Title: **INVENTORY AND COMPLETION OF CASE STUDIES SURVEY**

Date: January 2005

Asia-wide Programme: EU-INDIA ECONOMIC CROSS CULTURAL PROGRAMME

Project Title: IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE BUILDINGS

Project Contract N°: ALA/95/23/2003/077-122

Project Beneficiary: UNIVERSIDADE DO MINHO, PORTUGAL

Partners: TECHNICAL UNIVERSITY OF CATALONIA, SPAIN

CENTRAL BUILDING RESEARCH INSTITUTE, INDIA

UNIVERSITÁ DEGLI STUDI DI PADOVA, ITALY

1. INTRODUCTION

The present report was developed under the scope of Activity 1 of the project entitled “Improving the Seismic Resistance of Cultural Heritage Buildings”, within the Asia-wide Programme “EU-India Economic Cross Cultural Programme”. The aim of this activity is to develop, at a European-Indian level, the social and economic argument to support an earthquake protection program for monuments at risk and to collect existing background information on the four case studies to be studied.

From the monuments at risk from earthquakes in Portugal, Spain, India and Italy, a set of about forty monuments were selected on the basis of available geometrical data, historic and architectural significance, importance to local visitor economy, seismicity of the zone and seismic vulnerability according to simplified methods (ratio between walls area and total area; ratio between weight and total area; shear base action). This selection also includes the four major case studies, namely Church of Santa Maria de Belém (Lisbon, Portugal), Cathedral of Majorca (Majorca, Spain), Kutub Minar (Delhi, India) and Reggio Emilia Cathedral (Reggio Emilia, Italy).

For each structure, and from available and specially prepared documents (denoted here as inventory and structural performance forms), using archives and previous local surveys, the most important features contributing to the structural performance of the major spanned spaces were studied, i.e.:

- Type, span, rise, thickness of vaulting;
- Columns and perimeters walls: type of masonry, dimensions, openings;
- Type and positioning of lateral supports;
- Gravitational loading: intensity and distribution.

as well as the identification and documentation of any earthquake damage or structural strengthening interventions.

For the four case studies, a collection of detailed historic information and existing architectonic drawing surveys, to define fabric and structural lay-out was prepared. This information is to be used in the planning of the in situ tests and monitoring, and in the preparation of the numerical models.

Therefore, this report comprises the inventory and structural performance forms of the forty selected monuments as well as the detailed description of the four major case studies.

2. CONTENTS OF THE REPORT

INVENTORY AND STRUCTURAL PERFORMANCE FORMS:

- PORTUGUESE INVENTORY AND STRUCTURAL PERFORMANCE FORMS
- SPANISH INVENTORY AND STRUCTURAL PERFORMANCE FORMS
- INDIAN INVENTORY AND STRUCTURAL PERFORMANCE FORMS
- ITALIAN INVENTORY AND STRUCTURAL PERFORMANCE FORMS

CASE STUDIES:

- DETAILED DESCRIPTION OF THE MONASTERY OF JERÓNIMOS, PORTUGAL
- DETAILED DESCRIPTION OF MALLORCA CATHEDRAL, SPAIN
- DETAILED DESCRIPTION OF KUTUB MINAR, INDIA
- DETAILED DESCRIPTION OF S. MARIA ASSUNTA CATHEDRAL, ITALY

Title: **PORTUGUESE INVENTORY AND STRUCTURAL PERFORMANCE FORMS**

Asia-wide Programme: EU-INDIA ECONOMIC CROSS CULTURAL PROGRAMME

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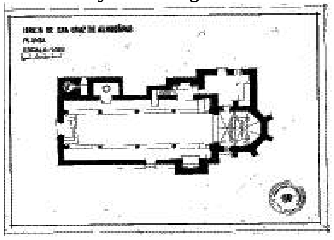
PT1- Church of Santa Cruz. Almodôvar – Beja. Portugal



(a) (b) (c)

Figure 1 – Geometry: (a) photo; (b) plan; (c) cross-section

[Source: DGEMN - General Directorate for Monuments and Sites].

National Classification: Construction of Public Interest (IIP)

Construction period: 16^{th}, 17^{th}, 18^{th} (construction supposedly initiated in 1501, with possible inauguration in 1740 according to the date engraved in the doorsill of the sacristy door)

Description:

Longitudinal plan with rectangular nave with small side-chapels, quadrilateral bell-tower at the left, polygonal apse and rectangular sacristy at the left. Stepped volumes with a distinct double-sloping roof, over the church, and a prismatic spire, over the bell-tower. Main façade in a single gable wall, with a single opening: a portal with three semicircular archivolts of torso colonettes. Side bell-tower with two levels, with window openings in the upper part with semicircular archivolt. Back façade highlighted by the lower volume of the chancel, polygonal and with stepped buttresses.

Interior with three naves, of four spans, separated by pointed arches and ashlar columns. The main nave, three times large than the side naves, has wood lath-work ceilings. Triumphal arch over the columns. Chancel with roof in star ribbed vault, supported in brackets.

Load-bearing walls in rendered stone masonry. Double-sloping roof with a timber structure.

Since 1962, DGEMN has carried out minor conservation Works.

Previous Seismic Damage:

It is likely that the 1755 earthquake hit the structure but any possible damage is not documented, due to the fact that Almodôvar is an isolated rural settlement, with few inhabitants and low regional importance.

PT1- Church of Santa Cruz. Almodôvar – Beja. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.14	0.18	3.87	5.07	1.88	2.46

Other Key Structural Features:

VAULT IN MAIN SPACE
☐ Yes ☒ No, Specify: Only in the ceiling of the chancel.
TYPE
☐ Barrel ☐ Crossed ☐ Domed ☒ Other, Specify: Star ribbed vault
GEOMETRICAL DATA (meters)
5.0 Span *s* **3.0** Rise *r* **-** Thickness at key *t* **1/1.7** *r* / *s* (-) **-** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
2.7 Free height L ϕ0.30 Cross-section[1] **36** Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
150 Vertical load **1615** Euler critical load **1/9** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
5.20 Maximum free height **0.55** Equivalent thickness[2] **1/9.5** Thickness / height (-)

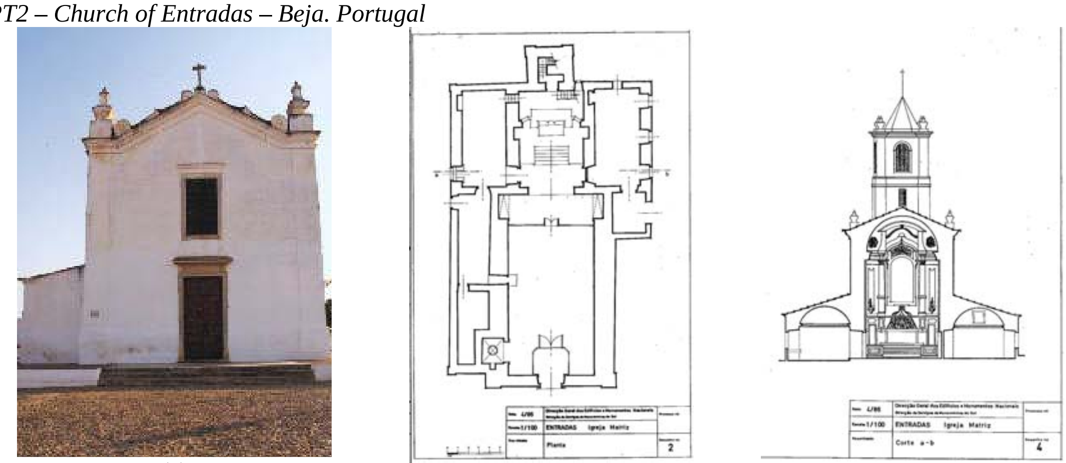
MAGNITUDE OF SEISMIC LOADING (m/s^2)
1.38 PGA for Type 1[3] **0.82** PGA for Type 2

[1] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[2] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

[3] Type 1 (moderate magnitude and close epicenter) and Type 2 (large magnitude and far away epicenter)

PT2 – Church of Entradas – Beja. Portugal



(a) (b) (c)

Figure 2 – Geometry: (a) photo; (b) plan; (c) cross-section

[Source: DGEMN - General Directorate for Monuments and Sites].

<u>National Classification</u>: Construction of Public Interest (IIP)

<u>Construction period</u>: 18^{th} (construction supposedly initiated in1745)

<u>Description</u>:

Church with vernacular architecture. Longitudinal plan with a rectangular nave and chancel. Lateral constructions and side bell-tower centred in the back of the chancel. Stepped volumes with a distinct double-sloping roof, over the church, and a prismatic spire over the bell-tower.

Main façade in a single gable wall. Back façade highlighted by the quadrilateral bell-tower, with upper vertical window opening with semicircular archivolt.

Interior with a single nave covered by a barrel vault ceiling supported by perimeter brackets.

Load-bearing walls and vaults in rendered stone masonry. Sloping roof with a timber structure over the vaults.

<u>Previous Seismic Damage</u>:

Hit once by a VI –VII intensity earthquake in 1858. It is likely that others important earthquakes hit the structure, but no associated damage is documented. It was damaged by the earthquake in 1969.

PT2- Church of Entradas – Beja. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.11	0.24	2.15	4.78	1.25	2.77

Other Key Structural Features:

VAULT IN MAIN SPACE

[x] Yes [ ] No, Specify:

TYPE

[x] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

6.5	Span s	2.3	Rise r	?	Thickness at key t	1/2.8	r/s (-)	?	t/s (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

-	Free height L	-	Cross-section[4]	-	Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
-	Vertical load	-	Euler critical load	-	Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

11.5	Maximum free height	1.8	Equivalent thickness[5]	1/6.5	Thickness / height (-)

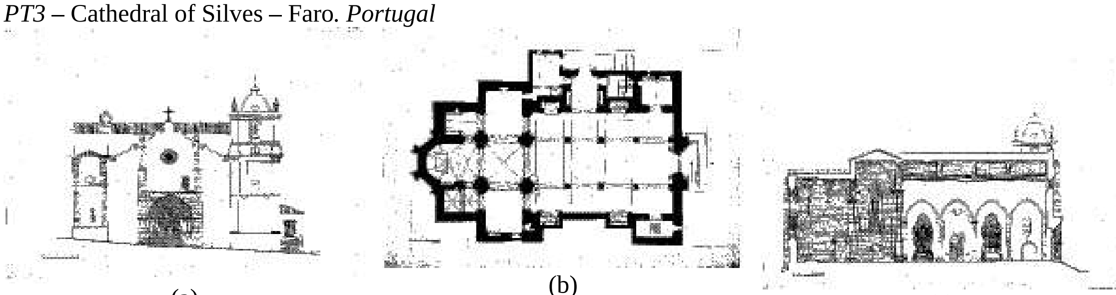
MAGNITUDE OF SEISMIC LOADING (m/s^2)

1.38	PGA for Type 1	0.82	PGA for Type 2

[4] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[5] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

PT3 – Cathedral of Silves – Faro. *Portugal*



(a) (b) (c)

Figure 3– Geometry: (a) main façade; (b) plan; (c) longitudinal cross-section

[Source: DGEMN - General Directorate for Monuments and Sites].

National Classification: National Monument (MN)

Construction period: 13th,14th,15th,16th and 18th

Description:

Longitudinal cruciform plan with rectangular naves, transept and a polygonal chancel (apse) with two lateral small rectangular chancels (apsidioles). Sacristy at the left side. Single sloping-roof over the lateral naves; double sloping-roof over the central nave, transept and over the both lateral chancels (apsidioles); triple sloping-roof over the sacristy; quadruple sloping-roof over the North tower and over the main chancel (apse).

Main façade in a single gable wall, highlighted by the central portal, of pointed arch flanked by pilasters, and by the lateral towers. The tower at the North side, with two levels, has a similar height of the lateral naves. At the South side, the bell-tower, which is higher than the North tower, is covered by a coved vault. Back façade with apse, upper crenelated and reinforced on the corners by stepped buttresses. Transept, apse and apsidioles with a massive baseboard.

