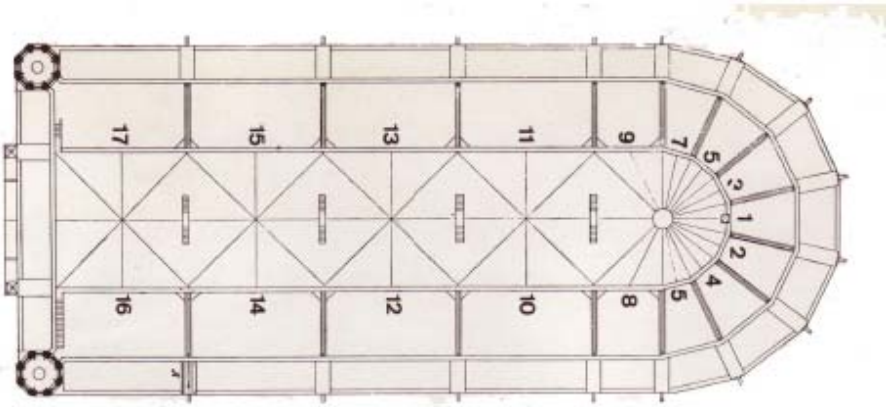


Figure 50 – The typology of the roof system (Nieto, A. and Diaz, E., 2008)

4.1.5 Previous Interventions, Alterations and Damage

The structure has suffered from some natural disasters, wars and fires throughout its history and some parts of it still carry these effects at present. In spite of all these happenings that damaged the structure, the building does not have encountered many alterations that would influence its structural characteristics.

Figure 51 – The tiled roof (Nieto, A. and Diaz, E., 2008)

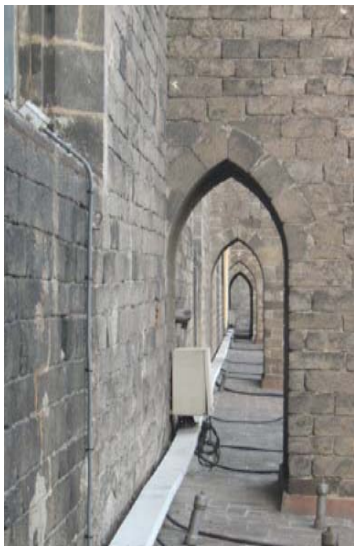


Figure 52 – The passages through buttresses (Nieto, A. and Diaz, E., 2008)

There is an evidence of two events causing damage in the structure during construction process. The first one is an earthquake occurred in 1373 caused the partial collapse of the Eastern tower.

One of the events that damaged the structure was the fire happened in 1379. The last bay was almost completed at that period when this event happened and the fire started in the timber scaffoldings spreading and causing damage by destroying them and the stone material was highly affected. (Nieto, A. and Diaz, E., 2008)

There is also evidence of an important earthquake in 1428 that caused the partial collapse of the rose window of the façade, killing 25 people. This piece was restored in 1459.

The structure was influenced due to the bombing in different periods during 17th, 18th and 19th centuries. It is possible to see the effects still remaining on the facades. Among all these events, a big damage occurred in 1936 due to a person set the structure into the fire during Civil War. The sources mention that the fire lasted 11 days and apart from all the timber elements and stone material, the archives of Santa Maria Del Mar were also lost (Nieto, A. and Diaz, E., 2008).

The previous studies showed that in 1987 the electrical system was restored but still were burned and four columns serious state of neglect, several points of the facade crumbling, many windows damaged and no protection and only worked the bells of the clock (one of the five located in the

tower). In the last decades have been conducted new cleaning and recovery various parties, including the main facade and stained glass (Nieto, A. and Diaz, E., 2008).

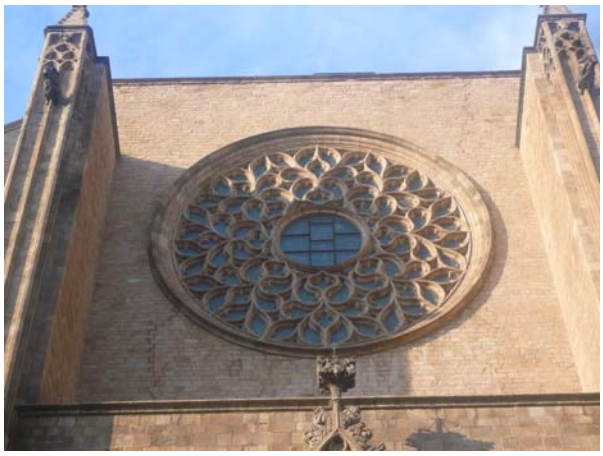


Figure 53 – The rose window which was restorated after the collapse

Figure 54 – The bell tower which was reconstructed

4.2 SANTA MARIA DEL PI

4.2.1 Location

Santa Maria Del Pi is the Gothic Church which was built in the same century with Santa Maria Del Mar. These two structures have some similarities in the plan layout and facade characteristics but Santa Maria Del pi is rather small when it is compared to Santa Maria Del Mar.

The structure is located in the centre of Barri Gothic surrounded with small squares in front of its main entrance and the back of the apses.

Most of the roads facing the structure are pedestrianized, narrow ones opening to the small squares highlighting Santa Maria Del Pi. On the north side of the structure, Plaça Del Pi with its symbolic pine tree and on the east and south Plaça Sant Josep Oriol were located.

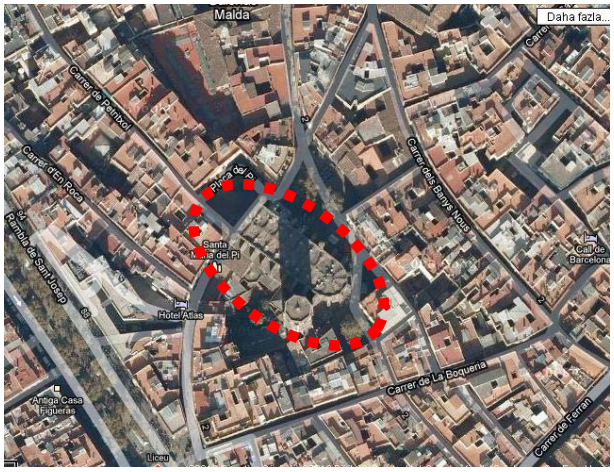


Figure 55 – General view of the location of St.Maria Del Pi (maps.google.com)

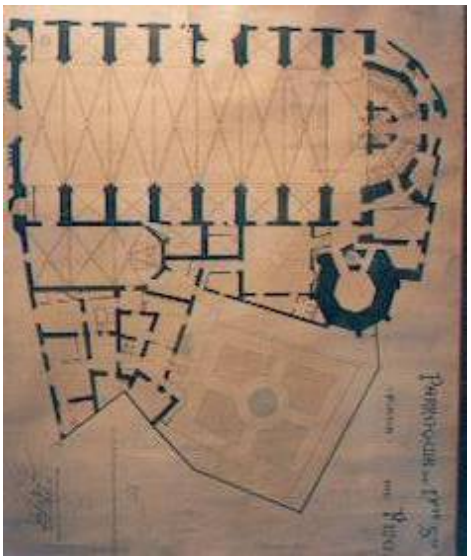


Figure 56 – An old plan view of St.Maria Del Pi

4.2.2 Historical Information

The building is named after the pineapple tree started to be built in 1319 and the construction lasted in 1391.

It is referred in literature that there used to be a little church where Santa Maria Del Pi is located now in the year of 413. This church is described as Paleochristian in the literature. The historical information indicates the presence of a Romanesque church outside the city walls extending through the west of Barcelona in the year 987.

The first construction works started in 1319 and the church which was designed with Catalan Gothic characteristics started to be built. Although some of the components that exist at present especially the interior timber structures are the restorated versions of the original ones which were destroyed in the big fire that occurred in 1936, the structure still keeps its integrity.

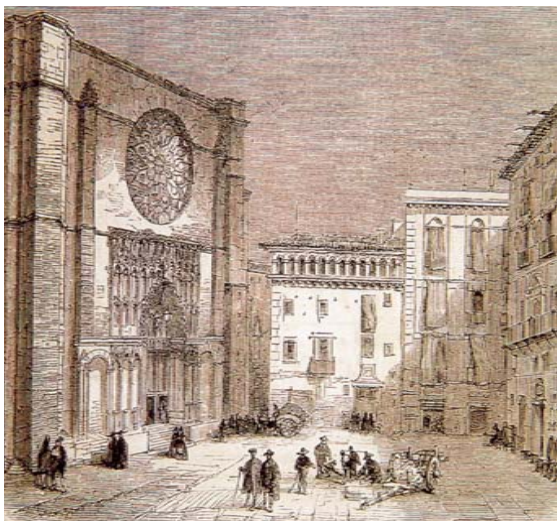


Figure 57 – An old figure depicting S.Maria Del Pi in 19th c(Giraldez, P., Gonzales, R., Roca, P. Vendrell)

Figure 58 – An old picture showing the damage after fire in 1936

4.2.3 Previous Studies

"The report on Santa Maria Del Pi regarding its construction and structural stability"

By Pere Roca, Francesc Caballé, Reinald Gonzàlez, Pilar Giràldez, Màrius Vendrell

The same type of comprehensive report as Santa Maria Del Mar was prepared for Santa Maria Del Pi with the collaboration of different institutes including Technical University of Catalonia (UPC) in December, 2007.

The work consists of the detailed description of the structure, the construction phases and materials that were used, the historical information, the morphological data, structural analysis, seismic and dynamic analysis and damage.

"Application of Capacity Spectrum Method to Medieval Constructions"

By Roberto Cuzzilla

As the study was briefly mentioned in Santa Maria Del Mar case, the Capacity Spectrum Method was used in order to analyze the structural behaviour of this Gothic Church.

4.2.4 Geometrical Characteristics

As it was mentioned before, the plan layout shows similarities with Santa Maria Del Mar.

The building has three entrances; one is obtained by the main facade which faces to the northwest direction and the other is from the side chapels facing to northeast direction.

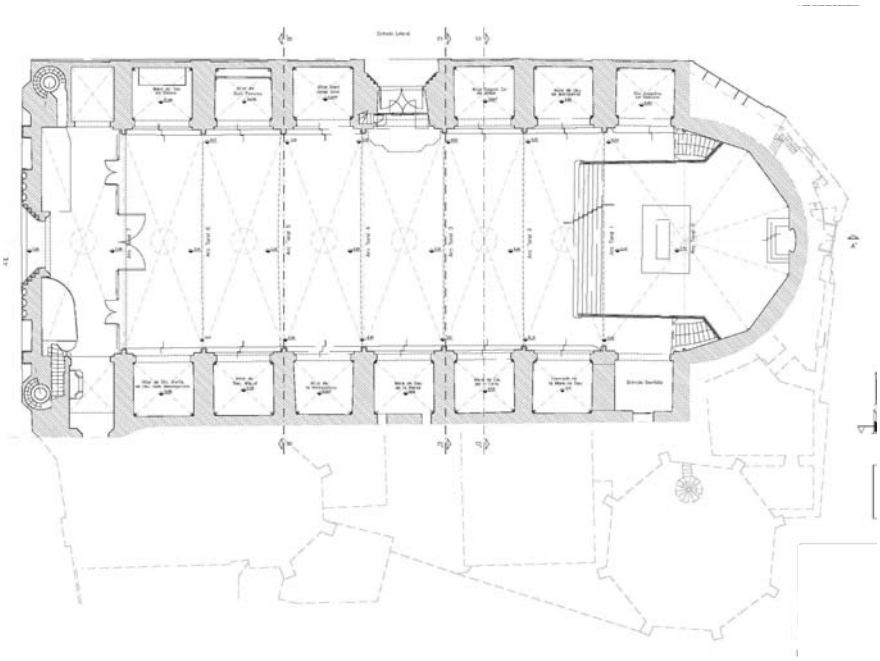


Figure 59 – The general plan layout of Santa Maria Del Pi

The structure was briefly described as the following;

"Started in the same decade as the church of Santa Maria del Mar, that of Santa Maria del Pi has exactly the scheme but without either the geometrical ruthlessness or aisles of the later church. The vaults of the seven narrow bays of the 19-meter-wide nave are restrained by solid external buttresses

between which are tall chapels. Above these are small windows in the west wall, provide the only illumination to the nave. The chapter house, now Blessed Sacrament chapel, was completed in 1486. At the south-west corner is the single very tall (54 meters) fat orthogonal bell-tower added in the fifteenth century (Woodward, C. 1992)"

The church has a symmetrical plan layout with a plain basilica design. The design is based on the characteristics like one single nave, small side chapels, and polygonal apse. The general dimensions of the building are approximately 28 meters in width and 58 meters in length.

The main nave is a single nave which is covered by rectangular cross vaults as the superstructure and supported by the side chapels each side. The interior length of the nave is 54 metres, the width is 16.5 metres and the height is 27 metres.

Figure 60 – The superstructure of the main chapel

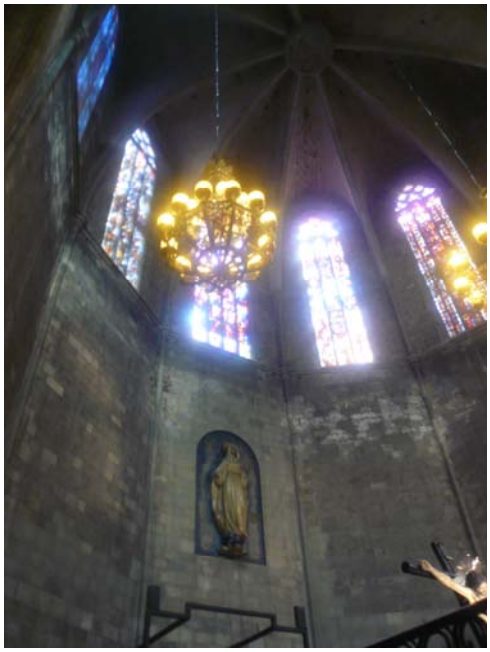


Figure 61 – The view of the apse

The side chapels are built in each side of the main nave varying in dimension with very small differences comparing to each other. They are almost square with the dimension of 3.90 to 4.45 in width and length.

Figure 62 – The ashlar masonry walls

Figure 63 – The view of the stone masonry

There are seven side chapels located on the southwest and six chapels on the northeast directions. The chapel in the middle on the southwest side corresponds to the side entrance on the northeast wall.

Figure 64 – The buttresses

Figure 65 – The view of the buttresses on the side facade

The vertical bearing elements are the walls, buttresses and the pillars in the structure. The walls are made of ashlar masonry. The facades can be evaluated by dividing into two parts. The first part rises from the ground level up to the height almost twelve meters and the second part goes up to 28 meters

height from the ground level constituting the highest level of the facades. The first part's wall is defined by the side chapels and on the second part, only the main nave rises along with the buttresses.

The facades show rather plain characteristics with these two levels revealing the buttresses in the second level and the stained glass windows in each level and between each buttress.

The side entrance on the northeast is called Ave Maria which still reflects the Romanesque features of the portico of the previous church. (Cuzzilla, R., 2008)

Figure 66 – The frontal door in the main entrance

Figure 67 – The entrance on the side facade

The semicircular apse which is accessible by a door designed in 1578 covered by vaults carrying also a key stone in the middle.

Santa Maria Del Pi's one of the main characteristics which gives it the popularity is the bell tower. The bell tower is octagonal in shape, rising to 54 metres. The walls at the base are 3.55 metres thick. It has a peal of six bells (http://www.parroquiadelpi.com)

Figure 68 – The view of north eastern façade

Figure 69 – View of the bell tower

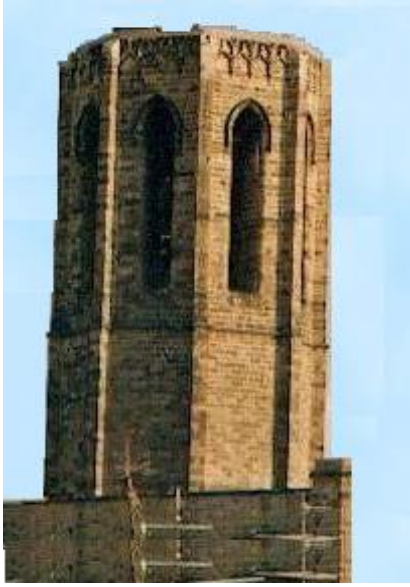


Figure 70 – Bell tower of St Maria Del Pi

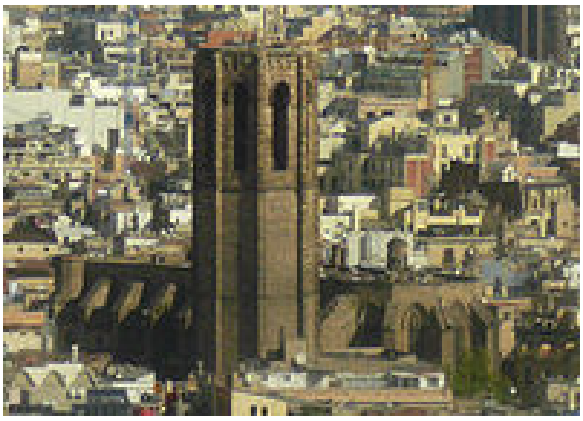


Figure 71 – The general view of the bell tower

4.2.5 Previous Interventions and Damage

The most important restoration that Santa Maria Del Pi has encountered happened in 1940 right after the big fire that destroyed the rose window in 1936. The restoration process consists of the rebuilding of the rose window again.

The damage still visible on the structure is related to the earthquakes that occurred in the year of 1428.

Figure 72 – The exterior view of the rose window

Figure 73 – The interior view of the rose window

Apart from the structural damage which will be explained later, the building has deterioration due to the different reasons. The main deterioration is the discoloration and black crust that are visible especially on the exterior facades. Lack of maintenance and the previous fires are among the possible reasons of these problems.

Figure 74 – The view of the vegetation and discoloration on the façades

4.3 BARCELONA CATHEDRAL

4.3.1 Location

The structure which is originally called as “Cathedral de la Santa Creu i Santa Eulalia” or “Cathedral of the Holy Crucifix and of Saint Eulalia” located at Plaça de la Seu in the center of Barri Gotic.

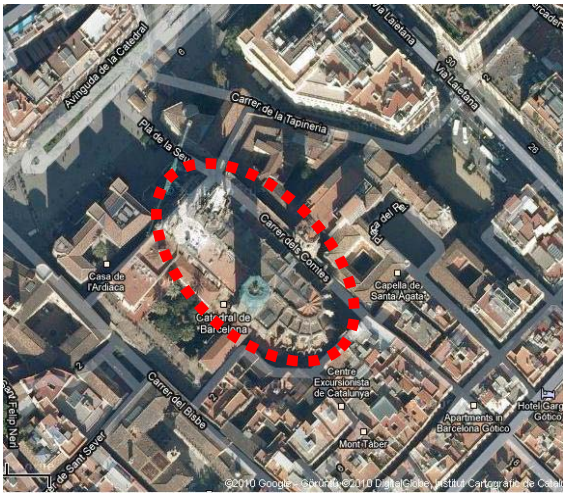


Figure 75 – The aerial view of the cathedral (maps.google.com)

Figure 76 – A historical picture of the front facade

4.3.2 Historical Information

The oldest information about Barcelona Cathedral refers that a basilica with three naves was standing in its place until the year of 925. The historical references indicate that a new cathedral was built around 1046 and this cathedral was replaced by a Roman Cathedral between 1048 and 1058.

Figure 77 – The view of the front façade

Figure 78 – The view of the entrance

As an addition to the Roman Cathedral, Capella de Santa Llucia was constructed between 1257 and 1268. The construction of Cathedral of Barcelona started in 1298 by the command of King Jaume II. The construction process required some changes on the site causing to demolish of the Roman Cathedral only keeping Capella de Santa Llucia.

Figure 79 – View of the cross vaults on the cloister

The construction work started with the naves in the year of 1298 at first and it took more than 100 years to finalize the works. As it is also common for the churches in general, the apse was constructed at first and finished in 1327. The final works regarding the construction of the nave kept on until 1417 (Roca, P., Molins, C. 2000)

After 1417, the construction of the cimborio started but the construction process stopped in the year of 1422. At that period, the cimborio was left unfinished. The construction of the building was completed in a long period. The main building was only finished in the year of 1460. The facade was constructed after many years the main building was completely finished. The date of the finishing of the construction of the facade is 1889. As a part of the last phase, the central spire was completed in 1913.

Figure 80 – The cross vaults on the apse and the lateral chapels

4.3.3 Previous Studies

"Wind and Earthquake Analysis of Spire of Cimborio of Barcelona Cathedral"

By Ahmed Elyamani Ali Mohamed

The study consists of the numerical model focusing on the spire. It was prepared in the second edition (2008-2009) of Msc- SAHC programme.

The general content of the thesis consists of the following;

- Different applied loads were estimated to define the seismic performance of the spire and the contributions of the different interventions techniques exist at present
- Finite Element Model of the spire was done
- A nonlinear analysis considering the self weight and push over analysis were applied

4.3.4 Geometrical Characteristics

The central nave of the structure has a span of 12.80 meters and the maximum height is 25.60. The span of the side aisles is 6.40 and was constructed as the half span of the central nave.

The construction was designed with three naves out of which the widest one is the central nave and the two other ones are aisles.

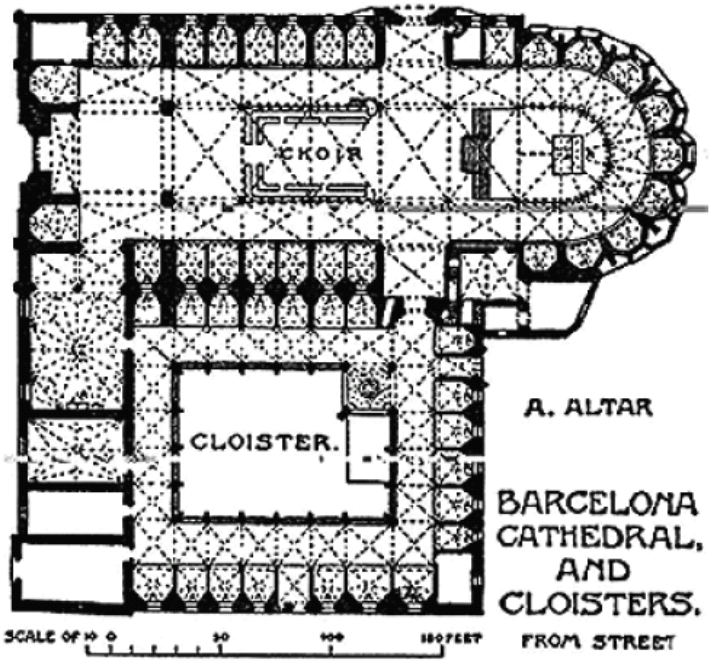


Figure 81 – The plan view of the Cathedral (Das, K.A. 2008)

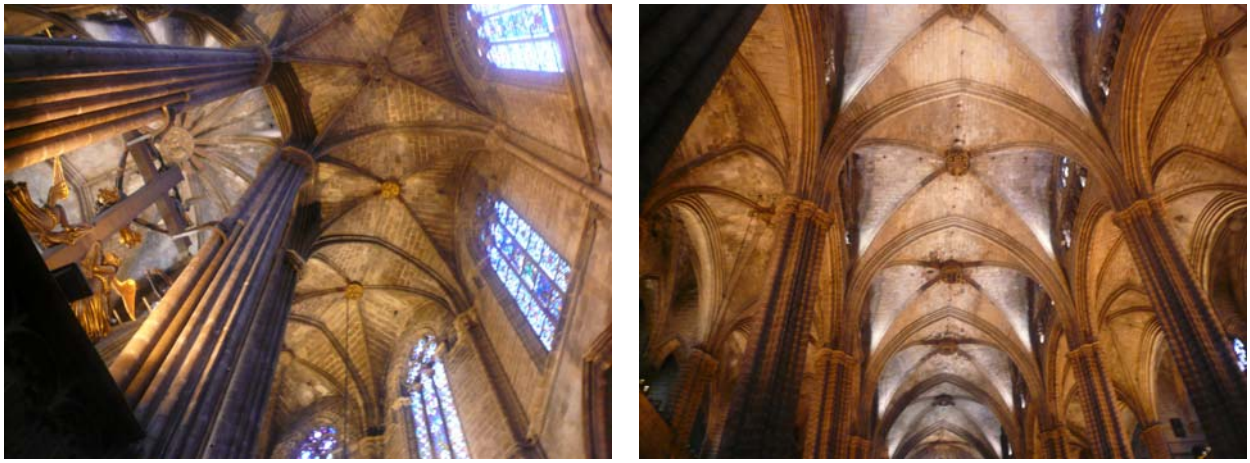


Figure 82 – The view of the superstructure of the interior of Barcelona Cathedral

As it was explained in the case of Santa Maria Del Mar, the building was not designed as using flying arches as structural purposes. Instead of this component, the buttresses were used. The mechanism works by the transferring of the thrust which is made by the superstructure of the main nave to the buttresses by the vaults and arches of the lateral naves. These buttresses serve as the flying arches having the same structural role.

The cathedral is rather different than the other famous cathedrals that were included in the scope of the study like Santa Maria Del Mar and Santa Maria Del Pi. The main characteristics of the construction are the large bell towers designed and ridged by the addition of Gothic pinnacles, Gothic churches and side chapels.

The general plan shape is composed of the central nave and aisles, crypt, cloister and altar.

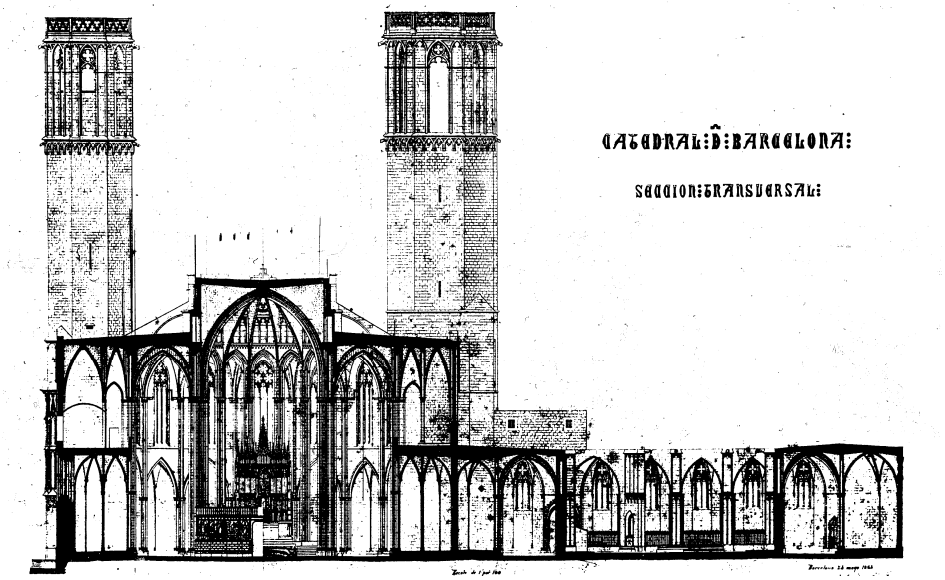


Figure 83 – The transversal cross section of Barcelona Cathedral

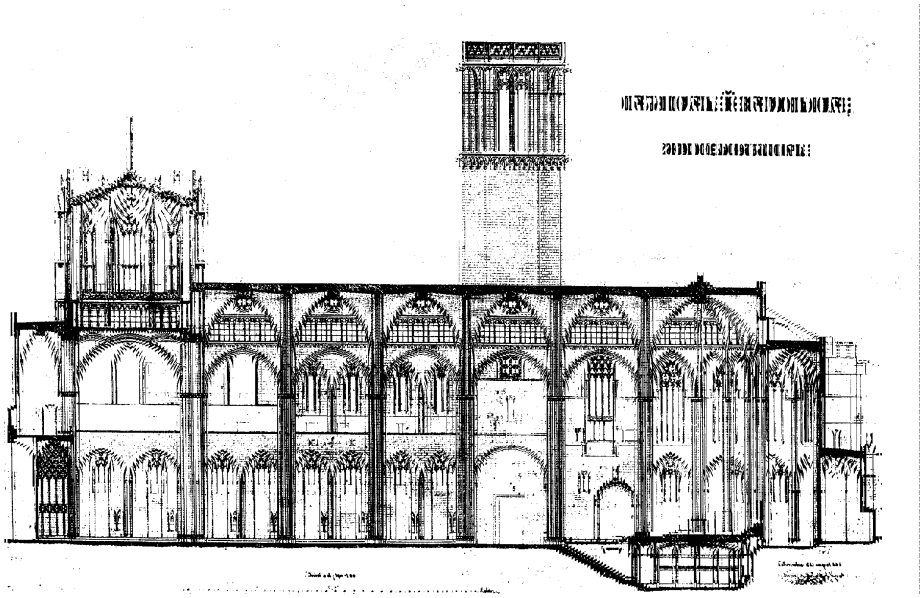


Figure 84 – The longitudinal cross section of Barcelona Cathedral

The building is not isolated but attached by the chapters which currently used as the museum.
The plan scheme of the structure is almost a rectangular shaped with a dimension of approximately 90 to 40 meter in width and length. The frontal facade and the altar are changing the general rectangular plan layout. Two clock towers and cimborio which is located on the first bay of the nave are the main characteristics of the structure.

Figure 85 – View of the piers

Figure 86 – Interior view of the apse

The frontal facade facing to west direction has a high entrance designed by the arches rising on each other.

Until the beginning of 20th century when architect August Font designed the cimborio, the construction was only with the low spandrels of the tambour and a provisory traditional tiled roof mounted in place of upper vaulting[18]. August Font constructed the actual cimborio 50 meters high spire of stone work. The total height of the current cimborio reaches up to 90 meter.

The flying arches used in the building serve as a part of draining system. Their geometry is very limited with very low thickness.

4.4 GIRONA CATHEDRAL

4.4.1 Location

The structure which is also called as "Catedrale de Santa Maria" is located in Girona on the banks of the river Ona. The structure has a dominant view from most parts of the area due to the location accessible by numerous stairs.

Girona Catedral is a massive structure with its cloister, semi circular apse and stairs located in the centre of the old city.

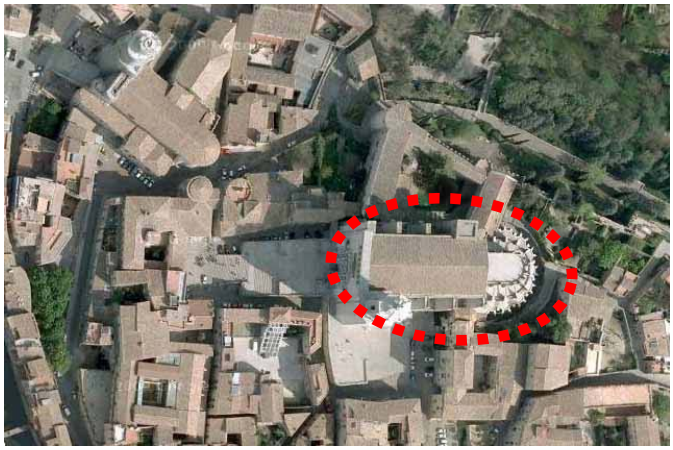


Figure 87 – The location of Girona Cathedral (maps.google.com)

Figure 88 – The general view of the cathedral

4.4.2 Historical Information

The cathedral is a mix of the Romanesque and Gothic style carrying the characteristics of the different periods that has contributions on its different parts.

Its known construction date is in the 11th century starting with the Romanesque style and following with the Gothic style in 13th century. The Romanesque cloister which gives importance and reputation to the cathedral was completed in 12th century and the tower which was actually planned to be constructed as two dating back to 11th century were able to finish in 18th century. The beginning of the construction date of the cloister and the tower is 1038.

The first information about a building around this area where the cathedral is located currently dates back to 717. This date is known as the transformation of the use from a church to a mosque by the

Arabs which proves that there used to be previous church standing in this plot even before this date. Following the conquer of the city in 785, the church was reconstructed again in 908.

It is possible to understand that the construction was in bad shape and was almost in ruins around 1015 from the documents that reached this date. After this period, the works in order to rehabilitate the construction was undertaken in the year of 1038.

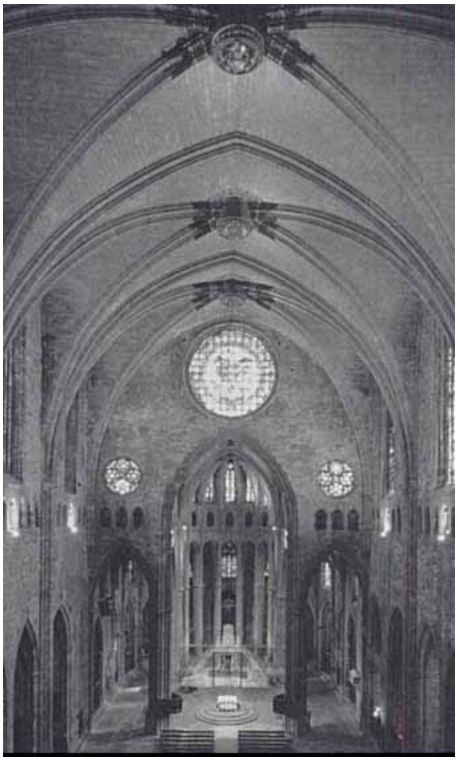


Figure 89 – An old photo of the single nave of Girona Cathedral

Figure 90 – Front facade in a photo dating back to 1950

The first known architect of Girona Cathedral is Enrique Narbonne. After his death, Jacob de Faverlis was appointed later then Bartolome Argenta who built the choir. A lot of names contributed on the construction works such as William Boffy, Rollin Vautier, Pedrı Cypress. Boffy is known as the first person to propose a nave of the same width as the choir, a single nave without aisles. The discussions about this issue were so raised that it took fifty years to finalise and meanwhile the construction works stopped. Finally it was concluded on construction the single nave which has 50 meter length, 23 meters width and 34 meters height.

Figure 91 – The view of the cloister (www.green-man-ofcercles.org/articles/cloisters_of_catalan_churches.pdf)

Figure 92 – The column heads in the cloister

The foundations for the facade started 1606 but the works were delayed for some reason and it could not be possible to finish until 1680. The classical Baroque facade was completed in the year of 1730. The massive staircases were completed in 1607.

Figure 93 – The view of the cathedral from the cloister

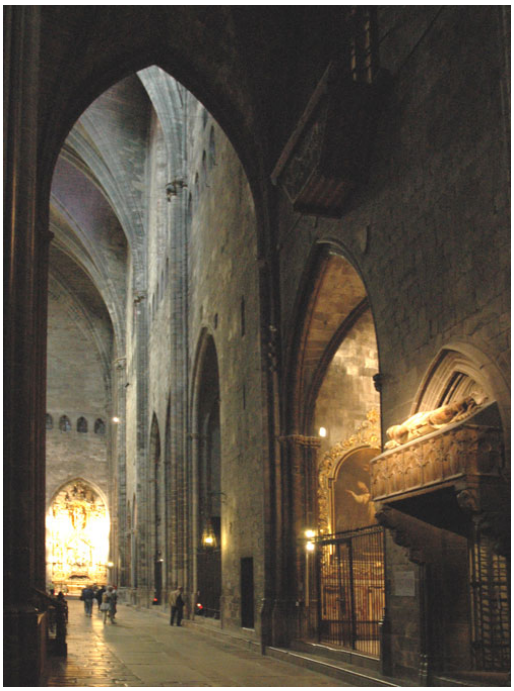


Figure 94 – Interior view of the cathedral

4.4.3 Previous Studies

No studies were obtained regarding Girona Cathedral.

4.4.4 Geometrical Characteristics

The construction has a more or less symmetrical plan. The clear width of the nave which is accessible from the centre of the front facade and from the side entrance is almost 23 meters. *Two different parts corresponding to two different construction periods can be distinguished. The first part including the apse and the first east bay is conceived as a conventional three nave church with an arrangement similar to Barcelona Cathedral.*

Figure 95 – General view of the side facade

Figure 96 – The view of the walls and the buttresses

Figure 97 – The clock tower

Figure 98 – The buttresses

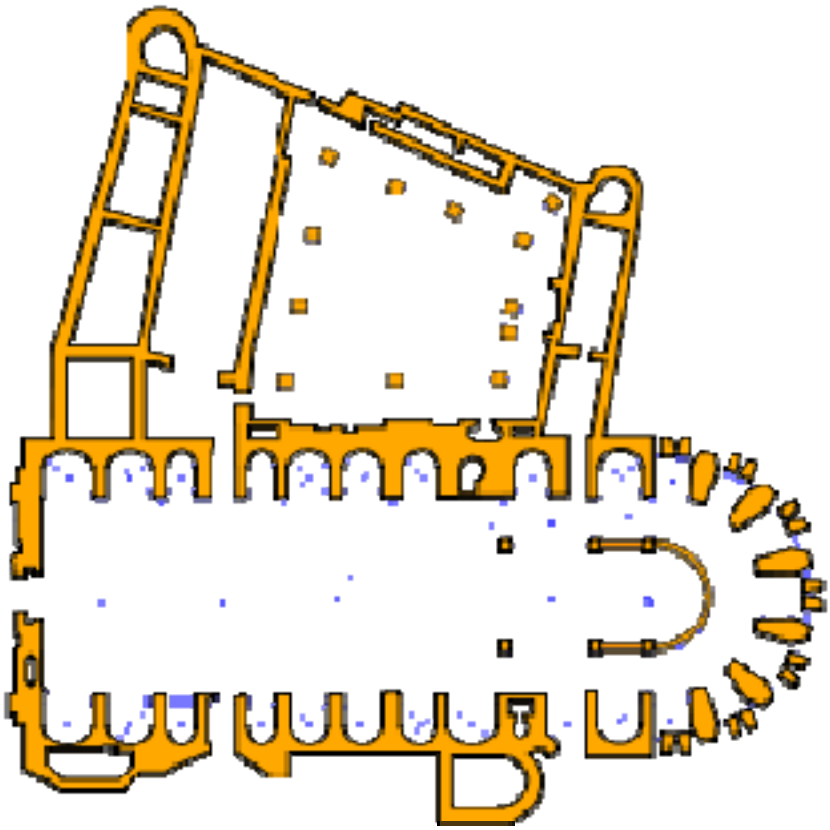


Figure 99– The general plan view of Girona Cathedral (en.wikipedi.org)

*Then during 15th century, it was decided to continue the construction using single vaults to cover the entire width in the transverse direction which lead to the largest cross vault span of Gothic construction, consequently the second and main body is covered with only four large vaults. Lateral Chapels exist between imposing buttresses embedded within the perimeter of the building (as usual in Catalan construction).*The Baroque facade is an ornamented one with a circular rose window and the statues of Faith, Hope and Charity.

Figure 100 – The exterior view of apse

Figure 101 – The flying arches

Figure 102 – The view of the front facade

Figure 103 – The view of the side facade

The orthogonal tower is located in the west facade.

4.4.5 Previous Interventions and Alterations

As it was explained in the history of the construction, the structure has been completed in a long process with the contribution of different people. That can be understood by the inspection of the different materials and techniques even the styles of different parts of Girona Cathedral.

It is known that monitoring has been performed on the structure in order to obtain more information about the cracks regarding their type and movement.

4.5 MALLORCA CATHEDRAL

4.5.1 Location

Mallorca Cathedral is located on the Palma de Mallorca which is the biggest of the Balearic Islands. It stands on the seaside within the bay of Palma facing the Mediterranean Sea.

The cathedral has been the centre of a lot of studies and successfully taken the attention of a lot of researchers and works. As a consequence, it is possible to see the results or the signs of various alterations that have been applied throughout time.

The major buildings around the cathedral's current place are the Palace of the Bishop or the Palace of the Almudania.

Figure 104 – General view of the location of Mallorca Cathedral (maps.goole.com)

Figure 105 – A General view of the cathedral (www.palmademallorca.net/)

4.5.2 Historical Information

Although the structure has undergone a lot of different construction phases and lasted in a long period until it gets its current condition, these works were not reported as much organised.

Regarding the historical information about the cathedral, it is known that there used to stand other structures in Roman period and then a mosque during the Arab period.

The remains that were found in the cloister of the cathedral are interpreted as the parts of the statues that belong to Roman forum previously located around this area. The reuse of paleo-Christian capital is the proof of that these was a religious structure here before the Muslim period (Eu India Economic Cross Cultural Programme. 2003).

Under the researches that have been carried out under the framework of “EU-India economic cross cultural programme, 2003”, the history of the structure was explained and categorised chronologically. As the study refers, the history of the construction was divided into five different periods.

The first period is explained as *“The Royal Construction”* which consists of the period between 1300-1368. The construction works started around 1300 with the support of Jaume II with the Chapel of Trinity. The tombs and the royal family were situated in this section.

The works went on with the completion of the Real Chapel which is the name of the apse part. The construction of this part started in 1311 and lasted until 1370.

In the second phase, the naves were constructed. This period starts in 1368 and lasts in 1601. It was highlighted that the three naves were designed by the architect Jaume Mates who also worked in the construction of the seven orthogonal piers. The stones of the piers were chosen by him from the quarries of Santanyí.

The door of Mirador was started to be done after this process in the year of 1400. The main west facade was completed in the year of 1601 in Renaissance style. Llompart’s article and Domenge’s hypothesis concentrate on the deterioration that happened due to the fall of an arc in the central nave in the year of 1490, April.

After 1600, the “Third Period” lasts until 1851. This period is mainly consisting of the substitution of the west facade. The problems regarding the vaults dominate the main content of this period. The highlights of the period are summarized in the following;

- According to the statement of Jovellanos, a group of experts gathered to inspect one of the vaults close to the facade due to the masonry was full of cracks. The date was registered as 10th of July, 1639 and the need of the rebuilding the vault came out as the result of these discussions and inspections
- Durliat’s researches showed that it was necessary to rebuild one of the arcs in the main nave and the first northern flying buttresses in 1655
- Jovellanos mentions about Domenge’s statement on the falling of an arc on the date of 20th, May in 1659.
- Fontsere states that Palma de Mallorca undergoes an earthquake at the end of March in 1660 and failure of two arcs occurred in this event.
- A report dates back to 1679 was highlighted by Cantarellas. According to this report, west facade displays an out-of plumb of four hand spans. In a second report with the date of 1803, the out of plumb amount is mentioned as four and a half hand spans.
- The reconstruction of the set of vaults on the nave occurred in 18th century after the collapse of the vault of second bay for the second time in 1698.
- In 1706, new collapses of the vaults are mentioned.
- Six flying buttresses were mentioned for propping up in 1739.
- Two new reports were done regarding the condition of the west facade and considering the situation, the definitive report proposing the demolishing of the facade was completed.