Interior with three naves, of four spans, separated by pointed arches over octagonal columns, which support the roof structure and the wood ceilings. Transept central ceiling with pointed ribbed vault, supported by massive cross-form columns. Lateral ceiling spans in barrel vault. Apse and lateral apsidioles connected by pointed arches and covered by pointed ribbed vaults. Load-bearing walls in ashlar masonry (sandstone from Silves). Sloping roof with a timber structure over the vaults.

Previous Seismic Damage:

The structure was hit by a serious earthquake in 1352-1353. In the 18th century it was damaged three times by different earthquakes. The 1755 earthquake provoked major damages, after which some interventions works was done. Most recently it was damage by the 1969 earthquake. Since 1931, some intervention works have been done by DGEMN.

PT3 – Cathedral of Silves – Faro. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.12	0.18	2.00	3.00	1.40	2.08

Other Key Structural Features:

VAULT IN MAIN SPACE

☐ Yes ☒ No, Specify: Just in abside and transept ceilings.

TYPE

☐ Barrel ☐ Crossed ☐ Domed ☒ Other, Specify: Diagonal pointed ribs

GEOMETRICAL DATA (meters)

4.8 Span *s* | **3.0** Rise *r* | **?** Thickness at key *t* | **1/1.9** *r* / *s* (-) | **?** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

11.5 Free height L | ϕ0.75 Cross-section[6] | **61** Slenderness $\lambda = L / (Inertia / Area)^{0.5}$ (-)

150 Vertical load | **3500** Euler critical load | **1/15** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

11.0 Maximum free height | **1.0** Equivalent thickness[7] | **1/11** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

1.38 PGA for Type 1 | **0.82** PGA for Type 2

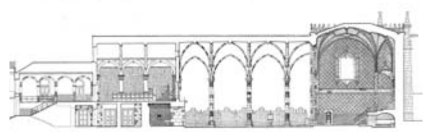
[6] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[7] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

PT4 – Church of the Ancient Jesus Monastery - Setúbal. Portugal

(a)

(b)



(c)

Figure 4– Geometry: (a) photo; (b) plan; (c) longitudinal cross-section
[Source: DGEMN - General Directorate for Monuments and Sites].

National Classification: National Monument (MN)

Construction period: end of 15th, 16th (vaulted the nave and construction of a new sanctuary, by substituting the original one), 17th.

Description:

Longitudinal plan with rectangular naves, chancel and choir. Combined volumes with a distinct double-sloping roof, over the nave and choir, and octuple-sloping over the chancel.

Main façade highlighted by stepped buttresses with torso poppy head (pinnacle or an apex). Portal with lightly pointed archivolts surrounded by a gablet. At the back the apse volume, higher than the others volumes, upper crenelated and with chamfered edge corners transforming its rectangular base in octagon-like. At the South façade there are two vertical important window opening with a centred mullion and filled with tracery. One opening is over the nave, another over the chancel. Interior with three naves, of three and half spans, separated by pointed arches supported by high torso columns. Ribbed (pointed) vault over the central nave and semi-barrel vault, supported by brackets, over the aisles naves. There is a transversal wall with four rectangular window openings, behind a balustrade, that separate the naves from the elevated choir. Barrel vault ceiling over the elevated choir. Chancel higher than the naves, with two spans covered by a star ribbed vault, supported in brackets. Apse with chamfered edges.

Load-bearing walls in ashlar and stone masonry reinforced on the top by a concrete ring. Sloping roofs with timber structure over the vaults.

Previous Seismic Damage:

It has been hit by intense historic earthquakes in 1531, 1755, 1858, and 1909. The 1755 earthquake caused several damages, especially on the choir vault. Most recently, damage was caused by the 1969 earthquake. Since 1930 DGEMN has done some conservation works.

PT4-Church of the Ancient Jesus Monaster - Setúbal. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.11	0.24	1.43	3.02	1.00	2.10

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify: Just in the choir and chancel ceilings.

TYPE

[X] Barrel [ ] Crossed [ ] Domed [X] Other, Specify: Star ribbed vault

GEOMETRICAL DATA (meters)

6.30	Span *s*	3.7	Rise *r*	?	Thickness at key *t*	1/1.7	*r* / *s* (-)	?	*t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

7.5	Free height L	ϕ0.50	Cross-section[8]	60	Slenderness $\lambda = L / (\text{Inertia} / \text{Area})^{0.5}$ (-)
700	Vertical load	1615	Euler critical load	1/15	Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

11.7	Maximum free height	0.75	Equivalent thickness[9]	1/16	Thickness / height (-)

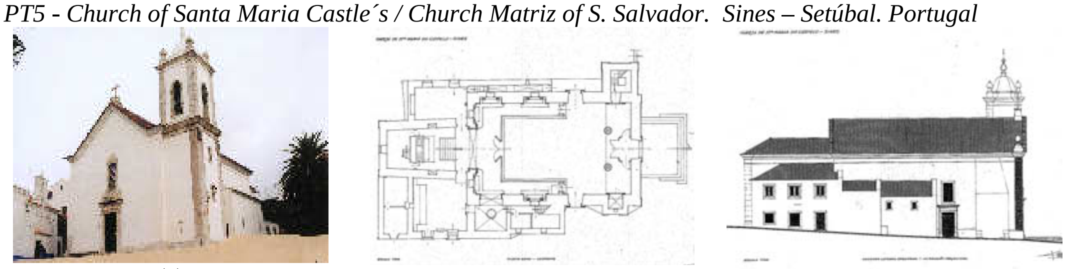
MAGNITUDE OF SEISMIC LOADING (m/s^2)

1.38	PGA for Type 1	0.82	PGA for Type 2

[8] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[9] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

PT5 - Church of Santa Maria Castle´s / Church Matriz of S. Salvador. Sines – Setúbal. Portugal



(a) (b) (c)

Figure 5 – Geometry: (a) photo; (b) plan; (c) lateral North façade.

[Source: DGEMN - General Directorate for Monuments and Sites].

National Classification: going on

Construction period: 18th (build in 1730, on top of an existent temple).

Description:

Longitudinal plan with rectangular nave, chancel, adjacent areas and side bell-tower. Stepped volumes with a distinct double-sloping roof, over the nave, sacristy, triple-sloping roof over the chancel and coved vault over the bell-tower.

Main façade in a single gable highlighted, at its right side, by the bell-tower, quadrilateral, with two levels, ashlar masonry corners and window openings in upper part with semicircular arch.

Lateral façades highlighted by the annexed volumes and by window and door openings framed with ashlar masonry. The South façade is highlighted by the side bell-tower.

Back façade with three rectangular window openings and ashlar edge corners.

Interior with a single nave, elevated choir, with timber balustrade supported by two ashlar columns. Each column has a circular holy-water stone. The nave has a barrel vault ceiling supported on a cornice. Triumphal arch over ashlar engaged columns.

Load-bearing walls in rendered stone and limestone masonry. Sloping roof in timber structure over the vaults. Window and door openings framed by an ashlar masonry. Floor pavement with stone slabs.

Previous Seismic Damage:

It has been hit by intense historic earthquakes in 1755, 1858 and 1909. The 1755 earthquake caused several damages. Most recently, damage was caused by the 1969 earthquake.

PT5 - Church of the Castle´s Santa Maria / Church Matriz of S. Salvador. Sines – Setúbal. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.12	0.15	2.78	3.68	1.56	2.06

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[X] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

11.5	Span *s*	2.8	Rise *r*	?	Thickness at key *t*	1/4.1	*r* / *s* (-)	?	*t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

-	Free height L	-	Cross-section[10]	-	Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
-	Vertical load	-	Euler critical load	-	Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

9.20	Maximum free height	1.30	Equivalent thickness[11]	1/7	Thickness / height (-)

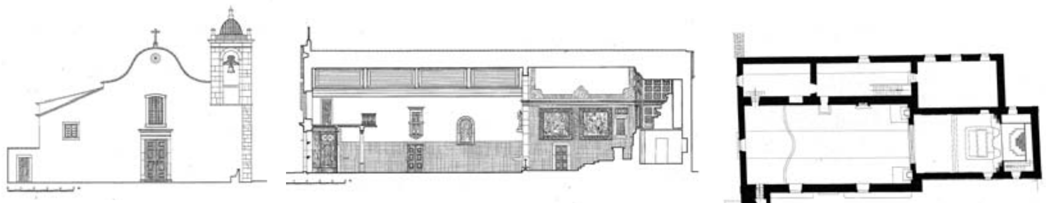
MAGNITUDE OF SEISMIC LOADING (m/s^2)

1.38	PGA for Type 1	0.82	PGA for Type 2

[10] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[11] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

PT6 – Church of S. Lourenço. V. Nogueira de Azeitão – Setúbal. Portugal



(a) (b) (c)

Figure 6 – Geometry: (a) main façade; (b) longitudinal cross-section; (c) plan.
[Source: DGEMN - General Directorate for Monuments and Sites].

National Classification: National Monument (MN)

Construction period: 16th (build on top of an existing medieval temple).

Description:

Longitudinal plan with a rectangular nave and chancel, adjacent rectangular areas at the north side. Quadrilateral side bell-tower on the corner West/South. Combined volumes with a double-sloping roof over the church and coved vault over the bell-tower.

Main façade in a curvilinear gable shape (between the eaves and the ridge of the roof). A prominent rectangular window beyond a rectangular portal with a straight architrave. South façade highlighted by the bell-tower and by distinct window and door openings over the nave and chancel. North façade with irregular window openings. Back façade in a single gable wall and with ashlar corners.

Interior with a single nave of trapezoidal wood ceiling. The nave is higher and wider than the apse, which is covered by a barrel vault ceiling. Triumphal arch over engaged columns.

Load bearing walls in rendered limestone masonry. Sloping roofs with timber structure.

Previous Seismic Damage:

It has been hit by intense historic earthquakes in 1755, 1858 and 1909. Most recently, damage was caused by the 1969 earthquake. Since 1947 DGEMN has carried out some conservation works.

PT6 – Church of S. Lourenço. V. Nogueira de Azeitão – Setúbal. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.09	0.17	2.85	559	1.44	2.82

Other Key Structural Features:

VAULT IN MAIN SPACE

[ ] Yes [x] No, Specify: Just in the chancel ceiling.

TYPE

[x] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

6.3 Span *s* | 2.9 Rise *r* | ? Thickness at key *t* | 1/2.2 *r* / *s* (-) | ? *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

- Free height L | - Cross-section[12] | - Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

- Vertical load | - Euler critical load | - Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

7.0 Maximum free height | 0.60 Equivalent thickness[13] | 1/12 Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

1.38 PGA for Type 1 | 0.82 PGA for Type 2

[12] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[13] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

PT7 – Church of S. Quintino. Sobral Mte Agraço – Lisboa. Portugal

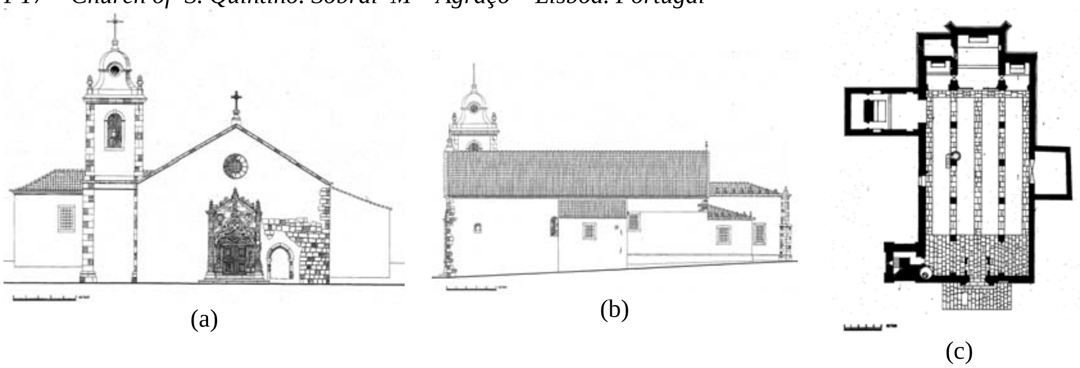


Figure 7 – Geometry: (a) main façade; (b) lateral façade; (c) plan.
[Source: DGEMN]

National Classification: National Monument (MN)

Construction period: 16th

Description:

Church with rural architecture. Longitudinal plan with rectangular naves with two small lateral chapels, one at the North another at the south side, and tripartite sanctuary area with apse and its lateral apsidioles. Quadrilateral side bell-tower at the corner North/West. Stepped volumes with a distinct single, double and triple-sloping roof.

Main façade in a single gable with a centred circular window opening beyond a portal (Manuelino's art), within a gablet. At its right side there is a blind door of pointed arch. Side bell-tower with two levels, with window openings in the upper part with semicircular archivolt, and quadrilateral bell roof cover. Back façade highlighted by the lower volume of the sanctuary area.

Interior with three naves separated by porticos, of five spans, with semicircular arches. Wood lath-work ceilings. Entrance with a small interior porch under the choir. Triumphal pointed arch over engaged columns. Apse and apsidioles with multi-ribbed vault ceilings. Lateral chapels with vaulted ceilings.

Load-bearing walls in rendered stone masonry and limestone ashlar.

Previous Seismic Damage:

It is likely that the structure has been hit by intense earthquakes in 1531, 1755, 1858 and 1909. In the 18th century there was important works to rebuild the Eastern and South façades, probably damaged by the 1755 earthquake. In 1969 it was in bad condition. Since 1934 DGEMN has carried out minor conservation works.

PT7 – Church of S. Quintino. Sobral M[te] Agraço – Lisboa. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.11	0.16	2.65	3.98	1.46	2.20

Other Key Structural Features:

VAULT IN MAIN SPACE

☐ Yes ☒ No, Specify: Just in apse and apsidioles ceilings.

TYPE

☐ Barrel ☐ Crossed ☐ Domed ☒ Other, Specify: Multi-Ribbed vault

GEOMETRICAL DATA (meters)

6 Span *s* **3.0** Rise *r* **?** Thickness at key *t* **1/2** *r* / *s* (-) **?** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

4.6 Free height L **ϕ0.65** Cross-section[14] **28.3** Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

150 Vertical load **1615** Euler critical load **1/9** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

8.0 Maximum free height **0.75** Equivalent thickness[15] **1/11** Thickness / height (-)

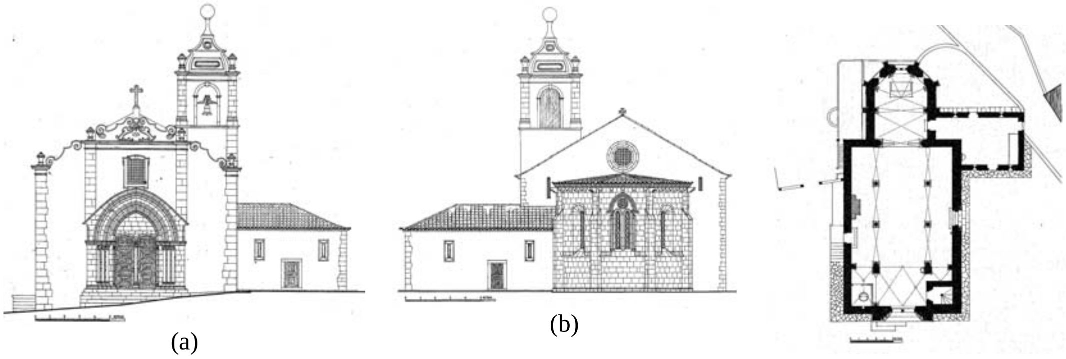
MAGNITUDE OF SEISMIC LOADING (m/s^2)

1.38 PGA for Type 1 **0.82** PGA for Type 2

[14] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[15] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

PT8 - Church of S. Maria. Sintra - Lisboa. Portugal



(a) (b) (c)

Figure 8– Geometry: (a) main façade; (b) back façade; (c) plan.

[Source: DGEMN - General Directorate for Monuments and Sites].

National: Classification: National Monument (MN)

Construction period: 13th and 14th

Description:

Longitudinal plan with three rectangular naves, polygonal apse, and rectangular sacristy at the right side. Quadrilateral bell-tower at west-south corner. Stepped volumes with a distinct double triple and quintuple sloping roof.

Main façade in a gable wall with a window beyond a prominent centred portal, of two tudor arches, surrounded by pointed archivolts and a jamb shaft within a gablet. South portal, of tudor arch, within a pointed arch. Back façade highlighted by the lower volume of the apse, with reinforced edges by chamfer buttresses.

Interior with three naves. The central nave is higher than the aisles; with porticos of four spans with pointed arches separate them. Wood ceilings. Triumphal arch over engaged columns. Apse and elevated choir with pointed ribbed vault ceilings.

Load-bearing walls and vaults in rendered stone masonry and limestone ashlar. Sloping roofs in timber structure.

Previous Seismic Damage:

It is likely that the structure has been hit by intense earthquakes at least in 1356, 1531, 1755, 1858, 1909 and, most recently, in 1969. The 1755 earthquake caused several damages. Probably it was hit by other earthquakes, not documented.

Since 1932 DGEMN has carried out minor conservation works.

PT8 - Church of S. Maria. Sintra - Lisboa. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.12	0.19	3.06	4.74	1.68	2.60

Other Key Structural Features:

VAULT IN MAIN SPACE

[ ] Yes [X] No, Specify: Just in chancel ceiling.

TYPE

[ ] Barrel [ ] Crossed [ ] Domed [X] Other, Specify: Pointed cross ribs

GEOMETRICAL DATA (meters)

5.10 Span *s* **2.6** Rise *r* **?** Thickness at key *t* **1/2** *r* / *s* (-) **?** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

5.10 Free height L **ϕ0.35** Cross-section[16] **58** Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

105 Vertical load **840** Euler critical load **1/15** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

8.0 Maximum free height **0.90** Equivalent thickness[17] **1/9** Thickness / height (-)

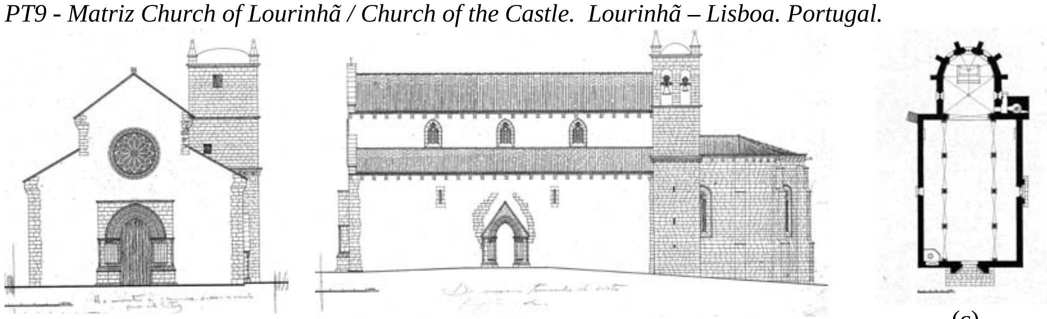
MAGNITUDE OF SEISMIC LOADING (m/s^2)

1.38 PGA for Type 1 **0.82** PGA for Type 2

[16] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[17] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

PT9 - Matriz Church of Lourinhã / Church of the Castle. Lourinhã – Lisboa. Portugal.



(a) (b) (c)

Figure 9– Geometry: (a) main façade; (b) south lateral façade; (c) plan
[Source: DGEMN - General Directorate for Monuments and Sites].

National Classification: National Monument (MN)

Construction period: 14th, 17th, 20th.

Description:

Longitudinal plan with rectangular naves polygonal apse and a quadrilateral bell-tower at its right side. Stepped volumes with a distinct single, double or quintuple sloping roof, over the church, and domical vault over the bell-tower.

Main façade stepped, bounded by ashlar corners and a single gable wall upper. Portal with five pointed archivolts under an important multi-foil rose window opening. Side bell-tower with three levels, window openings in the upper part with semicircular archivolt. South façade with a portal, of blunt arch, within a gablet. On the upper part, three window openings of pointed archivolt with a central mullion.

Polygonal apse, reinforced by six stepped buttresses, with five vertical window openings of pointed archivolt with a central mullion.

Interior with three naves separated by porticos, of four spans with pointed arches, over monolithic columns. Central nave higher and wider than the aisles. Wood ceilings. Triumphal arch over engaged columns. Apse cover by an pointed ribbed vault ceiling.

Sloping roofs with a timber structure.

Previous Seismic Damage:

It is likely that the structure has been hit by intense earthquakes at least in 1356, 1531, 1755, 1858, 1909 and, most recently, in 1969. Probably it was hit by other earthquakes, not documented. Since 1931 DGEMN has carried out some rehabilitation and conservation works.

PT9 - Matriz Church of Lourinhã / Church of the Castle. Lourinhã – Lisboa. Portugal.

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.11	0.19	3.11	5.48	1.60	2.81

Other Key Structural Features:

VAULT IN MAIN SPACE

[ ] Yes [X] No, Specify: Just in chancel ceiling.

TYPE

[ ] Barrel [ ] Crossed [ ] Domed [X] Other, Specify: Pointed cross ribs

GEOMETRICAL DATA (meters)

8.60 Span *s* **4.5** Rise *r* **?** Thickness at key *t* **1/1.9** *r* / *s* (-) **?** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

4.4 Free height L **ϕ0.50** Cross-section[18] **35.2** Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

390 Vertical load **4700** Euler critical load **1/9** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

6.80 Maximum free height **1.0** Equivalent thickness[19] **1/6.8** Thickness / height (-)

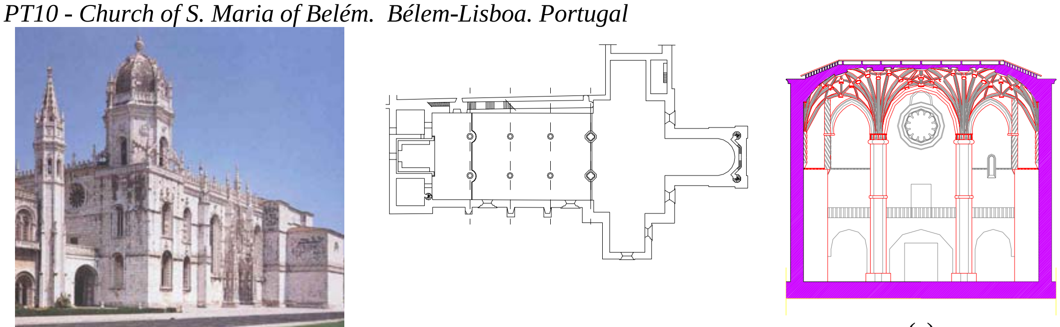
MAGNITUDE OF SEISMIC LOADING (m/s^2)

2.7 PGA for Type 1 **1.6** PGA for Type 2

[18] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[19] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

PT10 - Church of S. Maria of Belém. Bélem-Lisboa. Portugal



(a) (b) (c)

Figure 10 – Geometry: (a) photo; (b) plan; (c) cross-section.

National Classification: National Monument (MN); Mundial Monument (UNESCO 1983)

Construction period: 16th, 17th, 18th, 20th (the construction of Jerónimos Monastery, which include this church, was supposedly initiated in 1502 and concluded at the ends of 16th).

Description:

Longitudinal cruciform plan with rectangular naves, transept and apse. Stepped volumes with distinct double-sloping roof, over the naves, triple-sloping roof, over the apse and transept chapels, quadruple-sloping roof over the transept and octagonal dome over the bell-tower.

In front of the Tagus river is the south façade, upper straight crenelated and separated by buttresses. The west-south corner is highlighted by a quadrilateral volume, with two levels and window openings of semicircular archivolt, under the octagonal bell-tower with arch buttresses.