The latter period is called as “The reconstruction” period which takes place between 1851 and 1888. The works on dismantling the facade has started and continued during six months. The restoration project which was presented in 1854 completed in 1888. The new facade looking very different than the previous one proposed an increase in the section of the buttresses.

The last phase which is called as “Reforms” consists of the works of interventions. This phase starts right after the completion of the facade and lasts in 2002. This period consists of the contributions of various architects like J. Towers Garcia, Joan Rubió i Bellver, Guillem Reynés, Josep M. Jujol and Antoni Gaudi.

4.5.3 Previous Studies

“Safety assessment of Mallorca cathedral”

By Ajoy Kumar Das

The study is the final report of the Msc-SAHC programme during the perod of 2007- 2008 (first edition).

The content of the study is made of preparation of the numerical model considering the seismic loads and the gravity load. In order to evaluate the structural safety of the cathedral, the typical bay was taken as the base for the model.

Lay-Out of Seismic Strengthening of Mallorca Cathedral

By Patricia Rodriguez

By using also the previous works that have been completed regarding Mallorca Cathedral, this study aims at defining the safety level of the structure. The capacity spectrum method was used and seismic strengthening solution was implemented in the following. For the whole study, the east façade was taken into account. Different collapse mechanisms were added for the façade.

This study is a part of Msc-SAHC programme in the period of 2008-2009 (the second edition).

Static Monitoring Analysis of Mallorca Cathedral

By Emmanuel Godde

The thesis focuses on the post-processing of the static monitoring results of the cathedral. An existing numerical model was used in order to be updated in terms of checking seasonal thermal effect. The results of monitoring and the thermal simulation results were compared.

The final report of the study was delivered in 2009 as a part of Msc-SAHC programme.

4.5.4 Geometrical Characteristics

The cathedral has a main entrance opening to the central nave which has a width of 19.8 meters and 120 meters in length. The other two lateral naves are located symmetrically with a width of 8.75 meters. The structure is extending through east-west direction with an apse, a plain choir and the lateral chapels.

Figure 106 – Front façade of Mallorca Cathedral

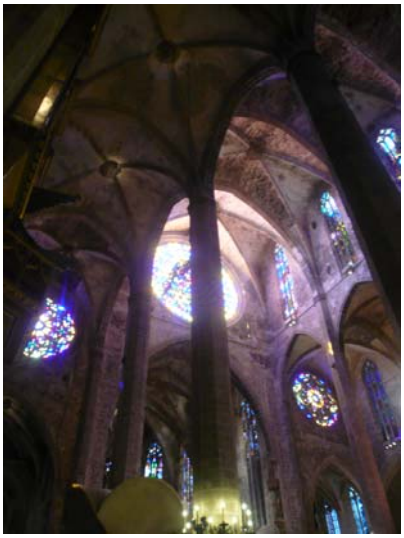


Figure 107 – Interior view of the cathedral

Apart from the main entrance, two side doors allow the access to the cathedral and are called as the door of Mirador and the door of Almonia. These entrances are almost located in the centre constituting a transept like stage.

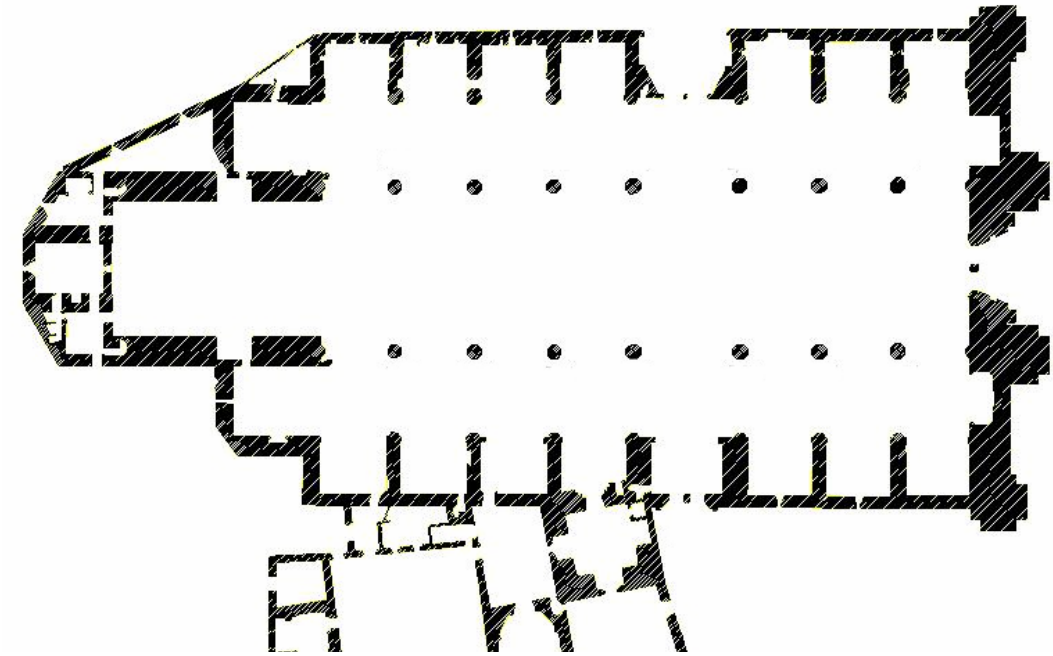


Figure 108 – General Plan Shape of the Mallorca Cathedral

The vertical bearing elements in the building are the piers, the buttresses and the masonry walls.

The studies regarding the morphology of the structure showed that the walls and the buttresses were both composed of block masonry composed of Mares stone which were obtained from local quarries. This kind of stone is a limestone based one with low compression strength. The inner parts of the walls and the buttresses were constructed with the same material as well as the outer leaves and the surfaces instead of the common use of rubble for the inner parts.

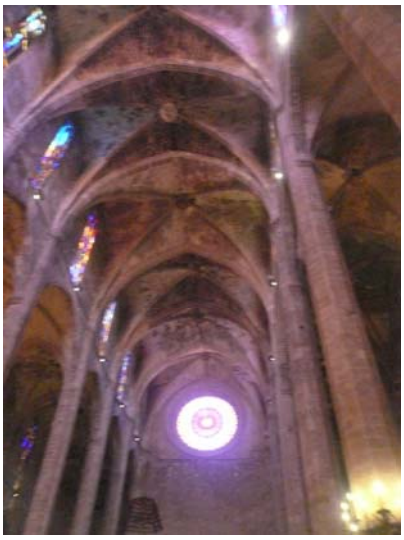


Figure 109 – The cross vaults and lateral chapels

The piers were designed as orthogonal having a diameter of approximately 1.7 meters. The type of the limestone used for walls change in the piers and instead of the one with low compressive strength, another type which has a better quality enduring a much more higher compressive strength was used.

The piers are solid and their section is composed of a large square inner stone and four pentagonal perimeter stones.

The horizontal elements are the flying arches, the vaults and the arches.

Figure 110 – The superstructure of the cathedral

Figure 111 – The flying arches on the cathedral

The structural arrangement of Mallorca Cathedral is quite unique with the use of the double battery flying arches. These arches were placed in order to transfer the lateral thrust of the central vault to the buttresses. Double battery of flying arches also connects transverse arches of the central naves with the buttresses. This creates a diaphragmatic action. *"The overload in the form of pyramid with square base over the key of the central vault provides vertical stability so far the in conjunction with the upper battery of double flying arches (Rodriguez, P. 2009".*

The vaults are not filled with rubble masonry as it is usually more common but slender stone wallets and slabs which are very light were used.

The Gothic cathedral is very important with its high central nave reaching up to 43.95 meter in the key stones and lateral naves extend to a height of 29.4 meter. The slender piers are 22.7 in height. The other difference that the cathedral has is the double battery flying arches. There are still discussions on the structural role of the upper battery of the flying arch.

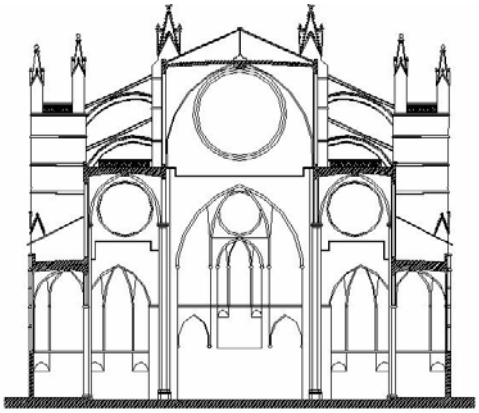


Figure 112 – The section showing the apse

Figure 113 – The interior view showing the apse

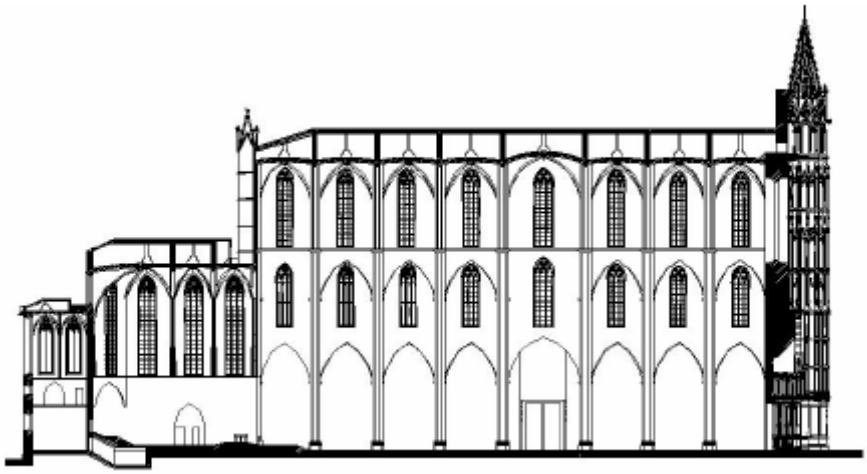


Figure 114 – The longitudinal section showing the side chapels

4.5.5 The Previous Interventions, Alterations and Damage

The first of the seismic events recorded as it has damaged the cathedral was in 1660. In the report of "Economic Cross Cultural Programme", it is indicated that Fontsere mentions about this earthquake explaining that the intensity was VII and it caused the collapse of the two arcs near the facade. The first report which was only written almost 20 years later of this event highlights that the vertical deviation in the facade was four hand spans. A possible correlation between the current out of plumb with this earthquake can be set.

The second earthquake registered was on the 15th May in 1851 with an intensity of VI and VII. The deteriorated parts on the facade collapsed as a consequence of this event.

The list of the earthquakes that influenced the area is documented as the following but due to the lack of any written information about the results and the effects of the other earthquakes that happened is not known clearly. Additionally in some reports, it is indicated that this damage mentioned due to earthquake already existed before these events.

1660- 18/19/26 March	Palma de MALLORCA	VII
1773- 7/8 December	Palma de MALLORCA	V-VI
1835- 16 June	Palma de MALLORCA	V
1835- 14 October	MALLORCA	VIII
1851- 15 May	MALLORCA	VI-VII
1852- 31 September	MALLORCA	V
1859- 18/19 March	Palma de MALLORCA	-
1876- July	Palma de MALLORCA	-
1880-1881	MALLORCA	-
1887- 6 May	Palma de MALLORCA	III
1887- 7/8 September	Palma de MALLORCA	IV

Table 6 – The recorded earthquakes influenced the area between 17th and 19th centuries

5. RECOGNITION OF THE DAMAGE

5.1 DAMAGE IN SANTA MARIA DEL MAR

General Damage and Deteriorations

Although the framework of this study is taking into account of the structural damage in order to relate these with the seismic occurrences, the other problems like the decay and the damage due to other reasons will be mentioned very briefly.

Santa Maria Del Mar has been suffering and still suffers from some major problems like discoloration, biological attack and erosion of the mortar on the joints.

Figure 115 – The visible loss on the cross sections of the masonry piers due to the fires (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

The results of the big fire that occurred in 1936 are still visible on the columns and walls which show difference than their original dimensions and from the black stains visible generally in most of the vaults, arches and stone surfaces. Some the columns have lost their original cross sectional area due to these fires. Although the columns have a high resistance due to the compact morphology they have, this loss of material situation makes them more vulnerable to the future possible damaging occurrences.

Apart from this, it is possible to observe some fissures on the columns resulting with the spallings on some parts of them. These cracks may be related to the high tension as a result of the deformations of the vaults and arches. The previous studies showed that the columns show a leaning of approximately 2 to 8 cm in transversal direction and of 4 to 7 cm in longitudinal direction (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007). Although this amount of leaning is considered in the normal limits for a historical structure like Santa Maria Del Mar (equal or less than 1/200), it is

important to analyze the reasons and the possible results with also the possibility of the further leaning in the future. The possible reasons of this leaning in the columns may be the construction process or the foundations since we already know that the foundation of the structure have components of previous buildings.

The construction joints seem to have been lost and in some parts, they started to open. The splitting of the material on the masonry columns and loss of material are highly observed. This is also mostly due to the fires that occurred in 1378 and 1936. The weather conditions and the humidity may also have contributions on this problem.

Santa Maria Del Mar still carries the effects of the Civil war period. The holes as a result of the bombing are still visible on the facades. These holes are the results of the years 1714, 1936 and 1939.

The vegetation and the small plants with their roots are causing damage on the stone surfaces especially on the buttresses and the upper levels of the facades. Discoloration is also observed as a result of humidity affecting the stone material especially on the facades.

The opening mortar joints are possibly due to the different construction periods which can cause to form cracks. The difference than the structural cracks is that these cracks are following the joints without damaging the stone units. This problem affects the perimeter walls and apart from the constructional reasons, these can be correlated with the differential settlements.

The leaning of the towers have also been measured. While the eastern tower shows a leaning of 6 cm, western tower shows a leaning of 15 cm longitudinally and 13 cm transversally (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007). As it is already known that the ancient earthquakes (1373) damaged the Eastern tower, this leaning can be correlated with the seismic actions. The amount is still less than moderate.

Figure 116 – The view of the holes due to the bombings during Civil War (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

Structural Damage

One of the general problems in the cathedral is mainly the vertical and diagonal cracks which can be traced both interior and exterior façades.

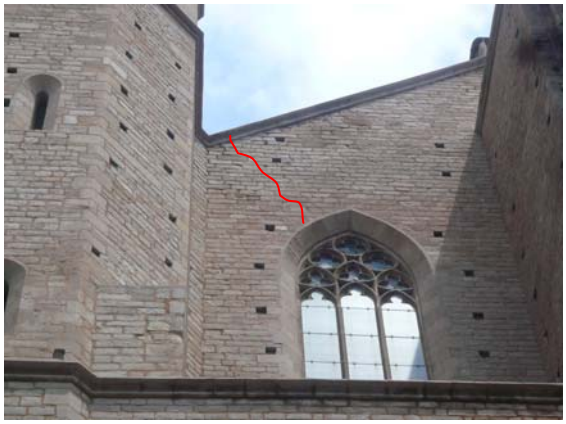


Figure 117 – The repaired crack on the main facade

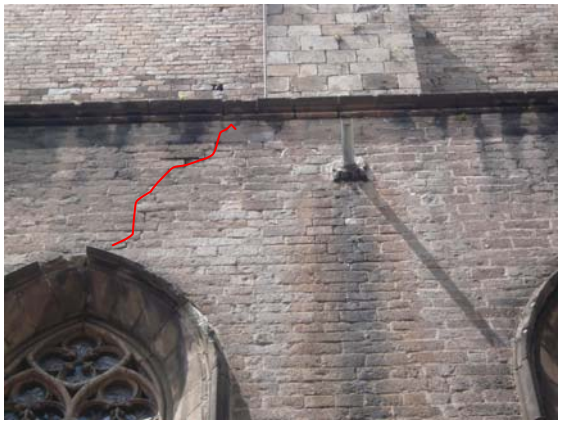
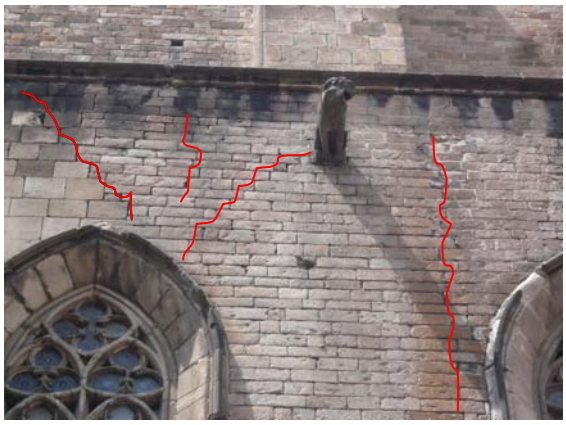


Figure 118 – The inclined crack on the façade

The crack pattern shows a similar behaviour generally in the building. Most of the cracks are usually visible starting from the lower level of the window and extending until the upper level of the arches of the side chapels. The cracks generally tend to appear diagonally following the mortar joints. The damage is more common on the apse part where the construction seems to have experienced some interventions in time. These interventions can be traced by the different construction technique and the material of the walls on the right direction of the apse entrance.



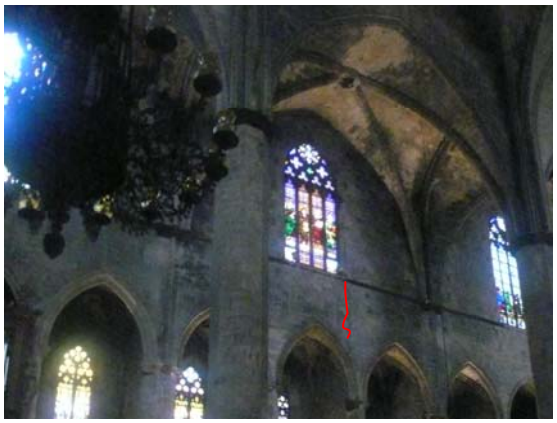


Figure 119 – The cracks following the joints on the exterior and the interior façades

The damage due to these diagonal and vertical cracks can be visible from exterior facades too.

The diagonal cracks concentrate on the main facade where the rose window is located. Two cracks which can be assumed as almost symmetrically corresponding each other are visible starting from the lower part of the rose window extending through and crossing the sill that defines the lower level of the stained glass windows on the upper level. The other crack almost in the same level shows a pattern similar to those two cracks closer to the one on the right finishing on the level of the sill.

The upper crack extends until the centre of the main arch. This crack is also diagonal.

Figure 120 – The cracks around the rose window

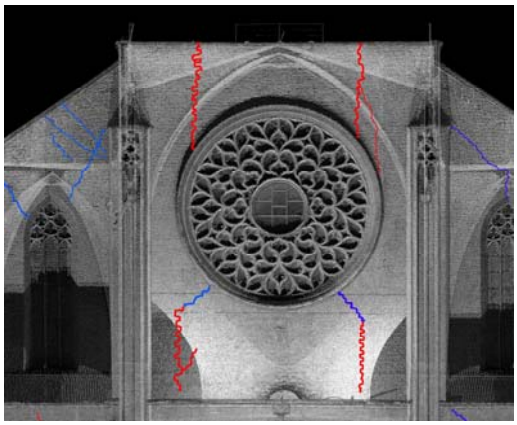


Figure 121 – The crack pattern on the exterior façade around rose window

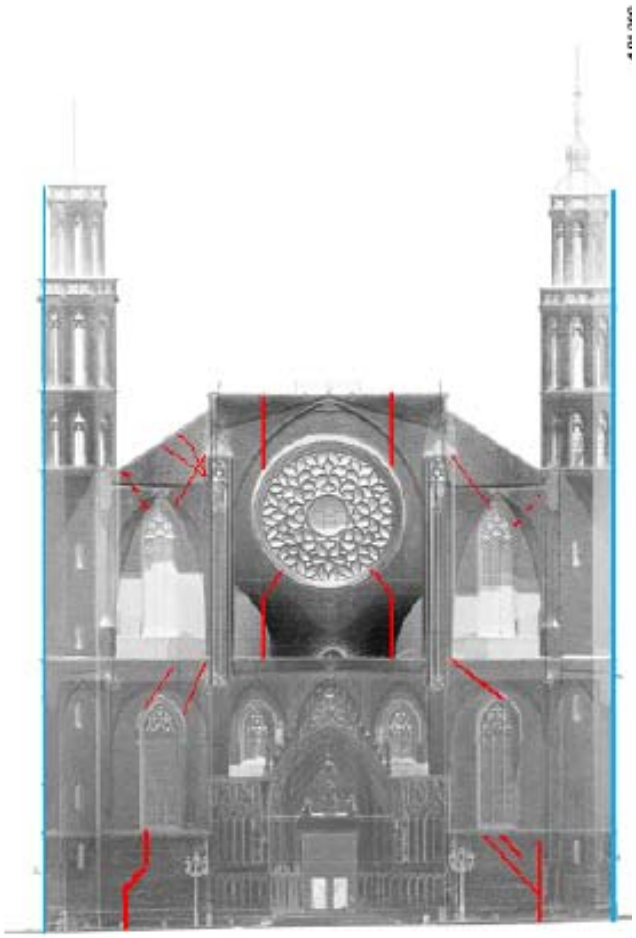


Figure 122 – The crack pattern on the front façade according to the previous studies (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

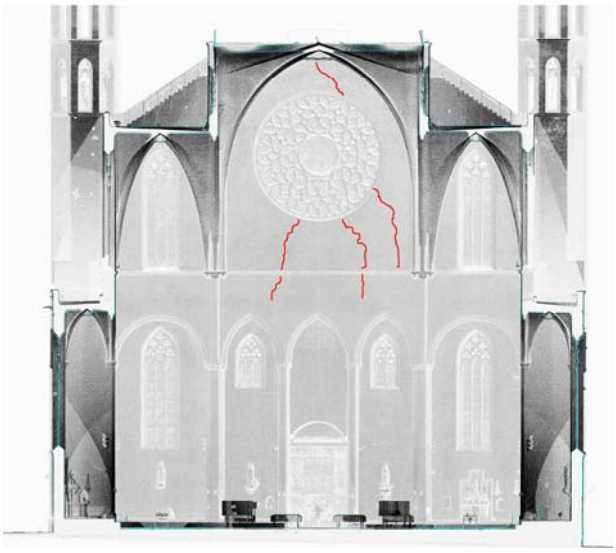


Figure 123– The crack pattern on the interior of the front façade

The vertical or inclined cracks which are visible under and above the openings could possibly be due to the earthquake and it can be explained as they made it possible to dissipate the seismic energy by cracking. If the possible reasons of these cracks are likely the earthquake, these cracks indicate that they prevented further damage in structural components in general.