Interior of three naves of four spans. Elevated choir, over a ribbed vault. The naves have similar height and are covered by a single barrel ribbed vault supported by eight octagonal massive columns and pendentive bracketings on the peripherical walls. There are not the traditional arches (longitudinal and transverse) that usually separate the naves, so the church looks like a unified, transparent and lightsome space. Transept with barrel ribbed vault supported by pendentive bracketings and longitudinal and transverse arches over two massive columns. Lateral chapels stepped with the transept highness. Triumphal arch over the columns. Apse semicircular with barrel vault ceiling with marble rendering. Load-bearing walls in masonry. Vaults, columns and walls rendering with limestone. Sloping roofs with a timber structure over the vaults.

Previous Seismic Damage:

It is likely that the structure has been hit by intense earthquakes at least in 1755, 1858, 1909 and, most recently, in 1969. Probably it was hit by other earthquakes, not documented. The 1755 earthquake, did not cause significant damage.

STRUCTURAL PERFORMANCE FORM

PT10- Church of S. Maria of Belém (Jerónimos Monastery). Belém -Lisboa. Portugal

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.12	0.17	0.80	1.20	0.97	1.41

Other Key Structural Features:

VAULT IN MAIN SPACE
[X] Yes [ ] No, Specify:
TYPE
[ ] Barrel [ ] Crossed [ ] Domed [X] Other, Specify: Barrel vault with triangular net ribs
GEOMETRICAL DATA (meters)
9.0 Span *s* **3.0** Rise *r* **0.10** Thickness at key *t* **1/3** *r* / *s* (-) **1/90** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
15.5 Free height L **ϕ0.90** Cross-section[20] **69** Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
1400 Vertical load **4000** Euler critical load **1/17** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
21.5 Maximum free height **1.70** Equivalent thickness[21] **1/13** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)
1.38 PGA for Type 1 **0.82** PGA for Type 2

[20] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[21] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

Structural Perfomance Form (Resume)

Ref.	Church	Vault in Main Space		Geometrical Data (m)				Columns in Main Space Data (m and kN)				Perimeter Walls Data (m)		Seismic Loading (m/s2)	
PT1	Santa Cruz	No, Specify:	Chancel	Span s:	5	r/s	3/5	Free height:	2.7	Vertical Load :	150	Max. Free height:	5.2	PGA for type 1:	1.38
		Type:	Star Ribbed	Rise r:	3	t/s	#####	Cross Section:	0.3	Euler Critical Load:	1615	Equivalent thicness:	0.55	PGA for type 2:	0.82
		Other,Specify:	-	Key t:	?			Slenderness:	36	Thickness/heigh:	1/9	Thickness/height(-):	1/9		
PT2	Santa Cruz	Yes		Span s:	6.5	r/s	1/3	Free height:	-	Vertical Load :	-	Max. Free height:	11.5	PGA for type 1:	1.38
		Type:	Barrel	Rise r:	2.3	t/s	#####	Cross Section:	-	Euler Critical Load:	-	Equivalent thicness:	1.8	PGA for type 2:	0.82
		Other,Specify:	-	Key t:	?			Slenderness:	-	Thickness/heigh:	-	Thickness/height(-):	1/6		
PT3	Cathedral of Silves	No, Specify:	Transept /Chancel	Span s:	4.8	r/s	5/8	Free height:	11.5	Vertical Load :	150	Max. Free height:	11.5	PGA for type 1:	1.38
		Type:	Pointed Ribbed	Rise r:	3	t/s	#####	Cross Section:	0.75	Euler Critical Load:	3477	Equivalent thicness:	1	PGA for type 2:	0.82
		Other,Specify:	-	Key t:	?			Slenderness:	61	Thickness/heigh:	3/46	Thickness/height(-):	2/23		
PT4	Ancient Jesus Monastery	Yes		Span s:	6.3	r/s	3/5	Free height:	7.5	Vertical Load :	700	Max. Free height:	11.7	PGA for type 1:	1.38
		Type:	Star Ribbed	Rise r:	3.7	t/s	#####	Cross Section:	0.5	Euler Critical Load:	1615	Equivalent thicness:	0.75	PGA for type 2:	0.82
		Other,Specify:	-	Key t:	?			Slenderness:	60	Thickness/heigh:	1/15	Thickness/height(-):	5/78		
PT5	S.Salvador	Yes		Span s:	12	r/s	1/4	Free height:	-	Vertical Load :	-	Max. Free height:	9.2	PGA for type 1:	1.38
		Type:	Barrel	Rise r:	2.8	t/s	#####	Cross Section:	-	Euler Critical Load:	-	Equivalent thicness:	1.3	PGA for type 2:	0.82
		Other,Specify:	-	Key t:	?			Slenderness:	-	Thickness/heigh:	-	Thickness/height(-):	1/7		
PT6	S. Lourenço	No, Specify:	Chancel	Span s:	6.3	r/s	1/2	Free height:	-	Vertical Load :	-	Max. Free height:	7	PGA for type 1:	1.38
		Type:	Barrel	Rise r:	2.9	t/s	#####	Cross Section:	-	Euler Critical Load:	-	Equivalent thicness:	0.75	PGA for type 2:	0.82
		Other,Specify:		Key t:	?			Slenderness:	-	Thickness/heigh:	-	Thickness/height(-):	3/28		
PT7	S. Quintino	No, Specify:	Apse / Apsidioles	Span s:	6	r/s	1/2	Free height:	4.6	Vertical Load :	150	Max. Free height:	8	PGA for type 1:	1.38
		Type:	Star Ribbed	Rise r:	3	t/s	#####	Cross Section:	0.65	Euler Critical Load:	12261	Equivalent thicness:	0.75	PGA for type 2:	0.82
		Other,Specify:	-	Key t:	?			Slenderness:	28	Thickness/heigh:	13/92	Thickness/height(-):	3/32		
PT8	S. Maria	No, Specify:	Chancel	Span s:	5.1	r/s	1/2	Free height:	5.1	Vertical Load :	105	Max. Free height:	8	PGA for type 1:	1.38
		Type:	Pointed Ribbed	Rise r:	2.6	t/s	#####	Cross Section:	0.35	Euler Critical Load:	839	Equivalent thicness:	0.9	PGA for type 2:	0.82
		Other,Specify:	-	Key t:	?			Slenderness:	58	Thickness/heigh:	2/29	Thickness/height(-):	9/80		
PT9	of the Castle	No, Specify:	Chancel	Span s:	8.6	r/s	1/2	Free height:	4.4	Vertical Load :	390	Max. Free height:	6.8	PGA for type 1:	1.38
		Type:	Pointed Ribbed	Rise r:	4.5	t/s	#####	Cross Section:	0.5	Euler Critical Load:	4692	Equivalent thicness:	1	PGA for type 2:	0.82
		Other,Specify:	-	Key t:	?			Slenderness:	35	Thickness/heigh:	5/44	Thickness/height(-):	1/7		
PT10	S. Maria Belém	Yes		Span s:	9	r/s	1/3	Free height:	15.5	Vertical Load :	1400	Max. Free height:	21.5	PGA for type 1:	1.38
		Type:	Barrel	Rise r:	3	t/s	1/90	Cross Section:	0.9	Euler Critical Load:	3969	Equivalent thicness:	1.7	PGA for type 2:	0.82
		Other,Specify:	Triangular net ribs	Key t:	0.1			Slenderness:	69	Thickness/heigh:	5/86	Thickness/height(-):	3/38		

Title: **SPANISH INVENTORY AND STRUCTURAL PERFORMANCE FORMS**

Asia-wide Programme:	EU-INDIA ECONOMIC CROSS CULTURAL PROGRAMME
Project Title:	IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE BUILDINGS
Project Contract N°:	ALA/95/23/2003/077-122
Project Beneficiary:	UNIVERSIDADE DO MINHO, PORTUGAL
Partners:	TECHNICAL UNIVERSITY OF CATALONIA, SPAIN
	CENTRAL BUILDING RESEARCH INSTITUTE, INDIA
	UNIVERSITÁ DEGLI STUDI DI PADOVA, ITALY

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   - Entire building
2- Cathedral of Mallorca
   - Typical bay
   - Entire building
3- Cathedral of Girona
   - Typical bay
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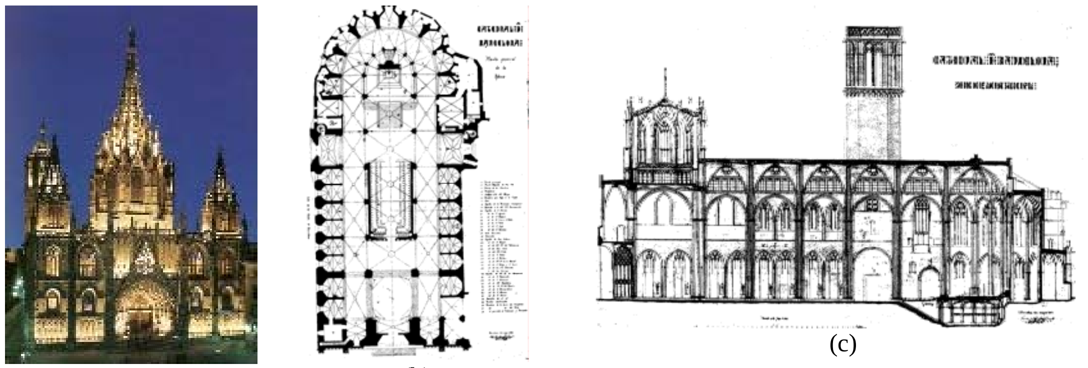
4- Library of the Monastery of Poblet
5- Church of the Castle of Penyafort (Sta. Margarida i els Monjos)
6- Church of Sant Miquel del Port (Barcelona)
7- Oratorium of Sant Felip Neri de Gràcia (Barcelona)
8- Church of Sta. Eulàlia del Papiol (Papiol)
9- Church of Matadars or of Sta. Maria de Marquet (Pont de Vilomara i Rocafort)
10- Church of Sta. Maria de Sales (Viladecans)
11- Monastery of Sant Cugat del Vallès
12- Church of Santa Maria de Ripoll
13- Church of Santa Maria del Mar
14- Cathedral of Granada
15- Cathedral of Sevilla

SP1- Cathedral of Barcelona, Spain



(a) (b) (c)

Figure A.1 – Geometry: (a) photo; (b) plan; (c) cross-section

[Source: Restoration Project of 1875, Files of the Chapter of Barcelona Cathedral]

<u>National Classification:</u> Catalogue of Cultural Heritage of National Interest (BCIN Catalonia)

<u>Construction period:</u> Begun during the second half of 13th c., continued during 14th c. and interrupted at the beginning of 15th leaving the cimborio and façade un-built. neo-Gothic façade built at the end of 19c. and cimborio at the beginning of 20c.

<u>Description:</u> Three-nave plan with 10 spans enlarged with lateral chapels between internally embedded buttresses. Circular apse covered following a deambulatory covered by 7 trapecial vaults. False transept limited by two lateral octagonal towers. Diaphragmatic transverse arches. The 19th c. cimborio was built, as intended by the medieval builders, on the first bay close to the façade and is supported on a medieval structure already made robust on-purpose. Limited at the South by the Gothic cloister, built during 14 c. and 15 c. The structure shows a peculiar arrangement, in which the vaults of the lateral nave, located almost as high, but not so high, as the vaults of the central one, act as effective flying arches able to transfer the thrust from the central vaults to the buttresses. Because of that, true flying arches are not needed and the existing ones were built only as draining devices. The vaults are complemented by a structural infill consisting of a mix of pottery and lime mortar with an upper stone tile roof. A water-proof finishing has been installed in recent times. No recent major restoration works have been undertaken during the last decades; however, a plan is now into development to set future studies and restoration works. The building seems in good condition except for damage caused by corrosion of iron insertions or anchors in the neo-Gothic façade and cimborio, as well as by the overturning of some of their (also modern) pinnacles.

<u>Previous Seismic Damage:</u> Experienced the effect of the 1428 earthquake with epicentrum in the Pyrenees, known to have caused damage in the Church of Sta. María del Mar in Barcelona (collapse of rose window and façade tower). It is uncertain whether some existing damage in the piers and arches of the first bay (cimborio) and apse are due to this (or other) earthquakes.

SP1- Cathedral of Barcelona, Spain (typical bay)

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.0451	0.0345	0.591	0.454	1.66	0.991

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[13.75] Span *s* [25.80] Rise *r* [1.0] Thickness at key *t* [1/0.53] *r* / *s* (-) [1/13.8] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[15.7] Free height L [I_y=0.0] Cross-section[1] [59] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

[1308] Vertical load [12012] Euler critical load [1/17] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[11.75] Maximum free height [0.55] Equivalent thickness[2] [1/21.3] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s²)

[0.39] PGA for Type 1 [ ] PGA for Type 2

---

[1] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[2] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP1b- Cathedral of Barcelona, Spain (entire building)

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.064	0.059	0.744	0.694	1.70	1.37

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[13.0] Span *s* [25.80] Rise *r* [1.0] Thickness at key *t* [1/0.53] *r* / *s* (-) [1/13.8] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[15.7] Free height L [Iy=0.06] Cross-section[3] [59] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[2396] Vertical load [12012] Euler critical load [1/17] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[11.75] Maximum free height [0.55] Equivalent thickness[4] [1/21.3] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

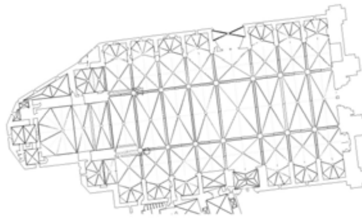
[0.39] PGA for Type 1 [ ] PGA for Type 2

[3] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[4] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP2-- Cathedral of Mallorca, Spain


(a)


(b)

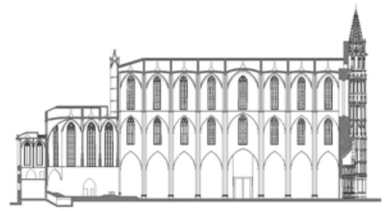

(c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section

[Source: Directory Plan for the Restoration of Mallorca Cathedral]

National Classification: Catalogue of Cultural Heritage of National Interest (Spain)

Construction period: Begun during the second half of 13th c., and continued through 14th c. and 15th c.

Description: Includes three different bodies, namely (1) the Trinity Chapel (first built part), a small vaulted space located at the East end of the complex, (b) the Royal Chapel, consisting of a imposing Gothic unique nave building with two spans and apse, and (3) the main body, built as a three-nave plan building with 8 large spans and lateral chapels between internally embedded buttresses. The 4th bay (from the West façade), of larger longitudinal span, constitutes a sort of false transept leading a lateral doors at each end. The diaphragmatic transverse arches of the naves are connected to a two-level, double battery of flying arches; however, the structural efficacy and real purpose of the upper ones is uncertain. The piers of the central nave, with octagonal cross section, are made of solid ashlar masonry with no rubble infill; their slenderness is extreme (see structural performance form). The building is limited at the North by a cloister and a tower of square plan. In the past, the spandrels of the vaults were probably filled with pottery and lime mortar and were finished by an upper stone tile roof. The building has experienced important repair works along its history and, in particular, during 18th c., when a significant number of the vaults of the central nave were repaired and even rebuilt. As it seems, the infill of the vault was then removed and the corresponding weigh was made up by installing massive dead-weigh stone pyramids on top of the keystone areas of the vaults and transverse arches. A new protection, consisting of a traditional pitched ceramic tile roof, was then constructed over the central vaults.

Previous Seismic Damage: Significant damage affecting the piers (cracking and large deformation) seems more related to the construction process, although historical earthquakes may have contributed to it. The original West façade was demolished during the mid of 19c. because of its very important out-of-plumb deformation, being replaced by a more robust neo-Gothic one. It is likely that the earthquake of 1851 affected the façade urging, in turn, the substitution. Other effects, such as the general deformation of piers towards the West, may be connected to the problems of the façade. Minor local damage (as movements experienced by the façade towers) can be associated to earthquake.

SP2- Cathedral of Mallorca, Spain (typical bay)

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.044	0.0544	0.373	0.461	1.196	1.459

Other Key Structural Features:

VAULT IN MAIN SPACE

[x] Yes [ ] No, Specify:

TYPE

[ ] Barrel [x] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

17.9 Span *s* | 44.0 Rise *r* | 1.0 Thickness at key *t* | 1/0.41 *r* / *s* (-) | 1/12.8 *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

33.0 Free height L | Φ=1.7 Cross-section[5] | 70.6 Slenderness $\lambda = L / (\text{Inertia} / \text{Area})^{0.5}$ (-)

5663 Vertical load | 22481 Euler critical load | 1/19.4 Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

18.0 Maximum free height | 1.30 Equivalent thickness[6] | 1/13.9 Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

0.39 PGA for Type 1 | PGA for Type 2

[5] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[6] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP2b- Cathedral of Mallorca, Spain (entire building)

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.099	0.085	0.577	0.497	1.85	0.83

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[17.9] Span *s* [44.0] Rise *r* [1.0] Thickness at key *t* [1/0.41] *r* / *s* (-) [1/17.9] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[33.0] Free height L [Φ=1.7] Cross-section[7] [70.6] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

[7745] Vertical load [18579] Euler critical load [1/19.4] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[18.0] Maximum free height [1.30] Equivalent thickness[8] [1/13.9] Thickness / height (-)

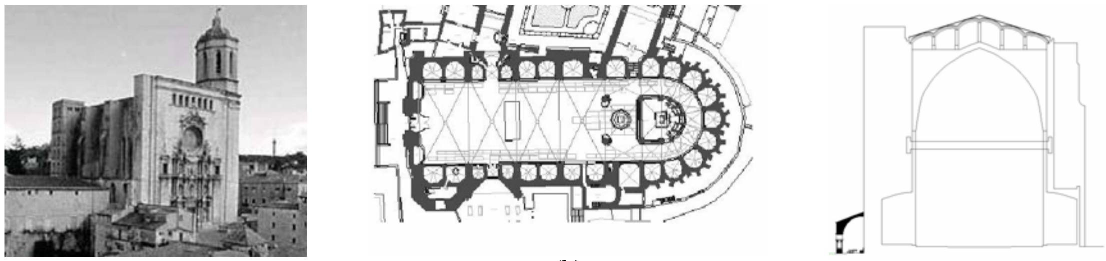
MAGNITUDE OF SEISMIC LOADING (m/s^2)

[0.39] PGA for Type 1 [ ] PGA for Type 2

[7] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[8] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP3- Cathedral of Girona, Spain



(a) (b) (c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Institution of Architects of Catalunya, Girona].

National Classification: Catalogue of Cultural Heritage of National Interest (BCIN Catalonia)

Construction period: Begun during 14th c. and completed in the second half of 15th c.

Description: Two different parts, corresponding to two different construction periods, can be distinguished. The first part, including the apse and first East bay, is conceived as a conventional three nave church with an arrangement similar to that of Barcelona Cathedral. Then, during 15th c., 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 4 large vaults. Lateral chapels exist between imposing buttresses embedded within the perimeter of the building (as usual in Catalan Gothic construction). The West façade is limited by an octagonal tower at its South corner. A Romanesque tower and cloister are preserved and limit the nave along its North wall. The building shows, overall, a very good condition of conservation; only slight deformation is recognizable along the internal vertical edges of the buttresses. Cracks existing close to some of the windows are likely to be in fact construction joints currently acting as expansion ones. Monitoring has been recently implemented to know more about the real significance and evolution of such cracks.

Previous Seismic Damage:

The main nave was not yet built when the 1427-28 series of earthquakes, known to have caused significant destruction in the region close to the Pyrenees and beyond, occurred. No damage has been recognized which can be clearly related to latter earthquakes.

SP3- Cathedral of Girona, Spain (typical bay)

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.081	0.084	0.491	0.514	0.804	0.811

Other Key Structural Features:

VAULT IN MAIN SPACE

[x] Yes [ ] No, Specify:

TYPE

[ ] Barrel [x] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

21.75 Span *s* | 33.95 Rise *r* | 1.05 Thickness at key *t* | 1/0.64 *r* / *s* (-) | 1/20.7 *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[ ] Free height L | [ ] Cross-section[9] | [ ] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$ (-)

[ ] Vertical load | [ ] Euler critical load | 1/ Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

34.7 Maximum free height | 0.75 Equivalent thickness[10] | 1/46.3 Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

0.78 PGA for Type 1 | [ ] PGA for Type 2

[9] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[10] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP3- Cathedral of Girona, Spain (entire building)

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.138	0.081	0.657	0.387	1.13	0.56

Other Key Structural Features:

VAULT IN MAIN SPACE

[x] Yes [ ] No, Specify:

TYPE

[ ] Barrel [x] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[21.75] Span *s* [33.95] Rise *r* [1.05] Thickness at key *t* [1/0.64] *r / s* (-) [1/20.7] *t / s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[19.55] Free height L [1.25x1.25] Cross-section[11] [55.92] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[2674] Vertical load [24657] Euler critical load [1/15.6] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[34.7] Maximum free height [0.75] Equivalent thickness[12] [1/46.3] Thickness / height (-)

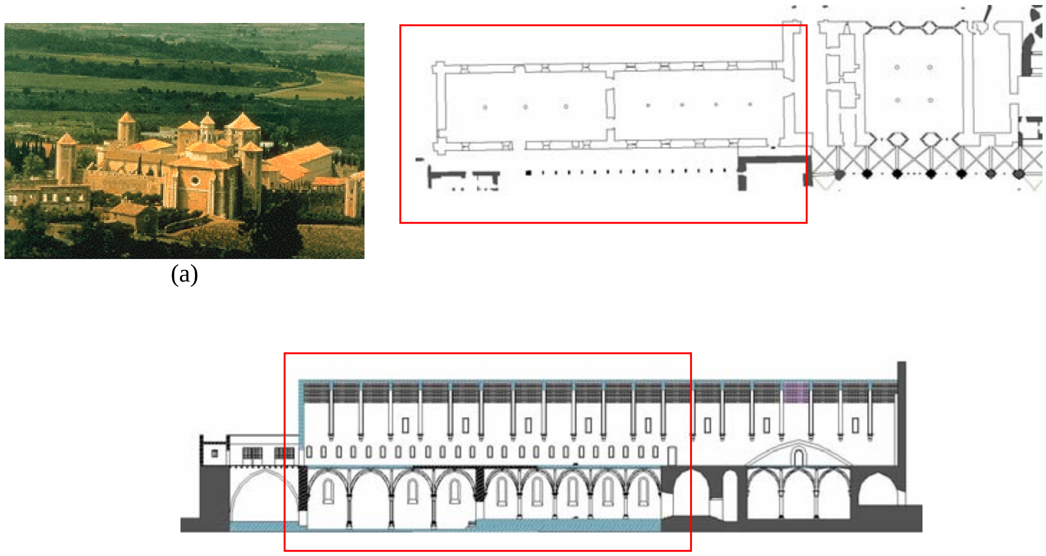
MAGNITUDE OF SEISMIC LOADING (m/s^2)

[0.78] PGA for Type 1 [ ] PGA for Type 2

[11] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[12] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP4- Library of the Monastery of Poblet, Spain



(a) (b) (c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section [Source: courtesy of Architect Jordi Portal].

National Classification: Catalogue of Cultural Heritage of National Interest (BCIN Catalonia)

Construction period: Built during 14c. (from 1343) and modified, yet preserving the Gothic architecture, during 17c.

Description: The building includes two stories used, in the past, as refectory (ground floor) and dormitory (1st floor) of the monastery. The ground level includes 9 spans in the longitudinal direction and 2 spans in the transverse direction. The intermediate floor is composed of a system of cross vaults sustained on wall cantilevers and interior stone monolithic columns. A structural infill made of rubble stone exists on the vaults. The second level is roofed by means of a traditional tile roof sustained by longitudinal timber beams supported, in turn, on a series of transverse diaphragmatic arches which spring from cantilevers clamped in the walls. The building is part of the Monastery of Sta. Maria de Poblet, one of the religious complexes with largest architectural and historical significance in Spain.