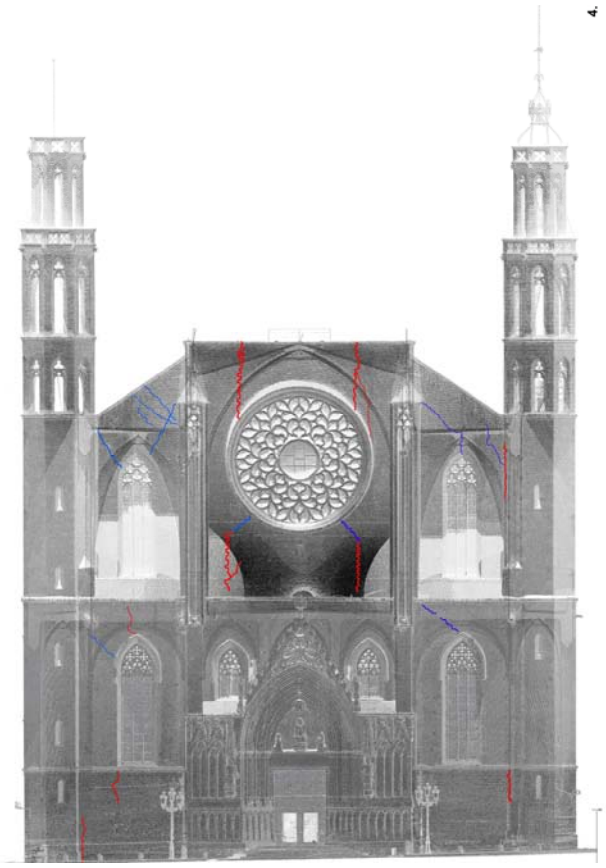


Figure 124 – The crack pattern on the front façade (June 2010)

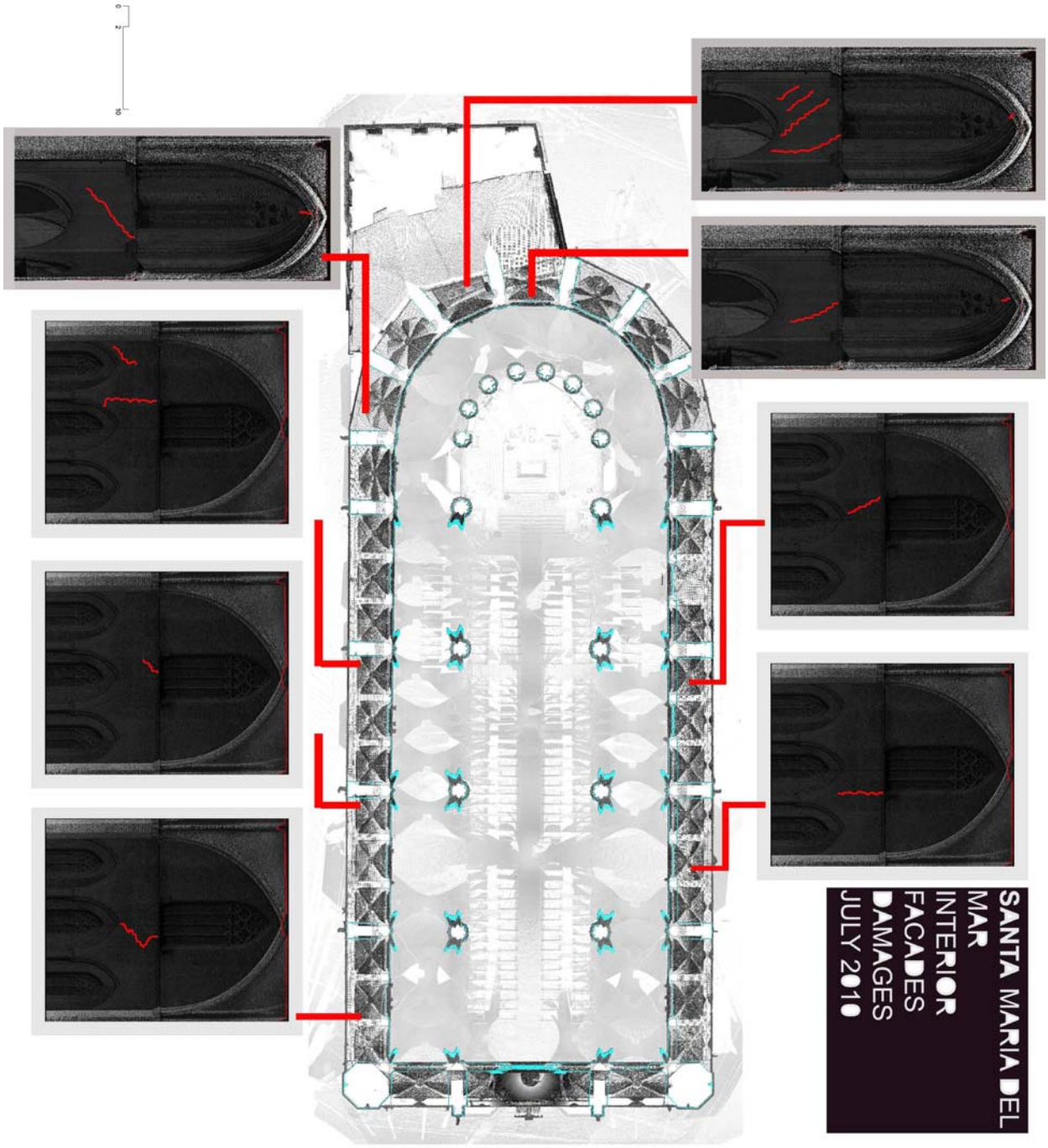


Figure 125 – The crack pattern on the interior façade

Figure 126 – The damage pattern on west façade

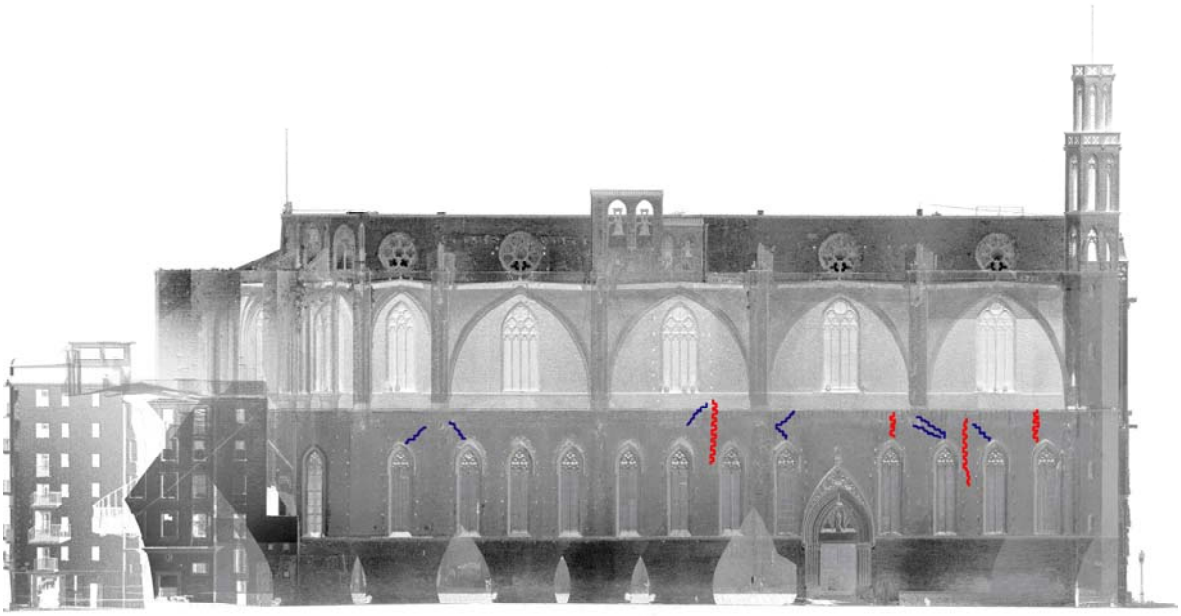


Figure 127 – The damage pattern on east façade

5.2 DAMAGE IN SANTA MARIA DEL PI

The stone surfaces have similar deteriorations as Santa Maria Del Mar. The surfaces of the stones in some parts on the facades are diffused, the mortar on the joints is lost and the shape of the stones is distorted due to the loss of material and erosion.

Vegetation is another problem that the structure is under the influence of.

Structural Damage

The crack which is located on the connection of the side walls with the main façade is an important damage. The crack is being monitored as a part of the previous studies. This crack is located on the northeast side whereas there is a symmetrical crack which is not as wide as this one on the southwest facade. These cracks are possibly due to the tendency of the separation between the facade and the side walls. The possible reason for these cracks can be seismic actions. The cracks have been repaired in the previous restoration works and after monitoring, the studies showed that these cracks are stable.

Figure 128 – View of the extending crack on the lateral wall connected to the main façade (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

There is out of plane movement of the side towers. The previous studies were able to define the total displacement of the two towers. The west tower shows a more significant leaning with up to 12 to 15 cm while the measurement of the leaning on the east tower shows up to 2 to 5 cm. This difference is actually can clearly be seen by visual inspection. The tower shows a ratio of 1/100 leaning when it is compared to the height which is an acceptable amount when considering the age of the structure. The studies that showed that the main facade shows a leaning up to 30 cm on the east and 16 cm on the west part (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007).

Figure 129 – The leaning of the front façade

There is a set of cracks on the main façade especially around the rose window. The inclined cracks following the joint mortars are located in the lower level of the rose window. Similar types of cracks are lying on top of the rose window. Some of these cracks are already repaired and it is possible to see the opening of some of these cracks in a low degree. The extending cracks are also visible along the façade between the towers and the main body. This separation is one of the most important problems of the structure.

Figure 130 – The structural cracks under the rose window

Figure 131 – The reconstructed part and the cracks above the rose window

Figure 132 – The extending crack on the main façade

There are two inclined cracks on the perimeter wall of the apse part. These two cracks show behaviour almost symmetrical to each other. This type of cracks especially when they are X shaped can be an indicative of a shear failure due to the seismic actions. But still these cracks can be the result of a differential settlement or these cracks can be interpreted as relieving arches.

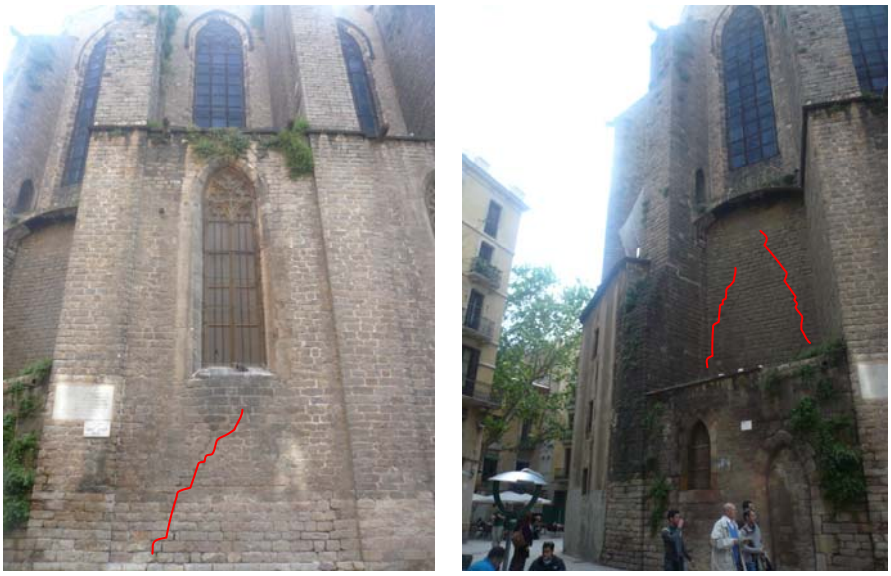


Figure 133 – Inclined cracks on the apse wall

The upper part of the rose window shows a different pattern. It is obvious from the difference on the stone material that this part has been reconstructed before.

Some of the arches and vaults have in plane deformations. The differential settlement of the two sides of the structure may have a contribution on the asymmetrical deformation of these arches and vaults. Some of the arches have lost the original shape in its plan configuration. The possible reason for these types of deformations may be related to the construction processes.

Figure 134 –The deformation of the arches (Caballe, F., Giraldez, P., Gonzales, R., Roca, P. Vendrell, M. 2007)

The side façades show cracks and separations which extend over the windows without damaging the stone units by following the mortar joints. In some parts, the cracks start from the ground level going up until the lower parts of the openings. Same types of cracks appear between the perimeter walls and the buttresses. These cracks are mostly vertical following the joints. The reasons of the cracks which especially start from the ground level are possibly due to the differential settlements.

The deformation and the cracks on the interior surfaces are important. They are visible on the typical bay of the structure.

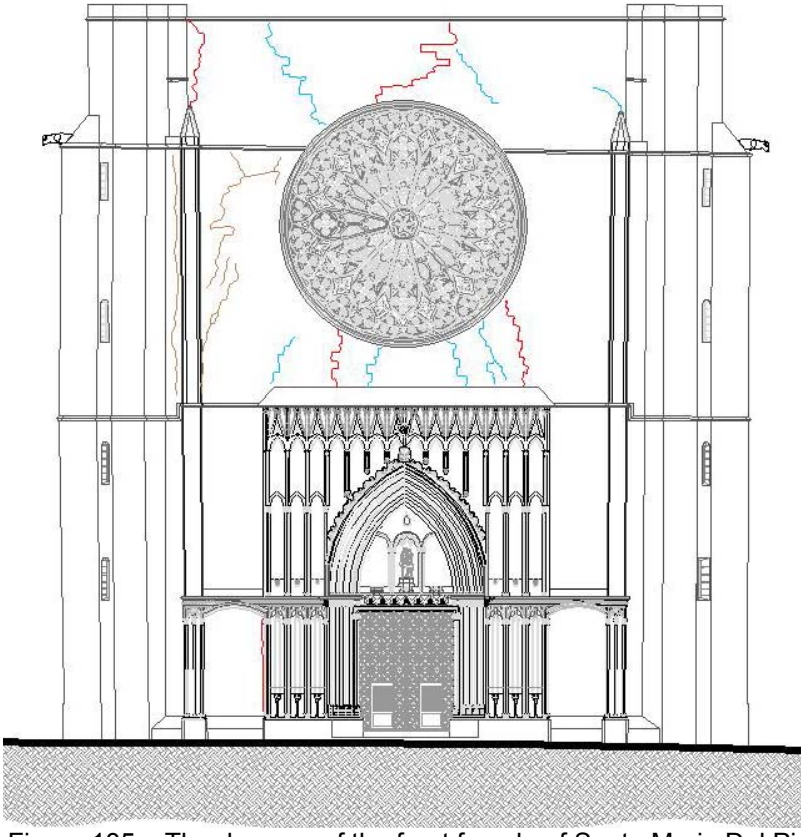


Figure 135 – The damage of the front façade of Santa Maria Del Pi

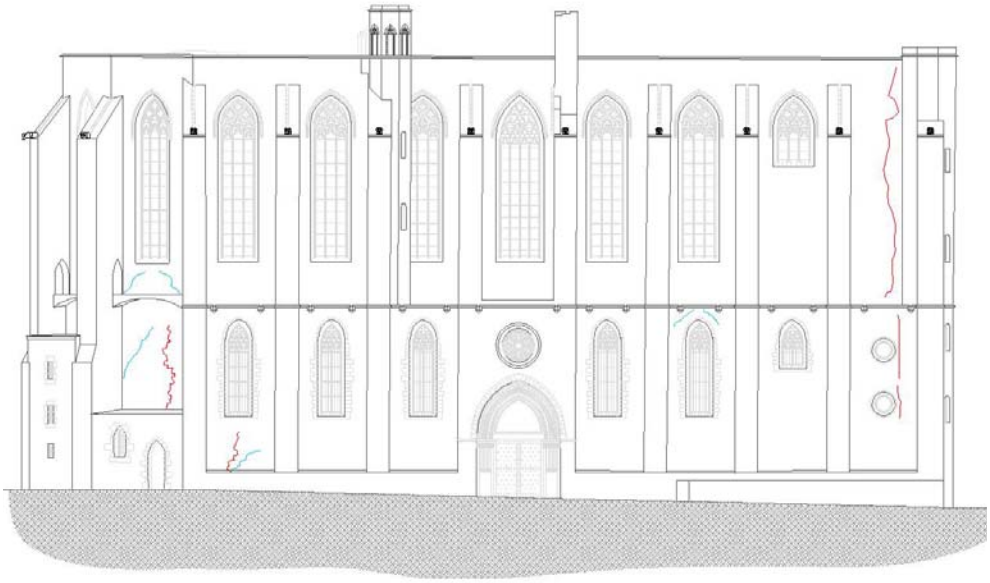


Figure 136 – The damage pattern of the side façade of Santa Maria Del Pi

5.3 DAMAGE IN BARCELONA CATHEDRAL

The visual inspection showed no damage on the vertical bearing elements. Since the frontal façade is under restoration, there is not any visible damage.

The separation on the joints is the main structural problems on the interior surfaces. This occurrence doesn't affect the vertical components and they are mainly concentrated on the cross vaults and the arches. The lateral chapels seem not to be influenced by any visible structural damage. The horizontal bearing elements constituting the superstructure of the main nave and the lateral nave on the left of the entrance have problems like the separation of the joints as mentioned. These problems are mainly concentrated around where the cimborio is located. The possible reason for this type of damage can be the different behaviour between the two parts where the high amount of load due to the cimborio exists and where it doesn't.

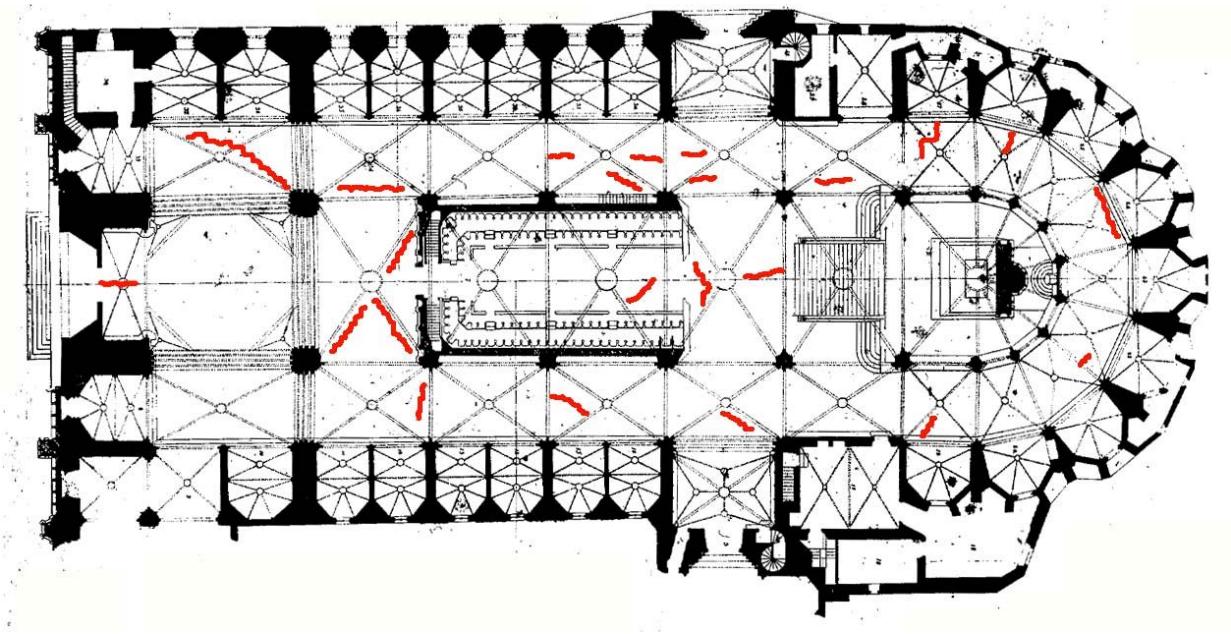


Figure 137 – Crack pattern on the vaults of the cathedral

5.4 DAMAGE IN GIRONA CATHEDRAL

Even though the structure is generally in good condition, there are some deformations and structural damage is visible. Deformation is observed in the internal vertical parts of the buttresses.

The cracks existing close to the windows are likely to be in fact construction joints as expansion ones.

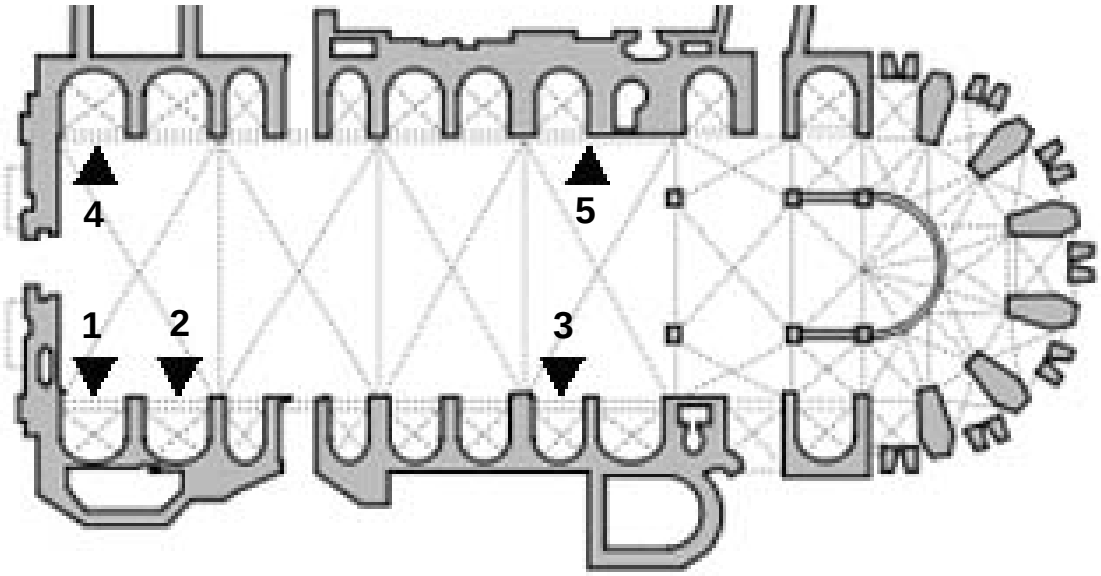


Figure 138 – The plan view showing the places of the damage

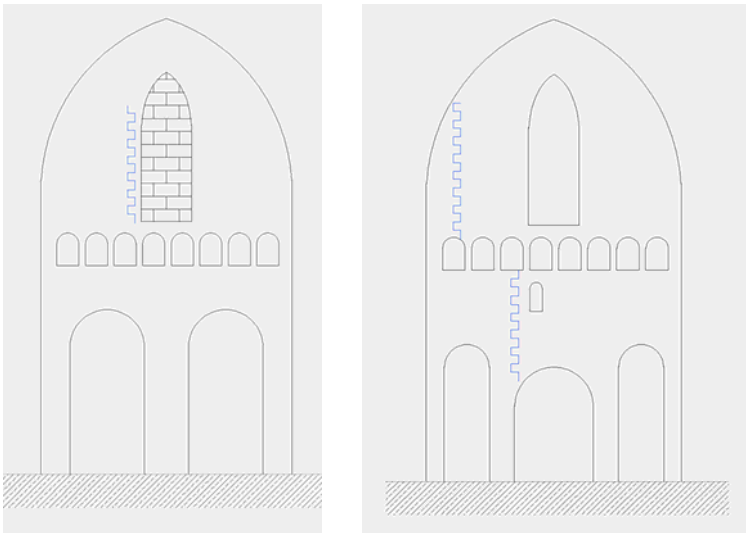


Figure 139 – The interior decays of number 1 and 2 regarding the Fig. 104

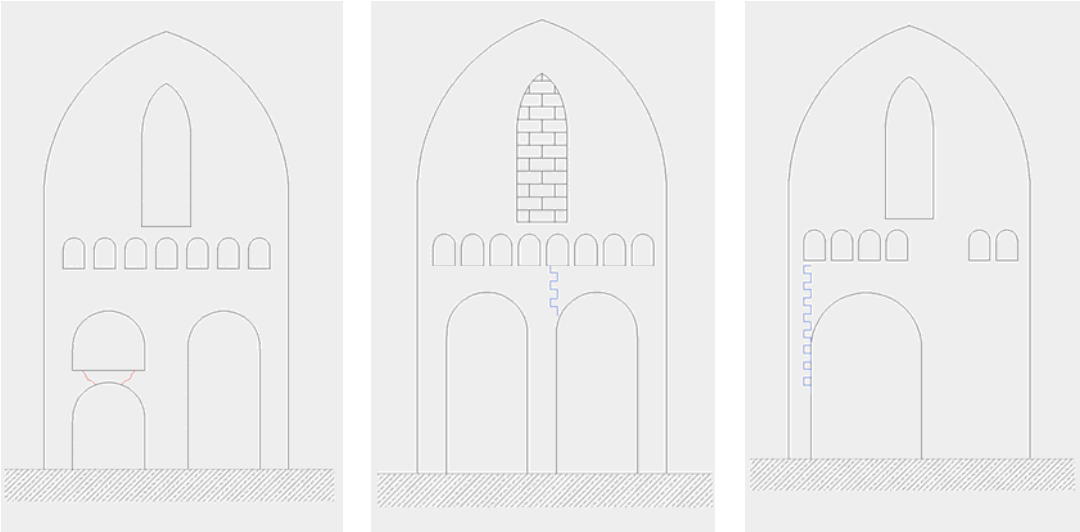


Figure 140– The interior decays of number 3, 4 and 5 regarding the Fig. 104

Regarding the damage, it is difficult to conclude that the cracks are due to an earthquake. During the time of the earthquake which happened along 1427-1428 and caused a lot of damage on the structures around Catalonia, the cathedral was not built completely yet at that time.

5.5 DAMAGE IN MALLORCA CATHEDRAL

The cathedral has some visible deformations and damage at present. The main frontal façade which faces to the west direction doesn't show any significant damage due to it has been recently restored.

Figure 141 – The south façade of the cathedral

Figure 142 – The rose window on the front façade

Before mentioning about the structural damage, it can be concluded that there is a general problem regarding the vegetation that especially influence the east and south façades where the restoration works have not been extended to. Discoloration on the stone units and loss of material is also observed.

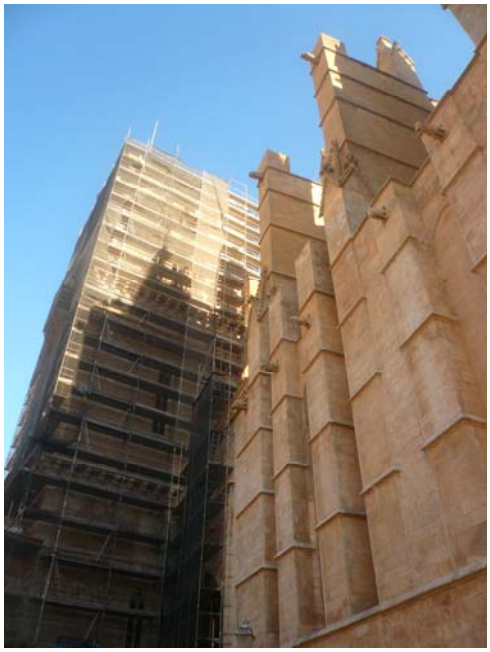


Figure 143 – The scaffoldings on the cathedral

Figure 144 – The vegetation on the façade

The southern direction of the structure where leads to the side entrance to the lateral chapels and the attached units is still under restoration and is covered with auxiliary equipments such as scaffoldings at present. Due to these works, it is not possible to undertake a whole visual inspection on these parts. The works that *González and Roca (2000, 2003-2004)* undertook showed the problems of the structure. These previous studies are very important since they indicate the main problems the structure shows in its recent history.

The reports on the previous works show that first significant problem is visible on the piers. The masonry piers show a curvature and lateral displacement in both directions (longitudinal and transverse) of the nave. Some cracks are visible on some piers. These cracks are mainly vertical shaping surface wedges partially expelled from the core of the pier. Significant deformations are visible on the flying arches. There are some signs showing the possibility that some of the flying arches were propped by some masonry columns and walls in order to prevent their possible failure. The cracks developed in the contact area of the transverse arches and the vaults of the central nave separated with each other by wide cracks (Das, K.A. 2008).

Figure 145 – The prop ups between the flying arches

Figure 146 – The cracks on the vaults (Eu India Economic Cross Cultural Programme. 2003)

The interior façades show damage due to the separation of the joints. The separations following the joints extend especially on both sides of the stained glass under the level of cross vaults. These cracks seem like construction joints rather than the structural problems. These separations generally follow an extending line going to the upper levels.

An extending crack is located on one side of the secondary entrance located on the east direction. This crack is more likely due to the differential settlement of different parts of the structure like the buttresses and the lateral walls.

The chapel located next to this entrance shows the signs of the previous alterations. The plastered interior surface of the chapel shows deep inclined cracks in various parts. The plaster seems to have a cement based character.

Figure 147 – The cracks on the plastered chapel

The buttresses and the lateral walls show some extending vertical cracks on the south direction. The same type crack is also visible on one of the lateral wall between two buttresses. This crack starts under the circular openings located on the chapels and extending to the lower levels.

Figure 148 – The vertical crack between the buttresses

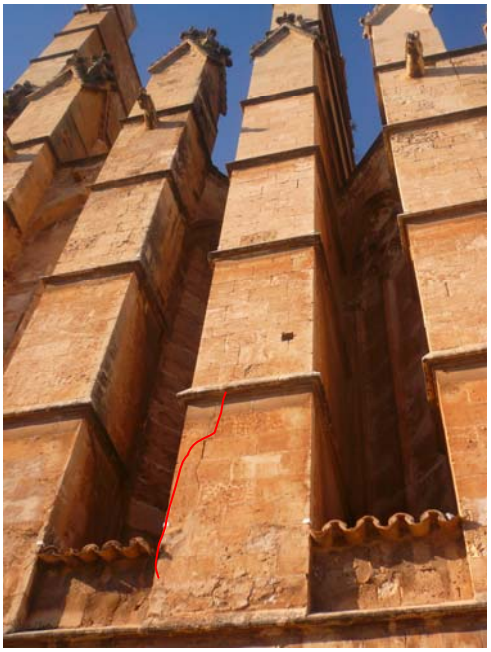


Figure 149 – Extending crack on the buttress

Apart from these problems, the most significant problem of the cathedral is the symmetrical inclined cracks. The cracks are located on the lower part of the stained windows located over the chapels and extend to the frontal lateral wall. On the right side of the entrance, there is also one extending and one repaired crack located on the sides of the stained glass windows between the two first chapels. The deformation regarding the out of plumb of the front façade is visible on both sides of the main entrance from interior. Two extending cracks going up to the rose window are located on both sides of the main entrance door from interior façade.

The east part of the structure where the apse part is located constitutes a vulnerable section since the height shows difference here. Due to this height difference, stiffness changes and a weak part occurs due to this.

Figure 150 – The inclined symmetrical cracks extending to the front façade

The damage in Mallorca Cathedral was planned to be controlled by the application of monitoring. The selected instruments were placed in the summer of 2003. The equipments aimed at measuring the impacts or the situation of the following;

- Temperature and humidity,
- Wind direction and velocity,
- Horizontal displacement between points,
- Piers inclination,
- Cracks (Godde, E. 2009)

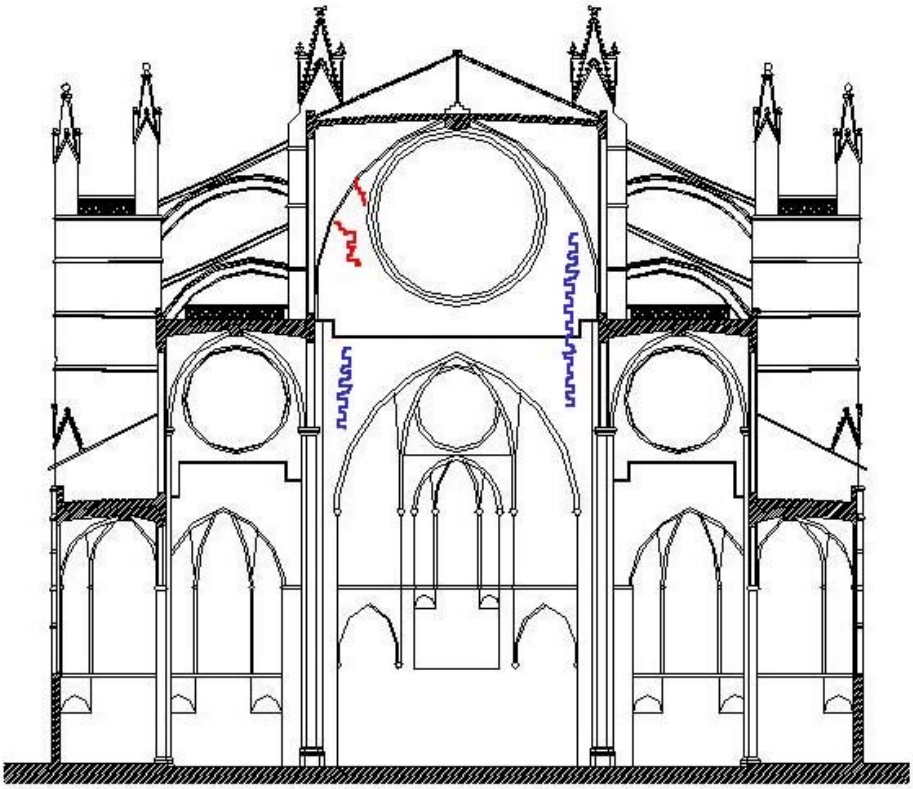


Figure 151 – The damage pattern on the interior of the apse part

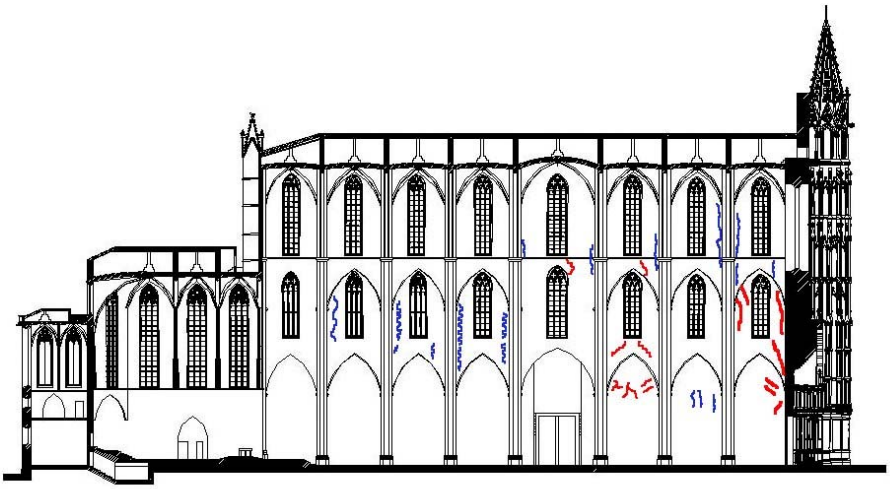


Figure 152 – The damage pattern on interior surface showing the right side of the entrance

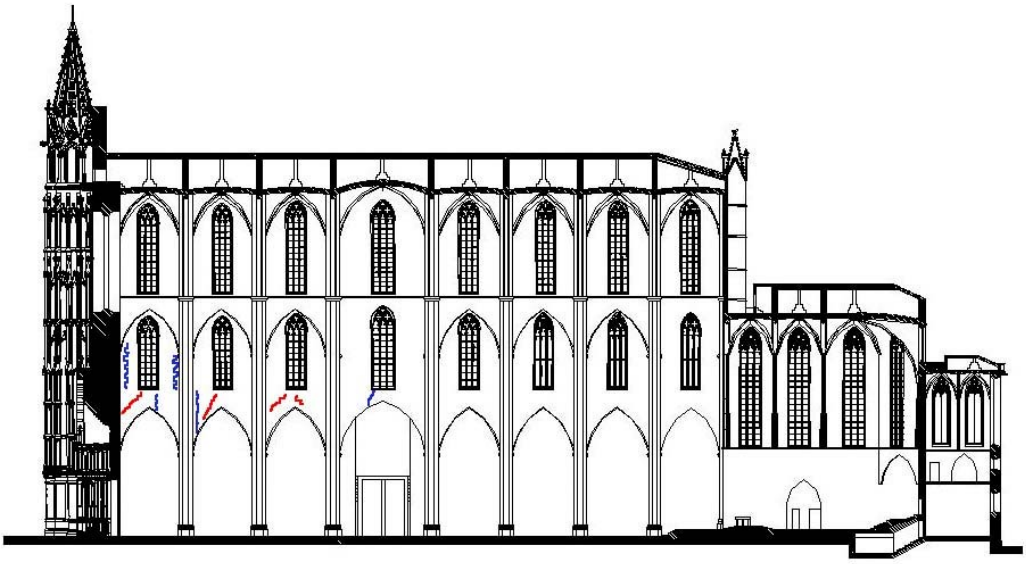


Figure 153 – The damage pattern on interior surface showing the left side of the entrance

Figure 154 – Extending decay on the entrance following the joints

The interior wall of the entrance shows decay as the extending cracks following the joints. The cracks seem like they are construction joints.

6. EVALUATION OF THE POSSIBLE COLLAPSE MECHANISMS

6.1 Santa Maria Del Mar

This part of the document will present the study in defining the possible collapse mechanisms the structure may experience following a seismic action. The possible mechanisms were defined considering the damaged parts trying to understand how the structure can behave. For this assessment, the most vulnerable parts of the church were considered. The most common parts to consider in terms of the occurrence of the possible collapse mechanisms for the churches are in the following;

- Bell towers
- Principal facade
- Apse
- Typical bay

Bell towers and the principal facade will be taken into account for the case of Santa Maria Del Mar. Considering the damage and evaluating with the typical collapse mechanism, we can conclude that the apse doesn't have a possible risk of collapse.

The most likely failure mechanisms that may occur can be categorized as the following;

- Overturning of the facade
- Overturning/ collapse of the upper part of the facade
- Triumphal Arch
- Bell tower
- Overturning of the upper part of the tower

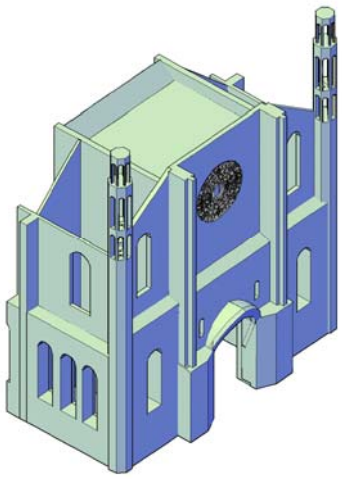


Figure 155 – The basic model of the front façade of Santa Maria Del Mar

6.1.1 Mechanisms- Main Façade

6.1.1.1 Out-of Plane Deformation / Overturning of the Main Façade

The general indicatives of this damage are;

- The existing cracks on the connections between the frontal and lateral façades.
- The vertical cracks on the main façades
- Lack of proper connections of the lateral walls

The vertical cracks that are visible on the frontal façade and around the rose window are important to activate this kind of failure mechanism.

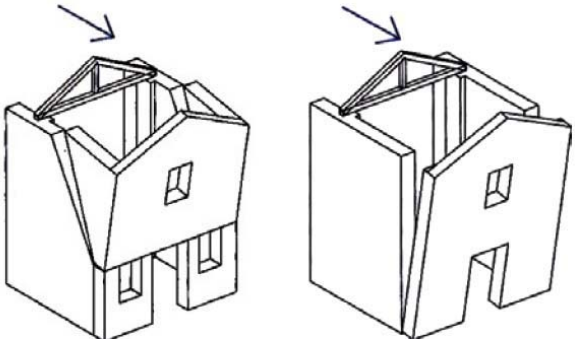


Figure 156 – Collapse Mechanism- Overturning of the Façade

These cracks are among the most important reasons why this mechanism should be taken into account. These cracks can activate this type of mechanism. But since the cracks seem like they have not reopened after the restoration in 1994, this mechanism is not the dominant mechanism that is likely to happen.