Previous Seismic Damage: According to contemporary records, an earthquake in 1792 caused damage in the inner columns. Deformation and cracking can be seen in arches, vaults and columns. Overall deformations are observed both in the longitudinal and the transverse directions. Some of the lesions can be clearly attributed to the fire experienced at the beginning of 20th c., but most are of uncertain origin. Some of the columns were substituted during a restoration undertaken during the 1970-1972.

SP4- Library of the Monastery of Poblet, Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.105	0.117	1.605	1.795	1.52	1.71

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

9.60	Span *s*	10.80	Rise *r*	0.45	Thickness at key *t*	1/0.89	*r* / *s* (-)	1/21.3	*t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

5.0	Free height L	*Φ=0.45*	Cross-section[13]	44.4	Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
405	Vertical load	3973	Euler critical load	1/11.1	Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

8.80	Maximum free height	1.20	Equivalent thickness[14]	1/7.33	Thickness / height (-)

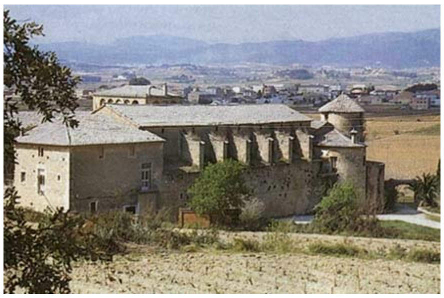
MAGNITUDE OF SEISMIC LOADING (m/s^2)

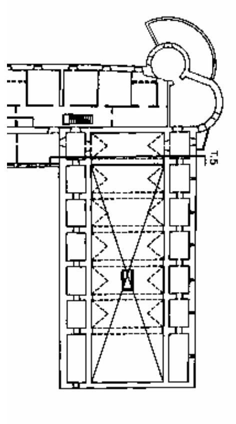
0.39	PGA for Type 1		PGA for Type 2

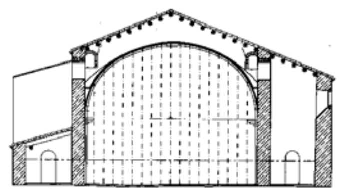
[13] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[14] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP5- Chruch of the Castle of Penyafort (Sta. Margarida i els Monjos) Spain







(b) (c)

(a)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Service of Local Architectural Heritage of Barcelona]

<u>National Classification:</u> Catalogue of Cultural Heritage of National Interest (BCIN Catalonia)

<u>Construction period:</u> 17^{th} c.

<u>Description:</u> Rectangular plan consisting of 6 bays covered with transverse barrel vaults and a 7^{th} bay, in the East, covered with an elliptical dome. The domes are sustained on transverse arches. The arches, the vaults and dome are made of brick masonry, while the walls and buttresses are of irregular stone masonry. The building is protected with a traditional tile roof built sustained on timber beams, in turn supported on diaphragmatic brick masonry walls built on the transverse arches. The buttresses, of large dimensions, are contained within the perimeter of the building thus limiting the lateral chapels. The building is limited by a circular tower at the North-West corner and is connected to the rest of the monastery buildings along the West façade. The church is part of the so-called Castle of Penyafort, a former monastery built during 17 c. in the place where, according to tradition, the Dominican canonist Saint Ramon of Penyafort (12-13c.) had been born.

<u>Previous Seismic Damage:</u>

Vertical cracks, of uncertain origin, exist along the intersection of the main perimeter walls of the building (particularly in the South-East corner.

SP5- Chruch of the Castle of Penyafort (Sta. Margarida i els Monjos) Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.028	0.144	0.267	1.384	0.13	1.68

Other Key Structural Features:

VAULT IN MAIN SPACE
[X] Yes [ ] No, Specify:
TYPE
[X] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:
GEOMETRICAL DATA (meters)
[8.80] Span *s* [15] Rise *r* [1.35] Thickness at key *t* [1/0.59] *r* / *s* (-) [1/6.5] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
[ ] Free height L [ ] Cross-section[15] [ ] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
[ ] Vertical load [ ] Euler critical load [1/] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
[15.0] Maximum free height [0.60] Equivalent thickness[16] [1/25] Thickness / height (-)

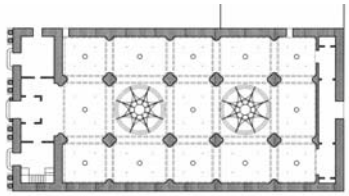
MAGNITUDE OF SEISMIC LOADING (m/s^2)
[0.039] PGA for Type 1 [ ] PGA for Type 2

[15] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

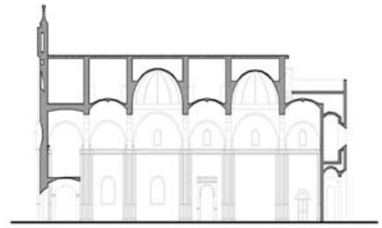
[16] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP6- Church of Sant Miquel del Port (Barcelona) Spain

(a)



(b)



(c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Files of the Municipality of Barcelona]

National Classification: Catalogue of Cultural Heritage of Local Interest (BCIL)

Construction period: Begun during 1753 and 1755 by the military engineer Carreño. Partial destruction, reconstruction and enlargement during 1862-63. Restaured in 1912 by architect Elies Rogent. Tile roof recently restaured.

Description: Conceived as the church of the new quarter of Barceloneta, in Barcelona, after the Succession War of 1712. It consists of a three nave building with central domes and lateral hemispherical vaults on transverse and longitudinal arches. All the structural elements (except the façade) are made of masonry brick. No buttresses exist, the stability of the building laying on the capacity of the system composed by the walls and lateral pillars. The entire building is covered by a tile roof on longitudinal wooded beams placed over diaphragmatic masonry walls built over the transverse arches. The building was originally isolated. Gradual densification of construction has caused it to be surrounded by other buildings (with very narrow construction joints between the walls).

Previous Seismic Damage: Abundant cracking and significant deformation affect the perimeters walls, arches, vaults and transverse diaphragmatic. walls. Significant overall transverse deformation towards the South side can be seen. Damage has not been yet been assessed, but soil settlements are likely to be involved in the production. As in other cases, the possible contribution of repeated minor earthquakes is not to be disregarded.

SP6- Church of Sant Miquel del Port (Barcelona) Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.063	0.098	0.566	0.884	0.71	1.07

Other Key Structural Features:

VAULT IN MAIN SPACE
[X] Yes [ ] No, Specify:
TYPE
[ ] Barrel [ ] Crossed [X] Domed [ ] Other, Specify:
GEOMETRICAL DATA (meters)
[6.40] Span *s* [10.50] Rise *r* [0.75] Thickness at key *t* [1/0.61] *r* / *s* (-) [1/8.5] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
[11.3] Free height L [Ix=0.33] Cross-section[17] [27.7] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
[7517] Vertical load [129247] Euler critical load [1/7.98] Thickness / height, if applicable (-)

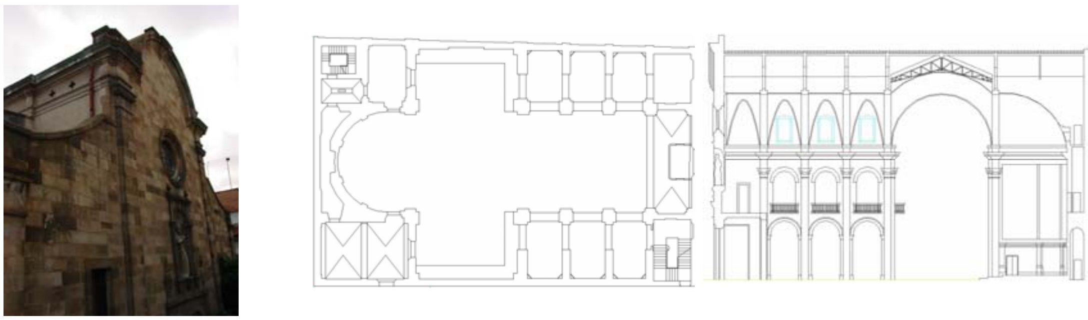
DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
[12.1] Maximum free height [1.05] Equivalent thickness[18] [1/11.52] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)
[0.39] PGA for Type 1 [ ] PGA for Type 2

[17] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[18] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thicknes

SP7- Oratorium of Sant Felip Neri de Gràcia (Barcelona) Spain



(a) (b) (c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Files of the Municipality of Barcelona]

National Classification: Catalogue of Cultural Heritage of Local Interest (BCIL)

Construction period: Built during 1883-1895 by architect Josep Artigas. Partly reconstructed at the beginning of 20 c. due damage caused by a fire.

Description: The design is inspired in the more ancient Oratorium of Saint Philip Neri in the old city of Barcelona (built in 18 c.). The one of Gracia shows Latin-cross plan consisting of a main nave complemented with side chapels between lateral buttresses, a true transept and a semicircular apse. An intermediate floor exists along the lateral chapels. The main nave is covered with a large brick masonry barrel vault stiffened with transverse arches, while the crossing and the apse are covered respectively with spherical dome and half-dome, both in brick masonry. The perimeter and inner walls are made of stone masonry. The building is protected by a traditional tile roof sustained on diaphragmatic masonry arches built on the transverse arches and steel structure over the domes.

Previous Seismic Damage:

Abundant cracking and significant affect the façade (showing a very significant vertical crack) and perimeters walls (showing both vertical and horizontal cracks) , arches, and buttresses . Damage has not been yet been assessed, but soil settlements are likely to be involved in the production of some lesions existing close to the façade. The possible contribution of repeated minor earthquakes to the production or extension of the mentioned lesions should not be disregarded.

SP7- Oratorium of Sant Felip Neri de Gràcia (Barcelona) Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.041	0.058	0.462	0.649	0.80	0.92

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[X] Barrel [ ] Crossed [X] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[10.55] Span *s* [19.80] Rise *r* [0.35] Thickness at key *t* [1/0.53] *r* / *s* (-) [1/30.1] / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[14.40] Free height L [Iy=0.30] Cross-section[19] [37] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[2956] Vertical load [72596] Euler critical load [1/10.4] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[7.20] Maximum free height [0.80] Equivalent thickness[20] [1/9] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

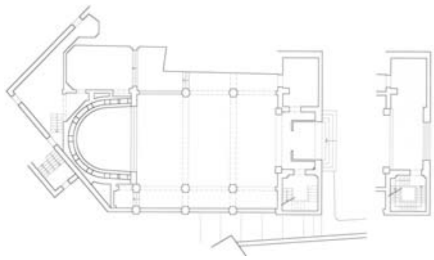
[0.39] PGA for Type 1 [ ] PGA for Type 2

[19] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

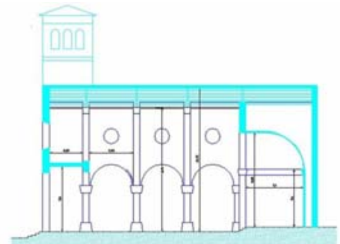
[20] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP8- Church of Sta. Eulàlia del Papiol (Papiol) Spain

(a)



(b)



(c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Restoration Project by Bis Arquitectes, Barcelona]

National Classification: Catalogue of Cultural Heritage of Local Interest (BCIL)

Construction period: Started to be built in 1944 to replace a previous ancient church destroyed during the Spanish Civil War.

Description: Rectangular in plan with a central nave and narrow lateral naves hosting lateral chapels. Semicircular apse with radial buttresses, covered by a masonry half-dome. The rest is covered by a traditional tile roof sustained on steel structure. Perimeter walls and façade made of brick masonry. Clerestory walls on semicircular masonry arches. The façade includes a square tower in its South-West corner.

Previous Seismic Damage:
Much damage exists, involving both severe cracking and deformation, in most of the structural parts of the building. Because of that, the building has been closed to public while waiting for complete and restoration. Most of the damage seems to be connected to soil settlements induced by the tower. Other causes are not yet to be disregarded.