Overturning of the Main Facade	

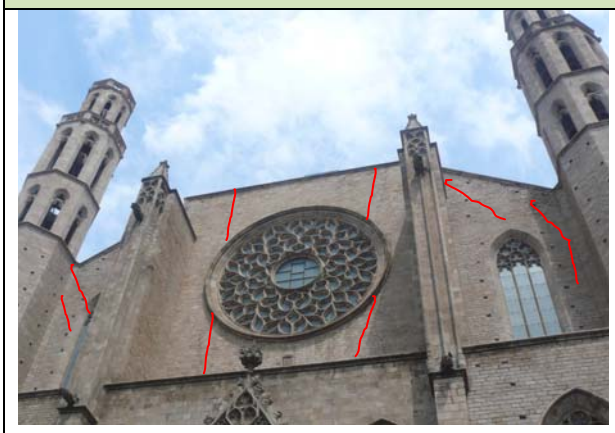
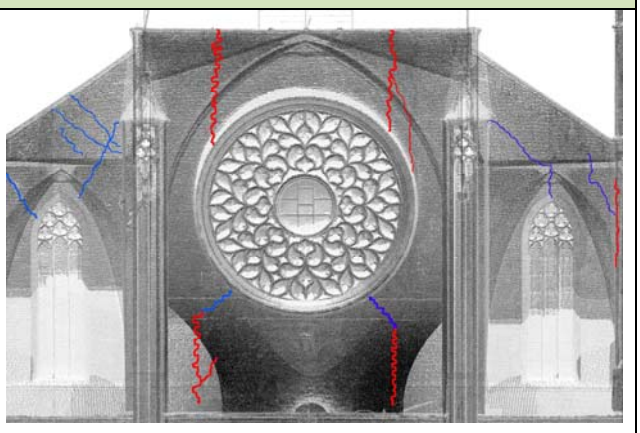

	

Figure 157 – The picture of the damage on the front façade	Figure 158 – The crack pattern on the front façade

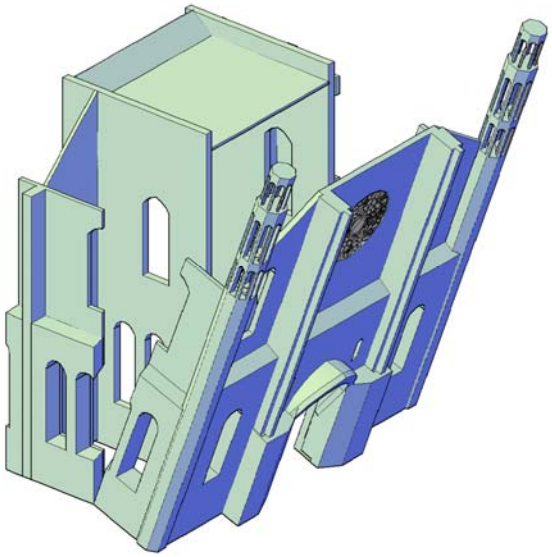


Figure 159 – The model of the collapse mechanism-
Overturning of the total façade

6.1.1.2 Out-of Plane Deformation / Overturning of the Upper Part of the Main Façade

The cracks which are visible on the upper parts of the front façades are usually the indicatives of this type of mechanism.

The reasons of these types of damage may be the differential settlements of the lower part of the façade and the superstructure. The differences in thickness of the wall through the height can trigger this phenomenon.

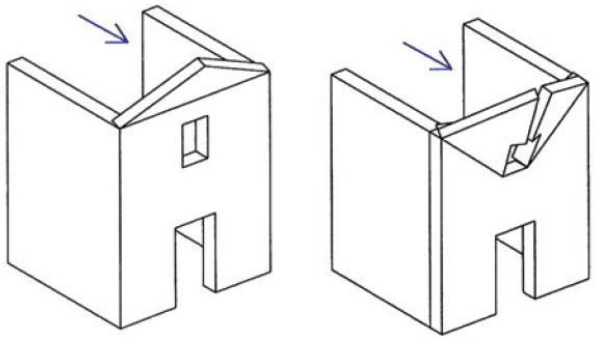
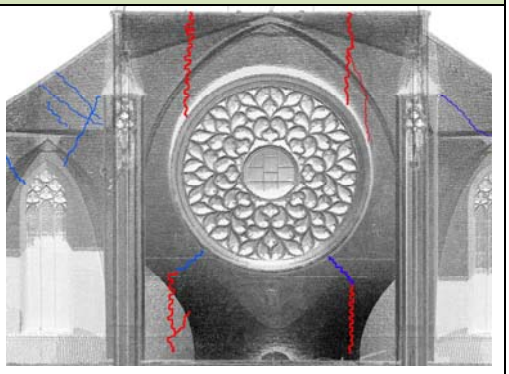


Figure 160 – Collapse Mechanism- Overturning of the Upper Part of the Façade

The repaired cracks around the rose window and the historical information regarding the collapse of this rose window after the earthquake of 1428 are the data that leads to the possibility of taking into account of this type of mechanism.

Overturning of the Upper Part of the Main Facade	
	
Figure 161 – The damage around the rose window	Figure 162 – The crack pattern on the upper part of the façade

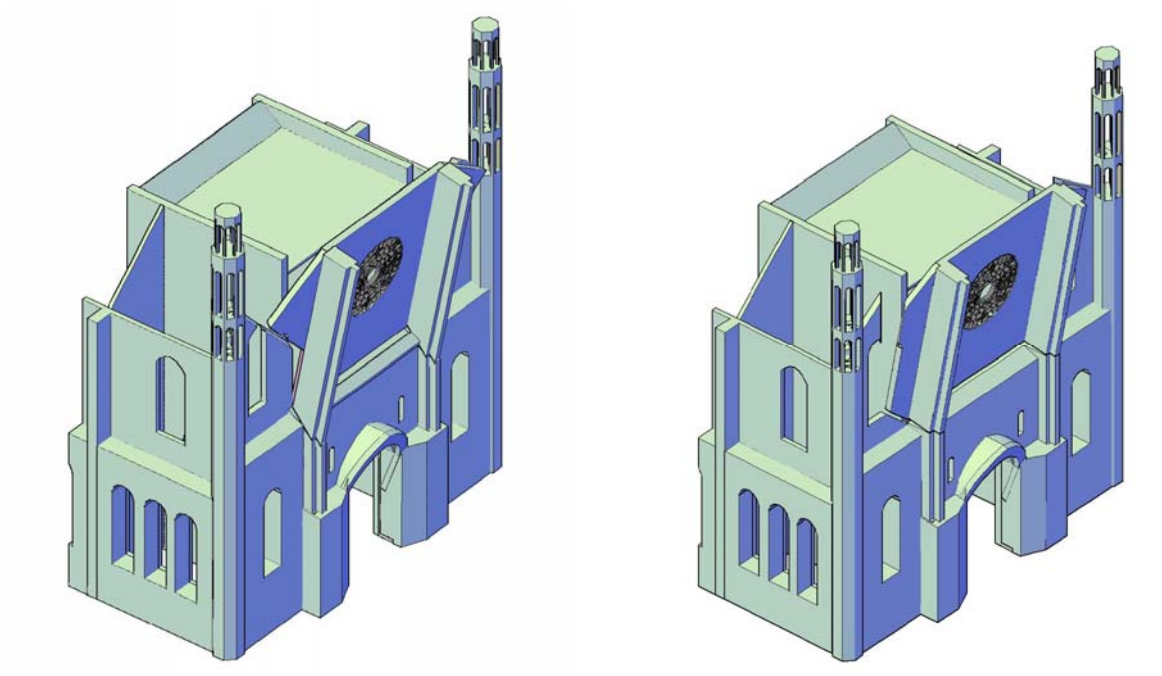
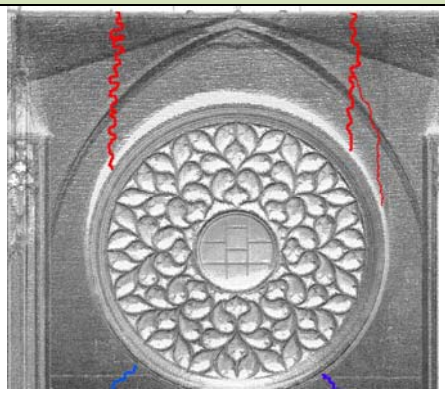


Figure 163 – The model of the collapse mechanism- Overturning of the upper part of the total façade

In the figure 163, the possible collapse mechanisms are shown. The model on the right shows a mechanism more likely to happen in terms of the damage observed.

6.1.1.3 Out-of Plane Deformation / Collapse of the Upper Part of the Main Façade

The existing damage pattern shows extending cracks on the upper part of the rose window. These cracks constitute a weak part on the opening and it should be considered among the vulnerable parts in case of an earthquake.

Collapse of the Upper Part of the Main Facade	
	
Figure 164 – The damage on the upper part of the rose window	Figure 165 – The crack pattern on the upper part of the façade

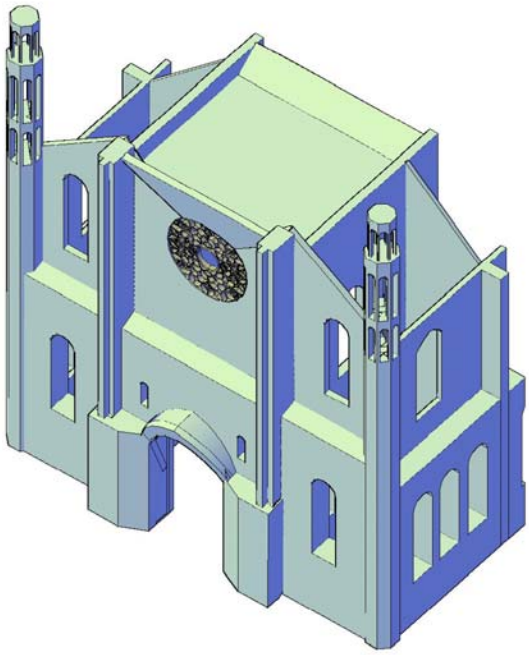


Figure 166 – The model of the collapse mechanism
- Collapse of the Upper Part of the Main Façade

6.1.2 Mechanisms- Bell Towers

6.1.2.1 Out-of Plane Deformation / Separation of the Bell Tower

Although the leaning of the tower is in low limits as it was indicated in damage section, it is important to consider the collapse mechanisms that are related to the bell towers. The indicatives for taking into consideration of this type of failure mechanism are as the following;

- The historical information about the partial collapse of the bell tower in 1373.
- The crack pattern which can be interpreted as a possible path for the possible tendency of separation of the tower from the part where the cracks are visible around the opening on both sides of the frontal part.

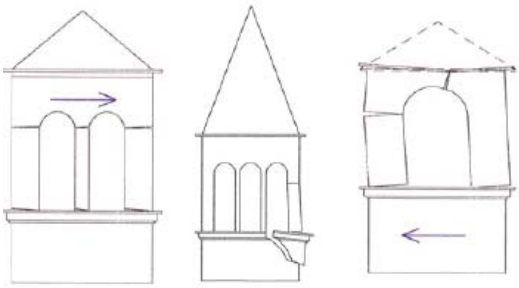
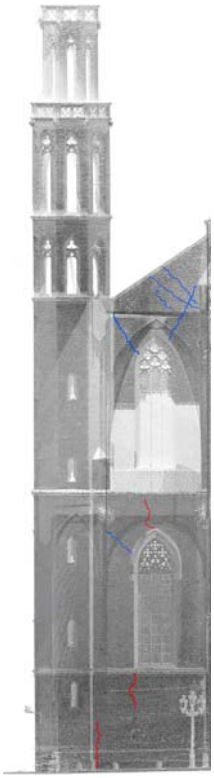


Figure 167 – Collapse Mechanism- Separation of the bell tower

Out-of Plane Deformation / Separation of the Bell Tower	
 Figure 168 – Photo of the damaged part on the front façade	 Figure 169 – The crack pattern regarding the bell tower

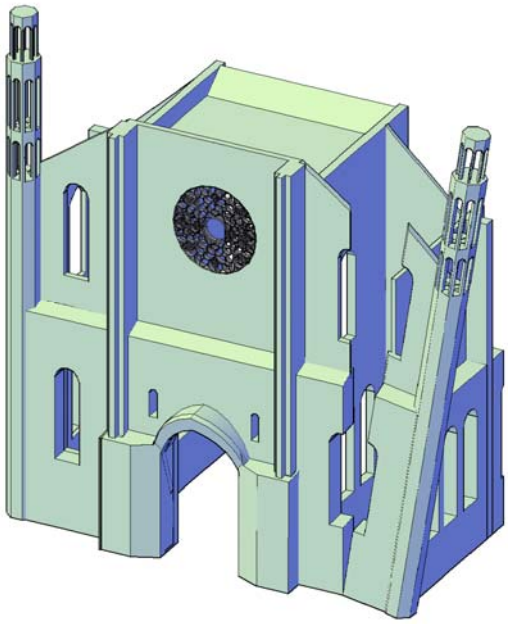
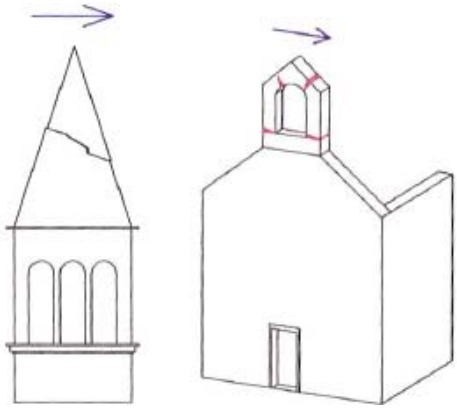


Figure 170 – The model of the collapse mechanism-
Separation of the bell tower

6.1.2.2 Out-of Plane Deformation / Collapse of the Upper Part of the Bell Tower

The towers of the cathedral are very slender in the plan shape and they extend to the highest point of the structure. These facts make them among the most vulnerable elements in terms of seismicity.

Out-of Plane Deformation / Collapse of the Upper Part of the Bell Tower	
 Figure 171 – Photo of the upper part of the tower	 Figure 172 – Mechanism of the collapse of the upper part of the tower

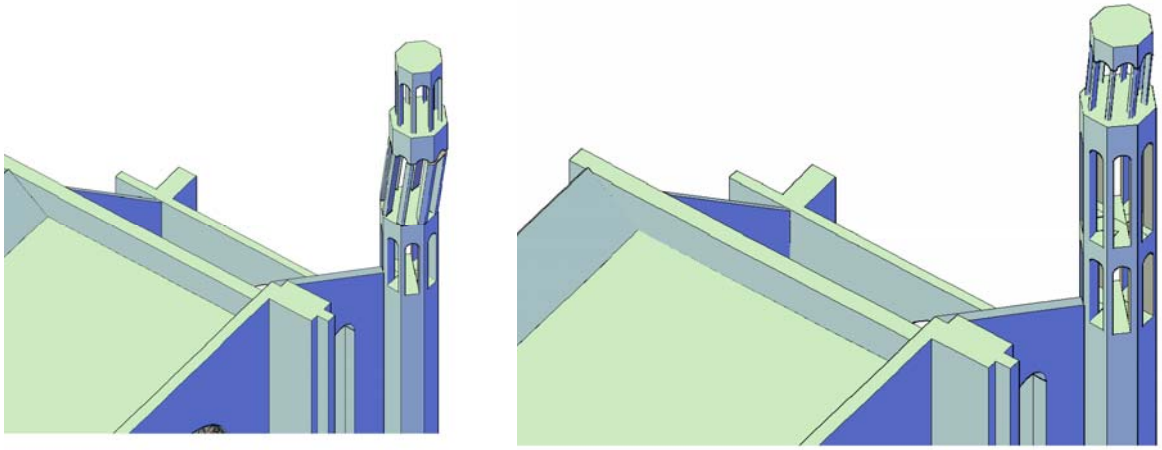


Figure 173 – Overturning and rotation of the upper part of the bell tower

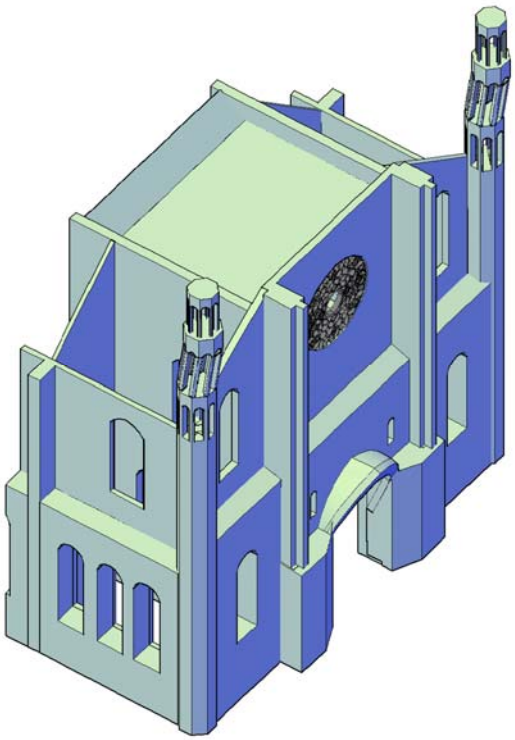


Figure 174– Collapse Mechanism- Overturning and rotation of the upper part of the bell tower

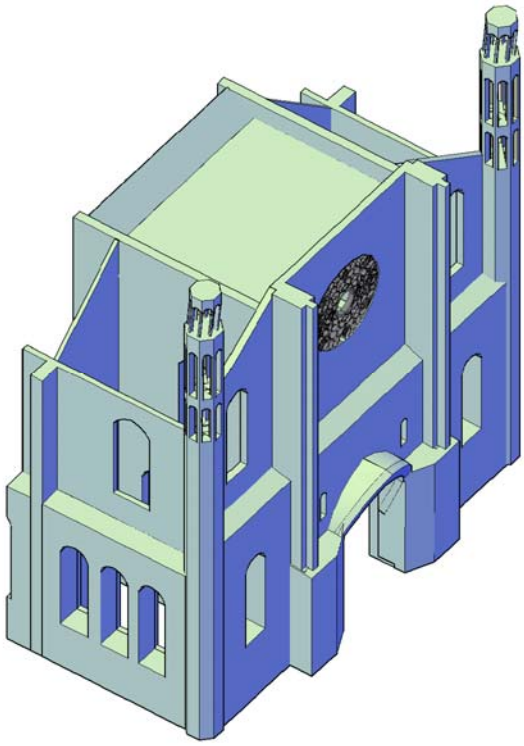
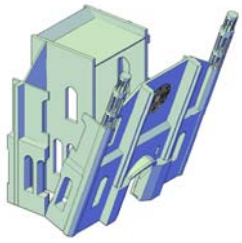


Figure 175 –Collapse Mechanism- Overturning and rotation of the upper part of the bell tower

SANTA MARIA DEL MAR		
Case	**Local Collapse Mechanism**	
1	Out-of Plane Deformation / Overturning of the Main Façade	

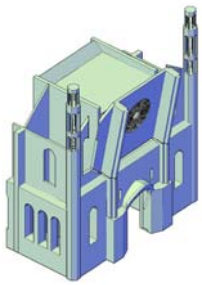
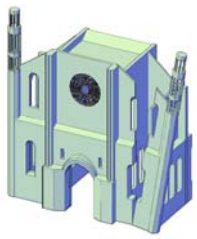
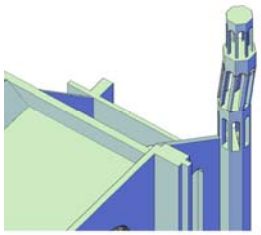
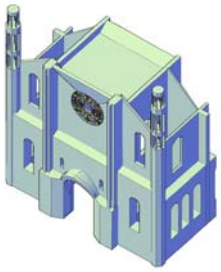
2	Out-of Plane Deformation / Overturning of the Upper Part of the Main Façade	
3	Out-of Plane Deformation / Separation of the Bell Tower	
4	Out-of Plane Deformation / Collapse of the Upper Part of the Bell Tower	
5	Out-of Plane Deformation / Collapse of the Upper Part of the Main Façade	

Table 7 – The collapse mechanisms considered in the study

6.2 Santa Maria Del Pi

As it has been applied for Santa Maria Del Mar, the same criteria were considered to evaluate which type of failure mechanisms would be expected for Santa Maria Del Pi. The photographic survey, historical information and the current damage were taken into account in defining the possible collapse mechanisms.

The most likely failure mechanisms that may occur can be categorized as the following;

- Overturning of the total facade
- Overturning/ collapse of the upper part of the facade
- Partial overturning of the facade
- Typical Bay

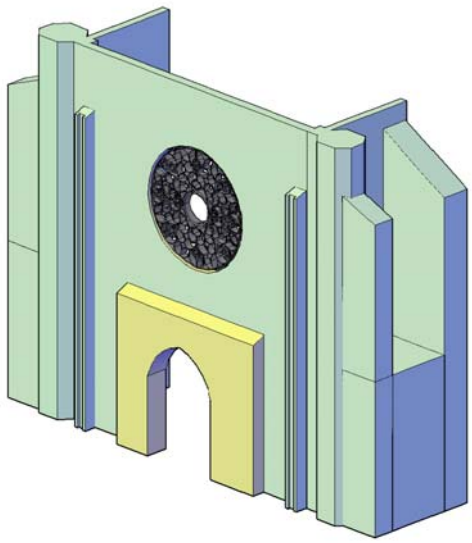


Figure 176 – The basic model of the frontal part of Santa Maria Del Pi

6.2.1 Mechanisms- Main Façade

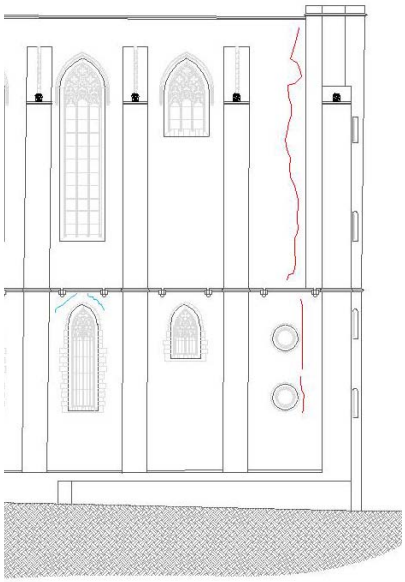
6.2.1.1 Out of Plane Deformation/ Overturning of the total façade

The main indicatives and the abacus how the collapse mechanism would be expected to occur was shown on Fig. 156

The main crack on the façades and the existing cracks in the connections of the perpendicular walls are the supporters for the failure.

Santa Maria Del Pi has the cracks symmetrically located in the side lateral walls. These cracks are just located adjacent to the front façade. This damage may be a sign of this type of collapse mechanism.

The leaning of the east and west towers and the differential settlements in different extends on the front façade may have a contribution of this type of failure.

Overturning of the Main Facade	
 Figure 177 – The view of the damaged part of the side façade	 Figure 178 – The extending crack on the side façade

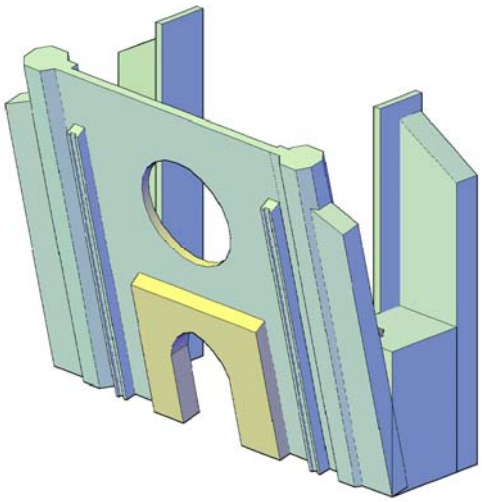
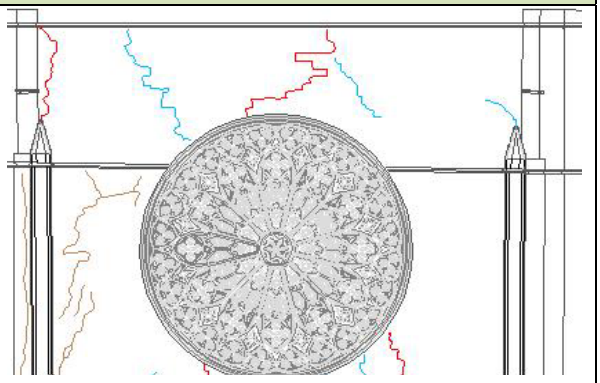


Figure 179 – The model of the collapse mechanism-
Out of plane movement of the total façade

6.2.1.2 Out-of Plane Deformation / Overturning of the Upper Part of the Main Façade

The cracks located on the upper part of the rose window on the main façade are the main reasons of a possible failure mechanism like the collapse of the upper part of the façade. The different stone pattern indicating the signs of the previous alterations, the historical data confirming that this part has

already had damaged before are among the arguments to prove that these type of failure should be taken into account. The scheme of the failure mechanism was displayed in Fig. 160

Overturning of the Upper Part of the Main Facade	
 Figure 180 – The cracks on the rose window	 Figure 181 – Crack pattern of the area abov the rose window

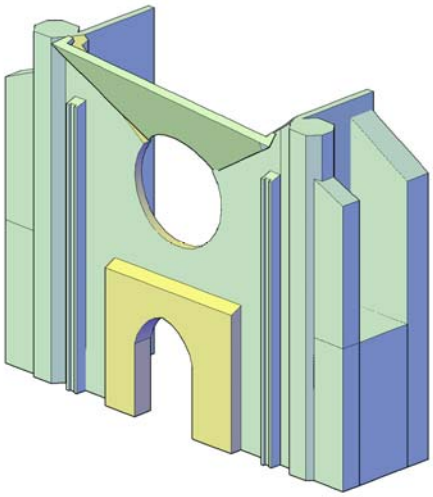
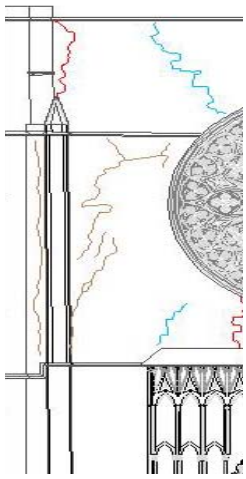


Figure 182 – The model of the collapse mechanism-
Overturning of the Upper Part of the Main Façade

6.2.1.3 Out-of Plane Deformation / Partial Overturning of the Main Façade

The extending cracks located on the sides of the main frontal part of the façade may have an influence on this type of failure. This damage makes the structure vulnerable against any kind of seismic action.

Partial Overturning of the Main Facade	
	
Figure 183 – The extending crack on the main façade	Figure 184 – The crack pattern of the side of the rose window

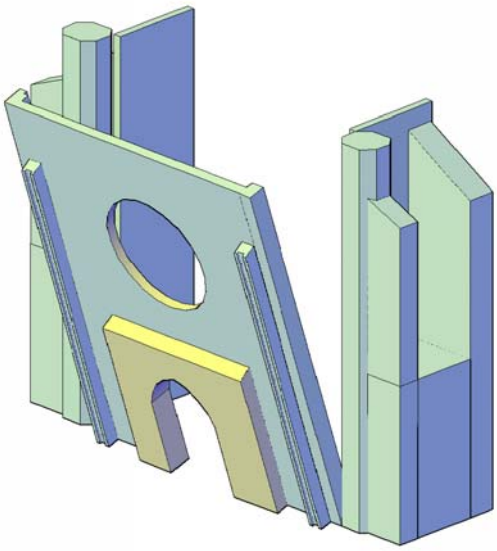


Figure 185 – The model of the collapse mechanism-
Partial Overturning of the Main Façade

6.2.2 Mechanisms- Apse

6.2.2.1 Out-of Plane Deformation / Overturning of the Buttresses on the Apse

The existing cracks, the inefficient buttresses or the irregularities in the height of different components like the lateral walls of the apse and the buttresses are the possible reasons for this type failure.

The poor connections between the walls and the buttresses are among the possible causes to have this type of local collapse.

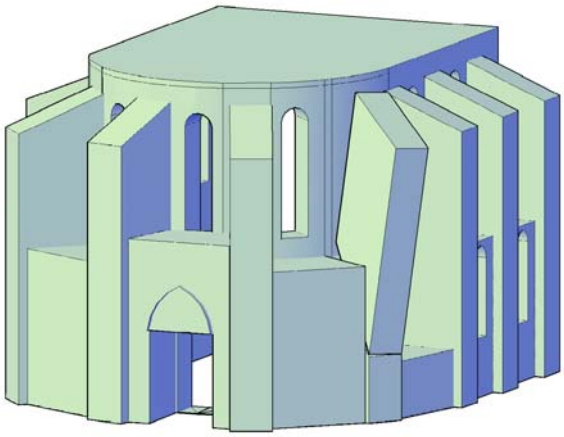


Figure 186– The model of the collapse mechanism- Overturning of the Buttresses on the Apse part

6.2.3 Mechanisms- Interior

6.2.3.1 Typical Bay

The typical bay of the structure was also considered thinking of the damage and deformation on the arches. This damage is supposed to have occurred due to the previous fires. The structure is a single nave structure and the possible hinges are assumed as the following;

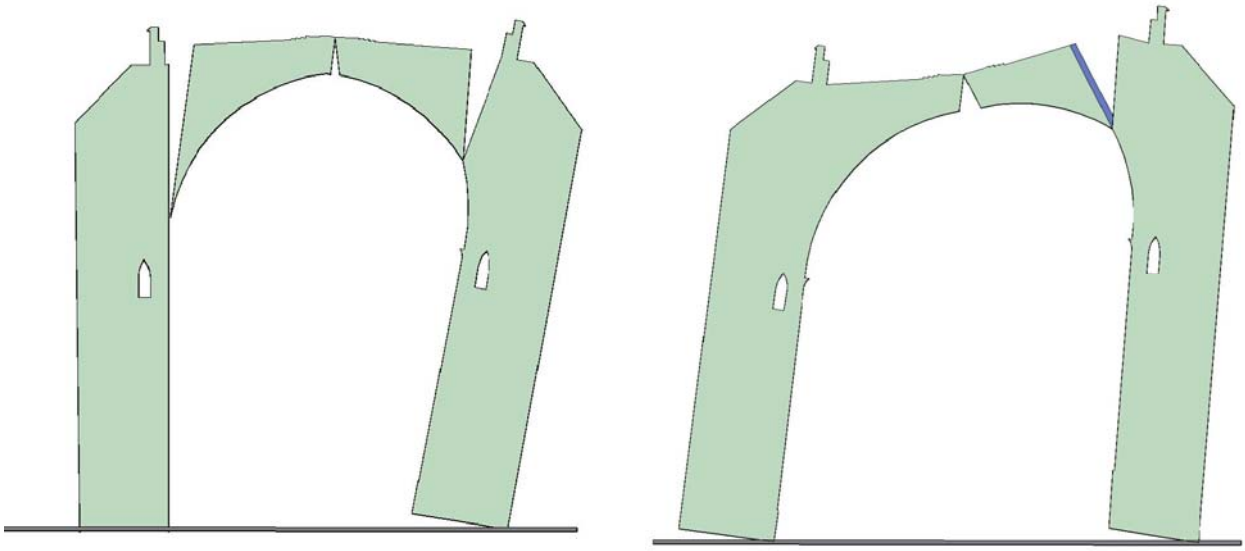
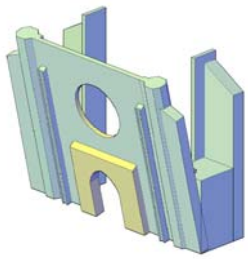
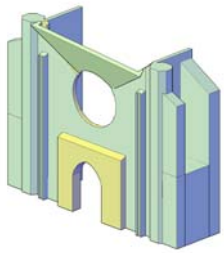
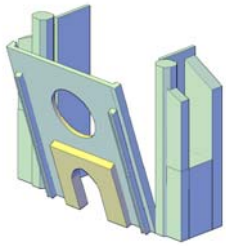
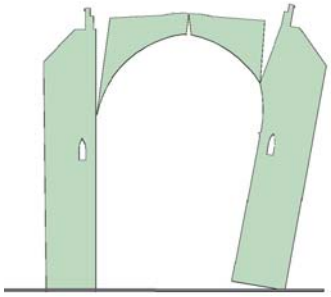


Figure 187 – The models of the possible collapse of the typical bay

The Fig. 188 shows the possible failure of the typical bay of Santa Maria Del Pi. The model on the left is more likely to occur in case of a seismic action.

SANTA MARIA DEL PI		
Case	**Local Collapse Mechanism**	
1	Out-of Plane Deformation / Overturning of the Total Façade	
2	Out-of Plane Deformation / Overturning of the Upper Part of the Main Façade	
3	Out-of Plane Deformation / Partial Overturning of the Main Façade	
5	Transversal Arch (nave and aisle)	

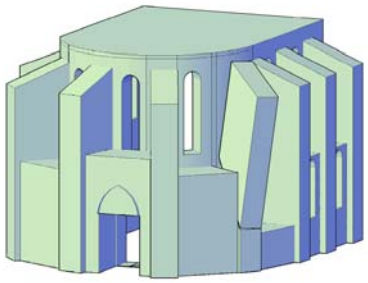
6	Out-of Plane Deformation / Overturning of the Buttresses on the Apse	

Table 8 – The collapse mechanisms considered in the study

6.3 Mallorca Cathedral

The possible collapse mechanisms were evaluated taking into account of the existing damage in Mallorca Cathedral. The same methodology applied on Santa Maria Del Mar and Santa Maria Del Pi was used for this case study too.

The possible collapse mechanisms that were considered for Mallorca Cathedral are as follows;

- Overturning of the total façade
- Overturning/ collapse of the upper part of the façade
- Typical Bay
- Bell Towers

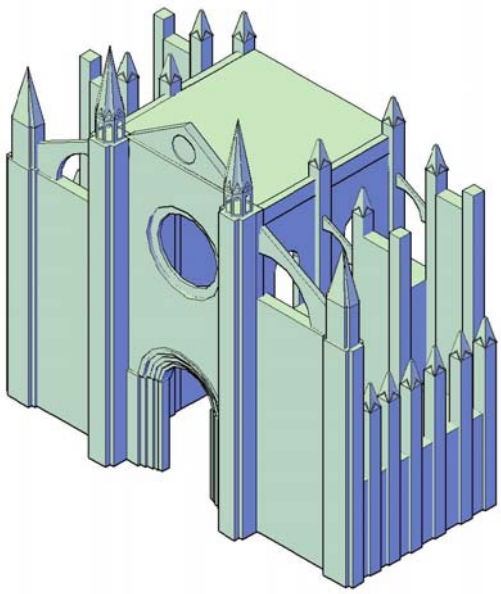
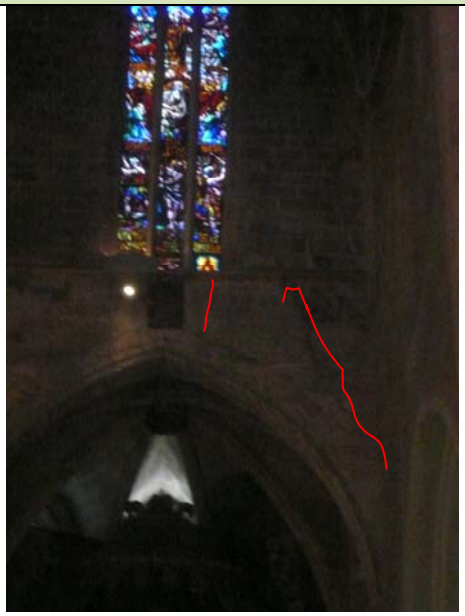
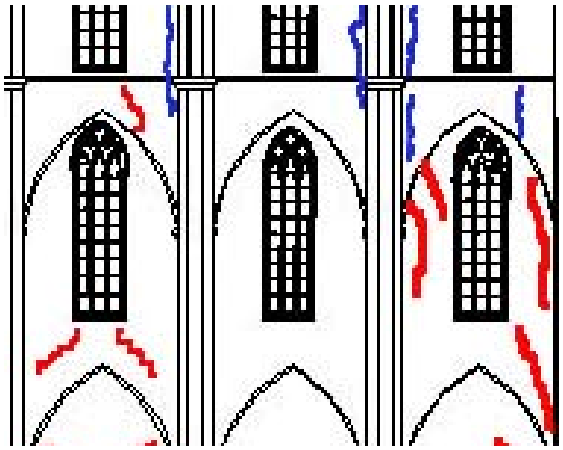


Figure 188 – Basic Model of the cathedral

6.3.1 Mechanisms- Main Façade

6.3.1.1 Out-of Plane Deformation / Overturning of the Total Façade

It is not possible to observe any damage on the front façade due to the recent restoration works but on the interior façades, the inclined cracks start on the upper level of the arches of the first chapels extending through the front façade are important in terms of the possibility of this type of mechanism. There is also the cracks start on the upper part of the entrance going up vertically until the lower levels of the rose window on both sides.

Overturning of the Main Facade	
 Figure 189 – The photo of the damage on the interior of the cathedral	 Figure 190 – The damage pattern of the crack on the interior of the cathedral

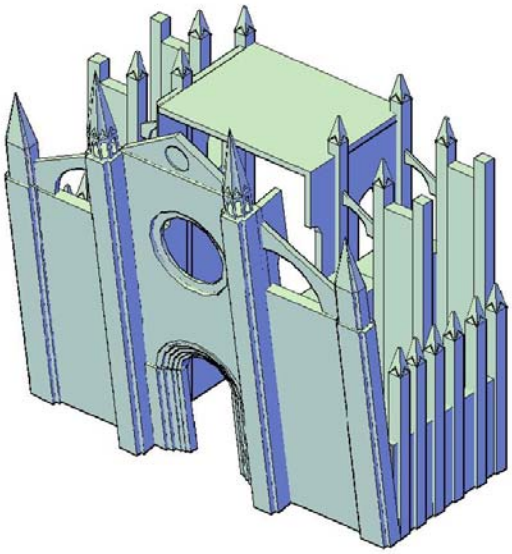


Figure 191 – Collapse Mechanism- Overturning of the total façade

6.3.1.2 Out-of Plane Deformation / Overturning of the Upper Part of the Main Façade

Due to the restoration works which prevent us to point out the structural problems, there is no evidence of any damage that may lead us to consider this type of collapse mechanism. But it is still very important to consider this failure mechanism since the triangular frontal part of the main façade constitutes a weak part in terms of seismicity.

The cracks located on the front façades are usually the main reasons to consider this type of collapse mechanisms. But in this case, the main indicator to take into account this type of failure is different due to there is no information or sign of the previous damage on the façade regarding the time before the restoration works.

It is possible to see the general view of the collapse mechanism in Fig.160

Overturning of the Upper Part of the Main Facade
 Figure 192 – The photo of the upper part of the front façade

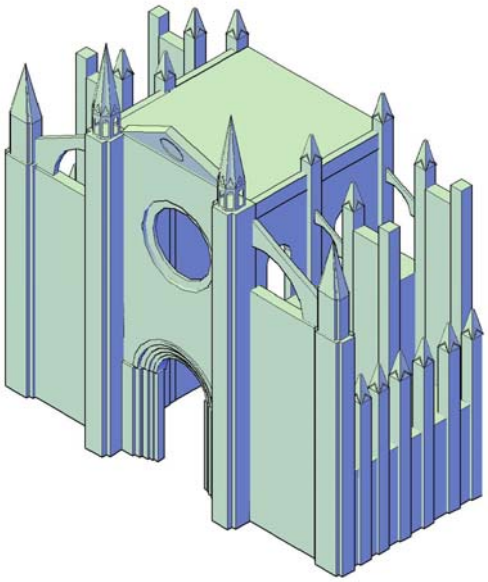


Figure 193 – Collapse Mechanism- Overturning of the upper part of the front façade

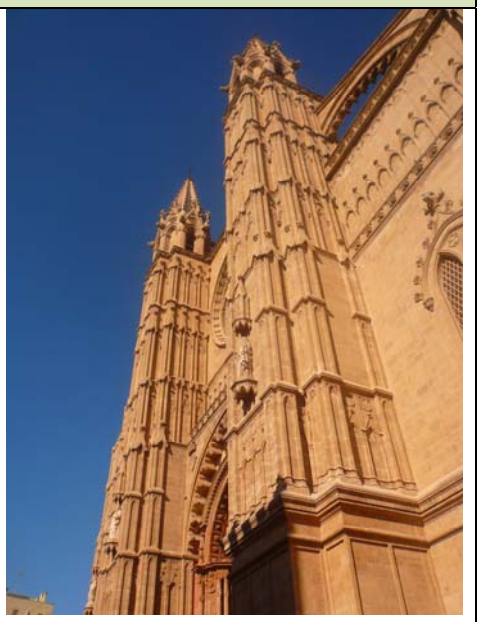
6.3.2 Mechanisms- Bell Towers

6.3.2.1 Out-of Plane Deformation / Separation of the Bell Tower

The evaluation of the collapse mechanisms are generally based on the consideration of the vulnerable parts of the churches or the large structures. The bell towers or the towers in general are among these vulnerable parts in these types of buildings. It is important to consider how they may behave under the possible seismic actions as they are usually very slender and may constitute or act as the weak points of the structure.

In other cases, the elongated cracks on the connection points of the towers with the lateral walls were the main indicators of the possibility of this type of collapse mechanism. As the height of the tower increases, it sometimes gets more slender as in the case of Santa Maria Del Mar. In this case, the possible collapse of the upper part of the tower is also considered among the possible failure types. These are not the main issues in Mallorca Cathedral but it is still important to highlight as these parts can behave separately under a seismic event since they are among the weak parts of the structure.