SP8- Church of Sta. Eulàlia del Papiol (Papiol) Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.035	0.042	0.701	0.840	0.55	0.66

Other Key Structural Features:

VAULT IN MAIN SPACE

[ ] Yes [X] No, Specify: Tile roof on steel structure

TYPE

[ ] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[8.25] Span *s* [10.90] Rise *r* [ ] Thickness at key *t* [1/] *r* / *s* (-) [1/] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[4.15] Free height L [Iy=0.02] Cross-section[21] [21] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[2091] Vertical load [55874] Euler critical load [1/5.97] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[6.30] Maximum free height [0.35] Equivalent thickness[22] [1/18] Thickness / height (-)

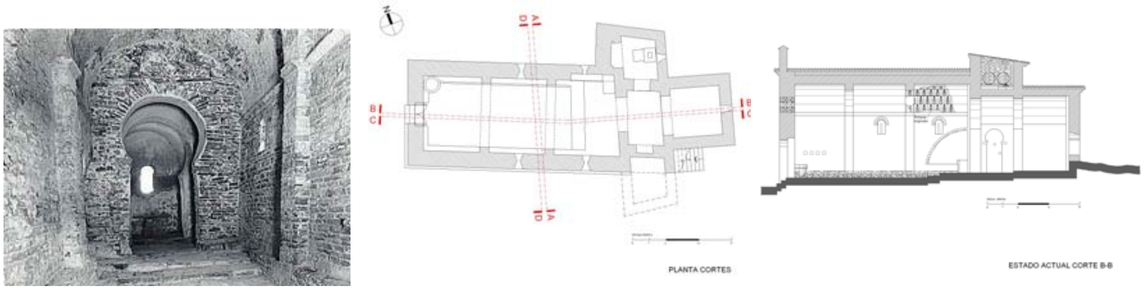
MAGNITUDE OF SEISMIC LOADING (m/s^2)

[0.39] PGA for Type 1 [ ] PGA for Type 2

[21] 050 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[22] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP9- Church of Matadars or of Sta. Mariade Marquet (Pont de Vilomara i Rocafort) Spain



(a) (b) (c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Service of Local Architectural Heritage of Barcelona]

National Classification: Catalogue of Cultural Heritage of National Interest (BCIN Catalonia)

Construction period: Begun during pre-Romanesque and continued during the Romanesque periods, 10-11 th c. Description: Latin-cross plan including the nave, a small transept and a rectangular apse. The nave includes a longitudinal barrel vault on thick masonry walls. All the structural components are on stone masonry. Both the wall and the main barrel vault are stiffened with inner extensions (small buttresses and transverse arches). The crossing is covered by a small masonry dome. The crossing and the apse are separated from the rest of the spaces by walls opened by narrow horseshoe-shaped arches.

Previous Seismic Damage: Due to important out-of-plumb deformation of the lateral walls, the building was provided, by the beginning of 20 c., with inner timber ties linking the springings of the stiffening arches. These ties, thought to be ineffective, were later removed. Cracks exist in the façade, walls and vaults. In its current very deformed condition, the building is vulnerable to the effect of an earthquake. The contribution of earthquakes (particularly of the seismic series of 1427-28) to the mentioned alterations is uncertain.

SP9- Church of Matadars or of Sta. Mariade Marquet (Pont de Vilomara i Rocafort) Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.095	0.193	1.175	2.398	1.09	2.29

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[X] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[7.70] Span *s* [11.90] Rise *r* [0.85] Thickness at key *t* [1/0.65] *r* / *s* (-) [1/9.06.] / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[ ] Free height L [ ] Cross-section[23] [ ] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

[ ] Vertical load [ ] Euler critical load [1/] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[7.30] Maximum free height [1.25] Equivalent thickness[24] [1/5.84] Thickness / height (-)

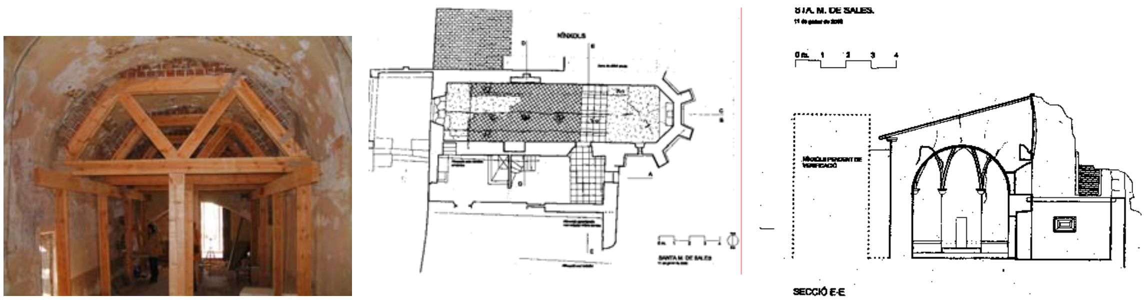
MAGNITUDE OF SEISMIC LOADING (m/s^2)

[0.39] PGA for Type 1 [ ] PGA for Type 2

[23] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[24] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP10- Church of Sta. Maria de Sales (Viladecans) Spain



(a) (b) (c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Service of Local Architectural Heritage, Barcelona]

National Classification: Catalogue of Cultural Heritage of Local Interest (BCIL)

Construction period: Romanesque (12th) over roman villa, with latter Gothic additions.

Description: Unique nave composed of a rectangular body, covered with a smooth barrel vault, and a semicircular apse with Gothic radial vaults. Exterior narrow buttresses along the lateral walls and radial exterior buttresses around the apse. Covered (until recently) by a traditional tile roof. Archeological works have permitted the to undercover an original stone pitched tile roof over the main vault. The walls are founded (with nor intermediate enlargement) on a very low-resistant lawyer of anthropic rubble. Has been surrounded, until recent times, by lateral buildings of rustic facture, until they collapsed due to lack of maintenance.

Previous Seismic Damage:
As in previous cases, the contribution of earthquake to the alteration of the building is uncertain. It any is clear, however, that the very significant out-of-plumb deformation shown by the lateral walls is related to the very poor quality of the soil on which they are founded; on the contrary, it is unclear why the problem has only manifested in recent times, while the building has been standing for more than 800 years. Yet in recent times, the buildings existing at the sides prevented the construction from completely collapsed; their disappearance has lead to an increase of the deformation and, in turn, to decision of propping the vaults on auxiliary timber centerings.

SP10- Church of Sta. Maria de Sales (Viladecans) Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.061	0.228	0.829	3.103	0.58	3.20

Other Key Structural Features:

VAULT IN MAIN SPACE

[x] Yes [ ] No, Specify:

TYPE

[x] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

3.70 Span *s* | 4.0 Rise *r* | 1.05 Thickness at key *t* | 1/0.94 *r* / *s* (-) | 1/3.52 *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[ ] Free height L | [ ] Cross-section[25] | [ ] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[ ] Vertical load | [ ] Euler critical load | 1/ Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

6.0 Maximum free height | 0.85 Equivalent thickness[26] | 1/7.06 Thickness / height (-)

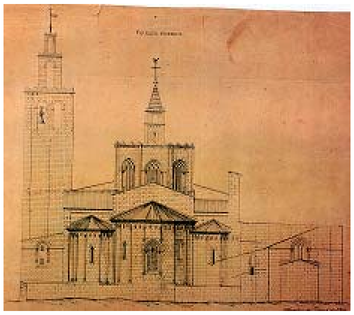
MAGNITUDE OF SEISMIC LOADING (m/s^2)

0.39 PGA for Type 1 | [ ] PGA for Type 2

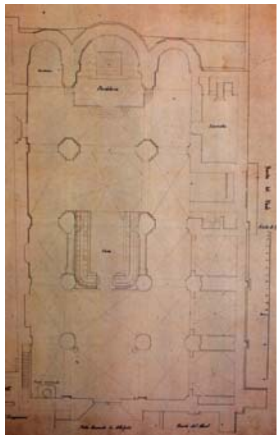
[25] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[26] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

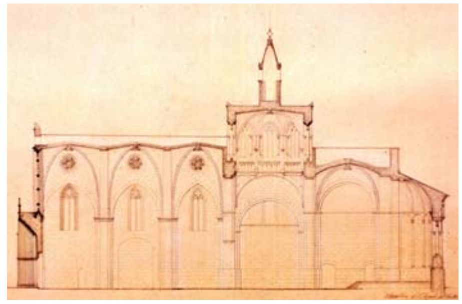
SP11- Monastery of Sant Cugat del Vallès, Spain



(a)



(b)



(c)

Figure A.2 – Geometry: (a) back façade; (b) plan; (c) cross-section
[Source: Architects College of Barcelona]

National Classification: Catalogue of Cultural Heritage of National Interest (BCIN Catalonia).

Construction period: Built during 12th-14th c. Latter additions built during 16th c. Restored during the latter decades of 20 th.

Description: This building is formed by three nave and the presbytery has three semicircular radial apses. The nave and the cimborio are covered by crossed vaults. A 41.70 m. high bell tower on the south façade of the church was built in the main body just between the chapels and the sacristy.

Previous Seismic Damage: No seismic damage has been recorded.

SP11- Monastery of Sant Cugat del Vallès, Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.126	0.076	1.142	0.688	1.62	0.87

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[8.40] Span *s* [18.0] Rise *r* [1.60] Thickness at key *t* [1/0.47] *r* / *s* (-) [1/5.25] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[9.30] Free height L [Iy=1.52] Cross-section[27] [16] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[5793] Vertical load [854172] Euler critical load [24/95] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[15.25] Maximum free height [1.60] Equivalent thickness[28] [1/9] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

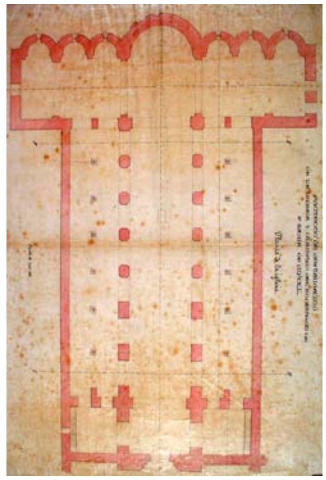
[0.39] PGA for Type 1 [ ] PGA for Type 2

[27] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[28] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP12- Monastery of Santa Maria de Ripoll, Spain

(a)



(b)

(c)

Figure A.2 – Geometry: (a) façade; (b) plan; (c) cross-section
[Source: Architects College of Barcelona]

National Classification: Catalogue of Cultural Heritage of National Interest (BCIN Catalonia).

Construction period: Began in 888 and finished at the 977 year as a five-nave church. In 1835 a great fire caused the collapse of the vaults and part of the walls. It was rebuilt during 1886-1893 as narrower construction comprehending only three-naves.

Description: This new building is formed by three naves and two bell towers in the principal façade. The main space is covered by a barrel vault and the apse is formed by 7 semicircular radial little apses.

Previous Seismic Damage: On february 2nd, 1428 an earthquake destroyed the dome and one of the bell towers.

SP12- Church of Santa Maria de Ripoll ,Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.047	0.096	0.467	0.954	0.72	1.65

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[X] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[8.90] Span *s* [18.90] Rise *r* [1.0] Thickness at key *t* [1/0.68] *r* / *s* (-) [1/8.9] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[5.95] Free height L [Iy=0.38] Cross-section[29] [14.72] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[1400] Vertical load [532196] Euler critical load [16/57] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[11.65] Maximum free height [1.50] Equivalent thickness[30] [1/8] Thickness / height (-)

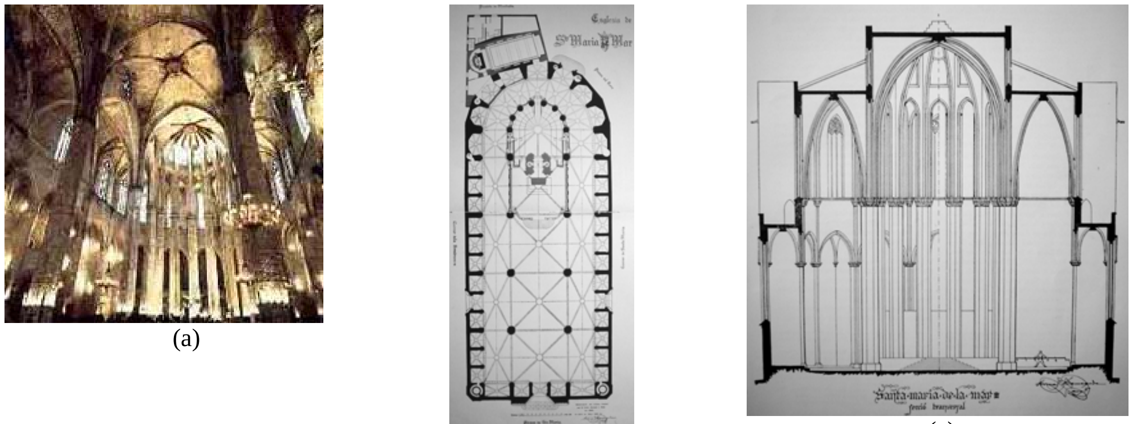
MAGNITUDE OF SEISMIC LOADING (m/s^2)

[0.98] PGA for Type 1 [ ] PGA for Type 2

[29] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[30] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP13- Church of Santa Maria del Mar, Spain



(a) (b) (c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section

[Source: Architects College of Barcelona]

National Classification: Catalogue of Cultural Heritage of National Interest (BCIN Catalonia).