The abacus of the mechanism was shown in Fig. 167

Out-of Plane Deformation / Separation of the Bell Tower	
	
Figure 194 – View of the towers on the front façade	Figure 195 – View of the towers on the front façade

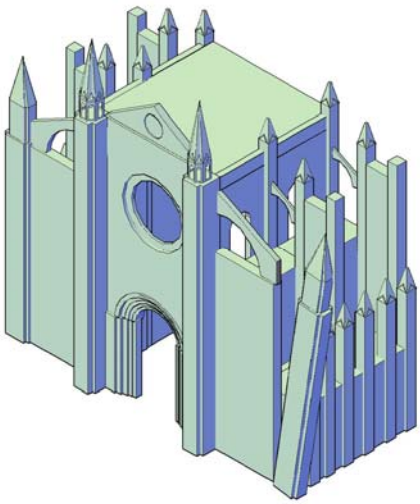


Figure 196 – Collapse Mechanism- Separation of the tower

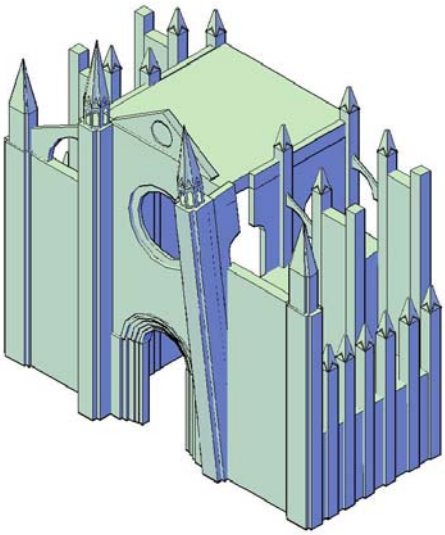
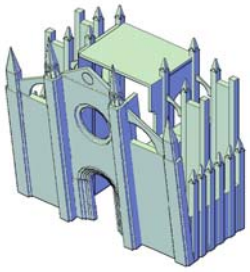
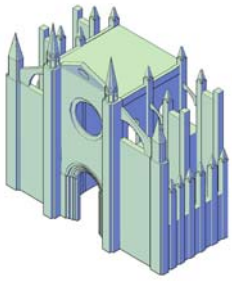
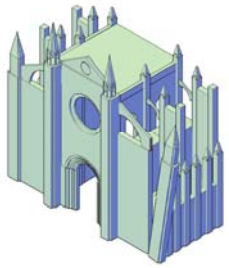
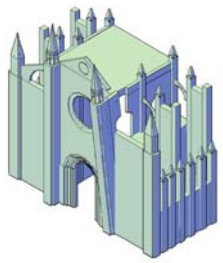


Figure 197 – Collapse Mechanism- Separation of the tower

MALLORCA CATHEDRAL		
Case	**Local Collapse Mechanism**	
1	Out-of Plane Deformation / Overturning of the Total Façade	
2	Out-of Plane Deformation / Overturning of the Upper Part of the Main Façade	

3	Separation of the Bell Tower	
5	Separation of the Bell Tower	

6.4 Barcelona Cathedral

The Cathedral of Barcelona shows a different behaviour than Santa Maria Del Mar and Santa Maria Del Pi. These three medieval Gothic cathedrals have similarities in the plan shapes and architectural components, they are located in very close distances and besides, they belong to same construction periods. In spite of all these similarities, the damage patterns and structural problems of Barcelona Cathedral are quite different than the other two cathedrals. The most important aspect of the cathedral to make it much more different comparing to the other two examples is that the massive buttresses and the exterior walls. The dimensions of the pillars under the cimborio level reach up to 2.50 meters while the thickness of the buttresses along the same direction with these pillars is approximately 2.80 meters. The thickness of the exterior walls is almost 1.80 meters. These features give the structure a high stability against any kind of damage.

Taking into account of the existing damage pattern and the structural components of the cathedral, it can be concluded that it is not expected any kind of collapse mechanisms to be generated under a seismic action. The damage can be very local such as the deformations on the arches but any failure regarding the collapse in not likely to happen in the structure.

6.5 Girona Cathedral

The cathedral does not show a significant damage in terms of structural integrity. Although this assumption is based on the qualitative inspection, the massive buttresses and the thickness of the walls are the possible leading reasons not having structural damage on the structure.

6.6 Conclusion

While defining the damage in the case studies, it is important to separate the structural damages into two types. In the first case, the damage which may have occurred due to the past earthquakes was highlighted. Later, the whole problems with different possible reasons were indicated.

The leaning in the Eastern tower in Santa Maria Del Mar could have a possible relation with the previous earthquakes. Although the leaning is not in high levels, the historical information shows that this tower was already damaged in 1373 earthquake.

Some of the inclined cracks that start on the upper level of the arches in front of the chapels, cracks located on and around the openings can have relation with the previous seismic actions. These can be the results of the energy dissipation of the horizontal forces.

The historical data also shows that the rose window collapsed following 1428 earthquake. The existing and repaired cracks are important in this sense. The crack pattern of two sides of the front façade show inclined cracks which could have caused by seismicity.

These cracks don't seem to re-open, they should be taken into account in terms of a possible earthquake.

These parts indicate the vulnerable parts and it is important to detect what happened in the past and what may happen in the future with these types of damage.

The leaning of the towers on the main façade and probably as a consequence, the two symmetrical cracks on both side walls may have caused by a past seismic action in Santa Maria Del Pi. The out of plane behaviour of the same façade and the towers may have caused these cracks after a horizontal force.

Similar to Santa Maria Del Mar case, Santa Maria Del Pi also shows the cracks around the rose window. Although there is information approving that the structure was influenced by 1428 earthquake, the exact effects were not known. The cracks around the rose window may have occurred due to a past earthquake. The other possible damage due to seismicity is the inclined cracks around the apse walls.

Although there are reports indicating that some deformations and the collapse of arches or deteriorated parts of Mallorca Cathedral following the earthquakes of 1660 and 1851, these information contradicts with some of the documents indicating that these problems were already existing before the earthquakes. The existing damages such as the two inclined symmetrical cracks located on the arch of the first chapels after the main entrance can be related to a seismic action.

7. INTERVENTIONS

7.1 Introduction

The seismic risk and the preparedness of the structures have to be evaluated together. In the areas which are moderate in terms of seismicity, the most important risk is not always the earthquakes but the fact that the structures are not constructed considering the seismic risks. The impacts of even moderate seismic actions can be dangerous since these impacts are usually ignored due to they are not significant or the results don't cause slight damage.

In recent history, many examples showed us that not only the intensity of the earthquake is a concern but being prepared for this risk is also very important. Low or moderate intensity seismic actions also caused damage and deaths even in the countries that are among the most leading ones about the seismic preparedness. The earthquake of 1427 is an important example. This earthquake caused the destruction of the whole buildings in Olot and the earthquake intensity was V-VI in Mercalli scale. Another example in Italy is Molise earthquake occurred in 2002. The magnitude was 5.9 in Richter scale and it caused the collapse of an elementary school in San Giuliano di Puglia resulting with the death of 30 students.

The possible effects of the seismic actions are usually disregarded in moderate or low seismic zones. This constitutes a risk considering that the structures are generally not built considering the seismicity. The preparedness of the structures against the seismic actions is also important for moderate seismic areas along with the ones in high seismic areas. The restoration and strengthening works are usually done superficially considering that the level of the seismicity is low and since these structures already weren't built considering the influence of possible earthquakes, they constitute risk under these kinds of actions. Although there may not be the total collapse danger of the structures in moderate seismic zones, the lack of maintenance, improper interventions for the structural damages become more important in terms of seismicity. These aspects become dangerous with a possibility of local collapses in these types of regions in case of an earthquake.

The conservation and the strengthening of the historical structures are already challenging subjects since they require awareness and knowledge in high levels. The seismic preparedness is another side of these terms. This fact was accepted after many destroying events occurred for high seismic zones. The regulations, new seismic zonations or the building codes were prepared, improved or updated after each seismic action. But since it is still a concept that is being improved and discussed around the world for these kind of high seismic areas, the possible results and effects for moderate to low seismic areas are usually ignored. The fact that it has being ignored in these areas causes lack of maintenance or proper care on the conservation of the structures and slow deterioration. Sometimes this slow deterioration due to improper and superficial interventions, lack of maintenance or even no

application and inspection on the structural safety and the performance cause sudden collapses either after moderate earthquakes or sometimes even without any need of a ground motion.

7.2 Strengthening in general

As it was explained, the first concern was the preparation and the analysis of the safety of the structures against seismicity. The second important challenge is how the strengthening should be.

The most important thing in the interventions on the historical constructions is to understand the structural behaviour. There is some major damage visible on the historical constructions and main reasons for this damage. The lack of proper connection between different components or the parts of the structures such as the buttresses, walls, towers, superstructures and so on is one of the reasons. The wide openings in the historical structures are among the prior reasons for the shear failures. Besides these, the historical structures especially the monumental ones like the churches, cathedrals, castles or so on are massive with a quite considerable weight and dense materials comparing to new construction technologies. In this case, it gets more important to have knowledge on these traditional materials and how they behave in the structure under different load cases like earthquakes. The complexity of these structures is another difficulty to pay attention to.

The main characteristics of the strengthening techniques and interventions should be well analyzed. All kinds of intervention are very important on historical constructions because the applications can result with very wrong situations. As a result, the structure can have extra loads or irreversible damage. The interventions and repairs should always be kept in minimum. They should be efficient, transparent without damaging the real identity of the structure and reversible as much as it can be. The cost of these applications should also be taken into account.

The decision about under which conditions the repair should be applied on the structure is very important. There are two phases of the effect of seismicity on this decision. First is the intervention decision regarding the impacts of the previous earthquakes and the second is the decision on the possible impacts of the future earthquakes. No matter the level of extent of the seismicity in a region, the existent effects of the previous seismic actions have to be taken into account in order to give the structure chance to repeat the same behaviour in possible future earthquakes. In this way, the structures gain the original state they once had before these occurrences and they can have the same stability to withstand the same type of actions.

7.3 General recommendations

Before mentioning about the possible interventions regarding structural point of view, the general recommendations for each case will be considered.

Santa Maria Del Mar

- The cleaning is suggested due to the discoloration caused by many of different reasons like the fires and the humidity and due to the removal of the existing vegetation and biological attack

- Local building is a possible solution in order to rehabilitate the holes that are the results of bombing during the civil war
- Stone consolidation can be applied for the diffused surfaces of the stone material especially for the exterior façades. Scuci- cuci (like for like replacement) can be applied on deteriorated parts on the façades where stone losses are observed in high degree.
- The decrease on the cross sectional area of the pillars due to the fires is visible and stone restoration can be applied in order to eliminate the negative effect of this situation. Injection is a possible type of intervention for the cracks visible on the pillars. In this case, a hydraulic based lime mortar is recommended. Another solution can be local rebuilding for the parts where the cross sectional area decreased due to the fire.
- The change of the corroded steel elements on the bell towers is recommended.

Santa Maria Del Pi

- The proper cleaning technique is recommended in order to eliminate the effects of the discoloration caused by the humidity, previous fires and the effects of vegetation
- Stone surfaces show diffused pattern especially on the exterior façades. To avoid this, stone consolidation can be recommended.

Mallorca Cathedral

- A light method of cleaning application is recommended for the vegetation and for the colour change due to humidity especially on the façade facing towards the sea. Since the structure is very close to the sea, the influence of the salt on the stone material can be detected by further tests and investigations and depending upon the results, protection of the stone material against the salt can be a recommended intervention.
- Injection for the cracks can be a possible intervention for the cracks on the interior and the exterior façades of the cathedral.
- The incompatible plastering applied inside of the chapels in some parts should be eliminated and more compatible mortar (lime mortar) should be applied instead.

7.4 Possible Interventions

Before mentioning about the possible interventions, it is important to highlight that this study is based on the general qualitative methods. The results are obtained by the relation set between the damage survey and the expected possible collapse mechanisms. As a result the possible intervention proposals are going to be evaluated considering these existent and possible damage.

Additionally, it is important that the further investigations should be carried out in order to make final decisions on the interventions. Quantitative methods are needed to apply any kind of intervention regarding the structural safety.

The proposals will be explained for each case;

Santa Maria Del Mar

The weakest parts in the structure are the main façade due to cracks around rose window and on two sides between towers and main frontal part and the inclined cracks on the interior and exterior on and

below the openings. These parts are already the vulnerable parts due to the damage and the possible influence of the past earthquakes. Apart from these, the upper parts of the towers should be taken into account since their vulnerability high in terms of seismic actions.

The possible intervention for the cracks in order to increase the structural strength of the masonry is injection. In order to avoid structural problems regarding different compatibility and adhesion, a hydraulic lime based mortar should be used in the applications.

Since it is known that leaning of the bell tower is stabilized, it is important to monitor the general behaviour in time before any kind of intervention decision. By injection application the connection between two sides where the tower is located with the rest of the façade would be achieved.

For the upper part of the bell tower which is vulnerable against the seismic actions, a reinforcing ring can be a possible intervention. But proper investigation and quantitative methods are needed to define the structural capacity of these parts.

- **Injection**, for the inclined cracks which don't follow the joints. The injection of the cracks is a possible intervention to consider in order regaining the structural stability to the cathedral. In this way, it is going to be possible to show the same type of damage pattern in case of an earthquake. As a result, it will be possible for the structure to dissipate the seismic energy thanks to this type of damage.
- **Repointing**, this intervention can be a solution for restoring the deteriorated mortar or the mortar which is not original. This technique does not offer the increase on the strength or stiffness but it increases the durability.

Santa Maria Del Pi

Tying of the main façade with the lateral side walls in order to avoid the lack of connection between the front façade with the other parts can be a possible solution. Injection can be seen as a complementary intervention for the symmetrical cracks on both sides of the structure.

This is important to provide the global behaviour and improve the connections between the masonry walls.

The cracks along the main façade and the ones around the rose window can be restorated by the applications of injection. The previous applications of repointing with incompatible materials should be changed with another mortar close to the original one such as lime mortar. This does not influence the strength of the masonry but has an impact on mechanical properties.

Injection can be considered for the X shaped cracks on the apse part and for the cracks on the connection points of the buttresses with the walls.

- **Tying** the front façade with the side lateral walls. One of the most significant problems of the structure is the symmetrical cracks on both sides of the building on the connection of these walls with the front façade wall. The application is important to regain the structural integrity and have a better connection in different parts or components of the structure. In this case, for the leaning of the front façade and the cracks on both sides, ties are good solutions considering their reversibility and efficiency.

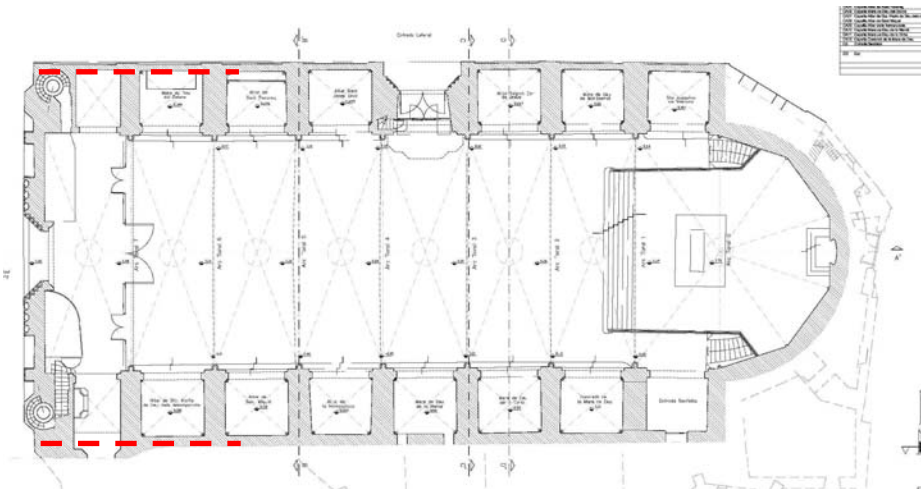


Figure 198 – The possible place for the proposed tie rods in Santa Maria Del Pi

- **Injection,** for the cracks on the side lateral walls and the cracks on some of the buttresses. The cracks on the apse part and the separation on the front façade can be restorated by the injection method.

Barcelona Cathedral

The cathedral does not show a very significant damage and the restoration works are still on-going in the structure. In order to make a certain decision on whether there is any need for intervention, further investigations about the structural safety of the building.

Mallorca Cathedral

Tying for the main façade with the lateral walls and the east part around apse where the height changes can be considered in order to avoid any tendency to separate in case of a seismic action. Besides of the tie rods, injection can be applied as a complementary for the cracks on the arches of the first chapels and the cracks on the walls and buttresses which mainly focus on the south façade.

- **Tying** the front façade. The inclined cracks on the clerestory wall extending to the front façade wall and the visible out of plane deformation on the front façade are the main reasons to consider this intervention. Steel ties are possible intervention technique for the façade since it will confront the leaning of this part of the structure avoiding a possible partial or total collapse in case of an earthquake. It is also a convenient technique since it is reversible.
- **Injection**, for the cracks on the south façade on the lateral walls, the cracks on the arches and the piers. It is an efficient method applied on historical masonry very often. There are some important aspects like the type of the mortar that is going to be used and the volume that the application is going to be done. This has to be confirmed after a proper inspection since this technique is not reversible.

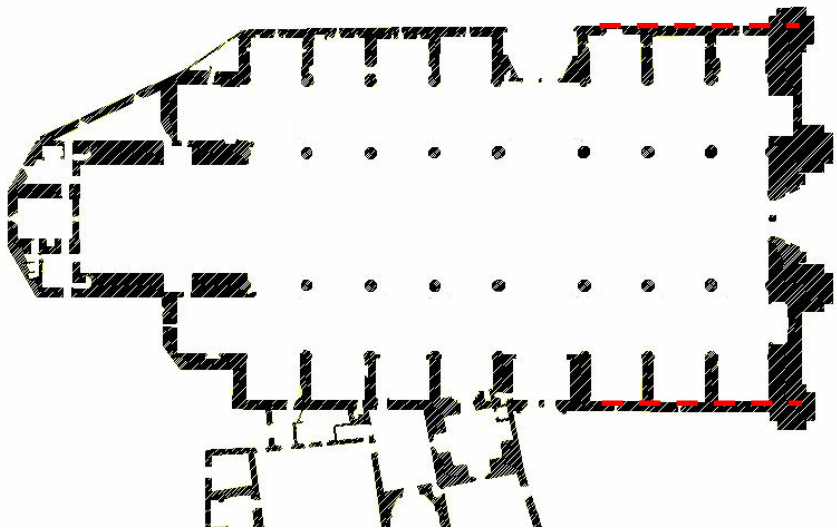


Figure 199 – The possible place for the proposed tie rods in Mallorca Cathedral

Girona Cathedral

The cathedral does not show very significant structural problems. The existent cracks don't seem as they are due to structural problems. Injection can be applied in order to remove this decays but it doesn't seem like there is a need for a deep injection application. The other general problem of Girona Cathedral is that there are previous alterations in the interior part of the structure such as infilled openings, cement based plasters and so on. The efficiency and the contributions of these applications should be investigated and considering the level of their contribution, these applications could be removed or they can be converted with more respectful material closer to the original ones.

The results of the previous monitoring should be analyzed and the behaviour of the structure should be inspected carefully. For the application of any kind of intervention, the inspections on the structural integrity of the building should be done using qualitative tools.

Apart from this, the apse part of the structure is mainly under the influence of humidity and discoloration due to this type of occurrence. In order to eliminate these effects, a cleaning method is recommended.

8. CONCLUSIONS

The seismicity has always been among the most dangerous and possible natural disasters for the historical monuments. In order to avoid the negative results of the earthquakes on historical constructions, it is important to understand the real behaviour of these structures. There are complex models, numerical tools, different qualitative approaches and analysis techniques to decide how the historical structures would behave under seismic actions. The problems of the structures, the history, the previous works that it had undergone and the previous seismic actions are always important aspects to look since they can give us hints on how the structure will behave in the future.

In the context of this study, five Gothic cathedrals were examined, the damage patterns were identified and the results were compared in terms of the possible reasons of this damage. All these stages made contributions on identifying the possible collapse mechanisms considering seismic actions. The damage, the importance of this damage, the existing indexes and the assumptions on how these structures could behave in case of an earthquake were overlapped. As a result, the possible collapse mechanisms due to earthquake were modelled. The aim of the study was to take the attention to the damage on the historical structures and the importance of this damage in terms of seismicity even though in a low to moderate seismic region. It is believed that these aims were accomplished and this study is regarded as a possible tool to help for further studies about these subjects.

The conclusions of the study can be summarized as;

- In order to identify the most common reasons of the problems of the structures that are in the context of this study, the damage patterns were mapped. Apart from the influence of the past seismic actions, the most common structural problems are possibly due to differential settlement and construction joints,
- To be able to define a correlation with the existing damage and the future earthquakes, the types of damage were analyzed using the theoretical data and previous researches. The failure due to seismic events occurs on the most vulnerable parts of the structures. This study shows these weak parts on the case studies around Barcelona, Girona and Mallorca,
- By analyzing the existing damage pattern and past damage due to seismic actions, it is understood that some of the damage could be related to earthquake. It is important to analyze the past effects of the earthquakes which mainly occurred during the IV. Centuries since these effects are helpful to understand the vulnerability of these examples;
- When the damage patterns were prepared for each case, it was possible to compare the structures and their problems. The inspection of each case showed that the existing damage in Girona Cathedral and Barcelona Cathedral were different than the other cases.

These structures have high stability due to their massive buttresses and walls were not influenced from the past earthquakes like Santa Maria Del Mar and Santa Maria Del Pi.

- Even though the region is moderate in seismicity, there are some structural problems on the case studies. It was important to show the most possible collapse mechanisms due to earthquake in order to prepare these structures against future earthquakes and improve the vulnerable parts of these structures against possible seismic events.
- By defining the structural problems in general and particularly possibly due to the past earthquakes such as cracks, deformations or out of plane movements, the vulnerable and weak parts of these structures were identified. The leaning of the bell towers or the principal façade in Santa Maria Del Pi, out of plane movement of Mallorca Cathedral or the cracks on the principal façade of Santa Maria Del Mar are examples of these weak parts. This data was used in order to identify where the failure could possibly be expected in a future seismic action.
- The recommendations and interventions that improved were outlined considering the structural problems without using any qualitative tools. The structural problems correlated with the possible damage in case of a seismic action were the tools to create general frame on what should be done. Considering these damage patterns caused by the earthquake and the possible collapse mechanisms due to earthquake the study highlights, qualitative methods should be used to define the dominant mechanisms likely to happen.
- The structures in the scope of the study appear to resist the possible earthquakes without any serious interventions to the cost of some damage. Some particular parts may need local or light strengthening applications in order to avoid further decay in case of an earthquake. The injection of the cracks in the case Santa Maria Del Mar is an example of these possible local interventions.

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