Construction period: In march 1329, Bernat Llull collocated the first stone, and the last vault was collocated in 1383.

Description: It's a masonry structure built in a sober, austere Gothic style. At the sides of the principal façade, there are two slender octagonal towers. The façade shows a rose window in its central part. The building is composed by three naves, formed by four sections and an apse that consists of a seven sides polygon, all covered by crossed vaults. There are eight octagonal piers with a free height of 16.50 m. and separated by 12 m. from each other, forming bays of 12 by 12 m. free span.

Previous Seismic Damage: On march 3, 1373 while the church was still in construction, an earthquake with an epicentral intensity of VIII-IX (MSK) was felt in the region. During this event some of its closing elements between some walls and interior arches were still not constructed. The main damage was the fall of the tallest portion of its bell tower, and the collapse of the main façade rose window.

SP13- Church of Santa Maria del Mar, Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.042	0.061	0.593	0.862	1.36	1.49

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[12.00] Span *s* [32.3] Rise *r* [1.25] Thickness at key *t* [1/0.37] *r* / *s* (-) [1/9.60] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[16.5] Free height L [Iy=0.44] Cross-section[31] [38] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

[4980] Vertical load [79700] Euler critical load [2/19] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[13.5] Maximum free height [0.85] Equivalent thickness[32] [1/16] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

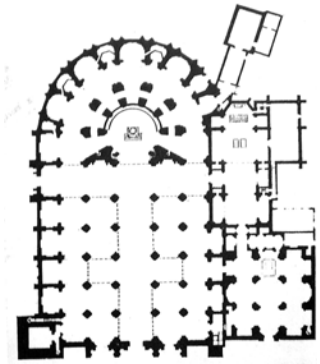
[0.39] PGA for Type 1 [ ] PGA for Type 2

[31] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

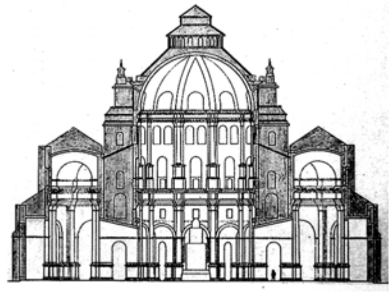
[32] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP14- Cathedral of Granada, Spain

(a)



(b)



(c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Architects College of Barcelona]

National Classification:

Construction period: Its construction began in 1492. By 1664 most the nave was finished. The masonry works were finished in 1704.

Description: A Gothic ground floor of five naves, with various side chapels and a double sanctuary or apse aisle make up a Renaissance-style structure with evident Gothic elements, as planned by Diego de Siloé. Especially eye-catching is the great height of the naves, achieved by using pedestales on which rest groups of split columns, with classic capitals and upper entablature. Crowning all of it are the ribbed ogival vaults and stained-glass windows depicting religious themes, some of them by Flemish masters, which illuminate the interior.The entrance arch or main arch narrows in its centre to adapt to the enormous circular vault which it supports.

Previous Seismic Damage:

SP14- Cathedral of Granada, Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.125	0.045	1.351	0.493	0.73	0.11

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [ ] rossed [X] med O [X] , Specify: Various, sextipartite and quadripartite crossed vaults

GEOMETRICAL DATA (meters)

[9.90] Span *s* [26.0] Rise *r* [1.45] Thickness at key *t* [1/0.3] *r* / *s* (-) [1/6.83] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[17.6] Free height L [Iy=0.75] Cross-section[33] [36] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[5813] Vertical load [120192] Euler critical load [9/80] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[14.0] Maximum free height [0.9] Equivalent thickness[34] [2/31] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

[2.26] PGA for Type 1 [ ] PGA for Type 2

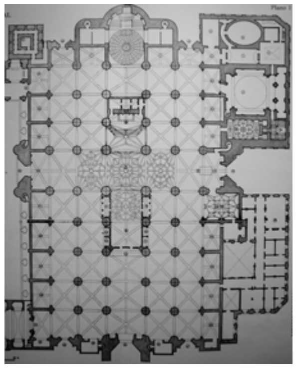
---

[33] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

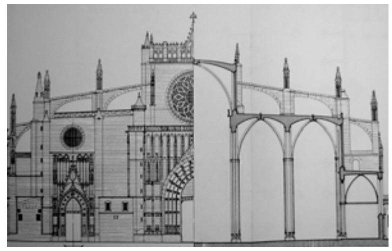
[34] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

SP15- Cathedral of Sevilla, Spain

(a)



(b)



(c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Architects College of Barcelona]

National Classification: Spain Historic Patrimony

Construction period: Begun during 13th c. and completed at the end of the 15th c.

Description: This Cathedral is formed by 5 naves and chapels between the buttresses. The roof is vaulted and the piers have 13 different cross section shapes forming three main groups: piers of the crossing, church main nave piers and chapel-buttressing piers. The piers have a stone masonry infill covered by brick masonry. This cathedral has no triforium like other final Gothic period buildings. The Cimborio was finished in October 10, 1506 and the building was opened on may 11, 1507.

Previous Seismic Damage: This cathedral suffered damage due to the 1504 earthquake. Due the previous seismic damage in some piers the Cimborio collapsed on December 25, 1511 destroying the transept and choir vaults. On December 25, 1883 some piers were damaged again by another earthquake; as la possible latter effect of this earthquake, another pier of the choir collapsed on august 1, 1888.

SP15- Cathedral of Sevilla, Spain

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.049	0.048	0.553	0.540	0.49	0.43

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

[16.2] Span *s* [37.3] Rise *r* [0.90] Thickness at key *t* [1/0.4] *r* / *s* (-) [1/18.1] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[17.4] Free height L [Iy=1.62] Cross-section[35] [29] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[8730] Vertical load [265452] Euler critical load [4/29] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[14.0] Maximum free height [1.0] Equivalent thickness[36] [1/14] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

[0.69] PGA for Type 1 [ ] PGA for Type 2

---

[35] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[36] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

Structural Perfomance Form (Resume)

Ref.	Church	Vault in Main Space		Geometrical Data (m)				Columns in Main Space Data (m and kN)				Perimeter Walls Data (m)		Seismic Loading (m/s2	
SP1	Cathedral of Barcelona	Yes		Span s:	13.75	r/s	1 7/8	Free height:	15.7	Vertical Load :	2396	Max. Free height:	11.75	PGA for type 1:	0.39
		Type:	Crossed	Rise r:	25.8	t/s	4/55	Cross Section:	1.05	Euler Critical Load:	11945	Equivalent thicness:	0.55	PGA for type 2:	
		Other,Specify:	-	Key t:	1			Slenderness:	60	Thickness/heigh:	1/15	Thickness/height(-):	3/64		
SP2	Cathedral of Mallorca	Yes		Span s:	17.9	r/s	2 1/2	Free height:	33	Vertical Load :	7745	Max. Free height:	18	PGA for type 1:	0.39
		Type:	Crossed	Rise r:	44	t/s	1/18	Cross Section:	1.7	Euler Critical Load:	18578	Equivalent thicness:	1.3	PGA for type 2:	
		Other,Specify:	-	Key t:	1			Slenderness:	78	Thickness/heigh:	5/97	Thickness/height(-):	6/83		
SP3	Cathedral of Girona	Yes		Span s:	21.75	r/s	1 5/9	Free height:	19.55	Vertical Load :	2674	Max. Free height:	34.7	PGA for type 1:	0.78
		Type:	Crossed	Rise r:	33.95	t/s	4/83	Cross Section:	1.43	Euler Critical Load:	26503	Equivalent thicness:	0.75	PGA for type 2:	
		Other,Specify:	-	Key t:	1.05			Slenderness:	55	Thickness/heigh:	3/41	Thickness/height(-):	1/46		
SP4	Library of the Monastery of Poblet	Yes		Span s:	9.6	r/s	1 1/8	Free height:	5	Vertical Load :	405	Max. Free height:	8.8	PGA for type 1:	0.39
		Type:	Crossed	Rise r:	10.8	t/s	3/64	Cross Section:	0.45	Euler Critical Load:	3973	Equivalent thicness:	1.2	PGA for type 2:	
		Other,Specify:	-	Key t:	0.45			Slenderness:	44	Thickness/heigh:	1/11	Thickness/height(-):	3/22		
SP5	Castle of Penyafort	Yes		Span s:	8.8	r/s	1 5/7	Free height:	-	Vertical Load :	-	Max. Free height:	15	PGA for type 1:	0.39
		Type:	Barrel	Rise r:	15	t/s	2/13	Cross Section:	-	Euler Critical Load:	-	Equivalent thicness:	0.6	PGA for type 2:	
		Other,Specify:	-	Key t:	1.35			Slenderness:	-	Thickness/heigh:	-	Thickness/height(-):	1/25		
SP6	S. Miguel del Port	No, Specify:		Span s:	6.4	r/s	1 2/3	Free height:	11.3	Vertical Load :	7517	Max. Free height:	12.1	PGA for type 1:	0.39
		Type:	Domed	Rise r:	10.5	t/s	2/17	Cross Section:	1.61	Euler Critical Load:	127464	Equivalent thicness:	1.05	PGA for type 2:	
		Other,Specify:		Key t:	0.75			Slenderness:	28	Thickness/heigh:	1/7	Thickness/height(-):	2/23		
SP7	S. Felip Neri de Gràcia	No, Specify:		Span s:	10.55	r/s	1 7/8	Free height:	14.4	Vertical Load :	2956	Max. Free height:	7.2	PGA for type 1:	0.39
		Type:	Barrel/Domed	Rise r:	19.8	t/s	1/30	Cross Section:	1.57	Euler Critical Load:	70976	Equivalent thicness:	0.8	PGA for type 2:	
		Other,Specify:	-	Key t:	0.35			Slenderness:	37	Thickness/heigh:	6/55	Thickness/height(-):	1/9		
SP8	S. Eulàlia del Papiol	No, Specify:		Span s:	8.25	r/s	1 1/3	Free height:	4.15	Vertical Load :	2091	Max. Free height:	6.3	PGA for type 1:	0.39
		Type:	Tile roof on steel structure	Rise r:	10.9	t/s	#####	Cross Section:	0.8	Euler Critical Load:	57611	Equivalent thicness:	0.35	PGA for type 2:	
		Other,Specify:	-	Key t:	?			Slenderness:	21	Thickness/heigh:	16/83	Thickness/height(-):	1/18		
SP9	S. María de Marquet	Yes		Span s:	7.7	r/s	1 1/2	Free height:	-	Vertical Load :	-	Max. Free height:	7.3	PGA for type 1:	0.39
		Type:	Barrel	Rise r:	11.9	t/s	1/9	Cross Section:	-	Euler Critical Load:	-	Equivalent thicness:	1.25	PGA for type 2:	
		Other,Specify:	-	Key t:	0.85			Slenderness:	-	Thickness/heigh:	-	Thickness/height(-):	1/6		
SP10	S. Maria de Sales	Yes		Span s:	3.7	r/s	1	Free height:	-	Vertical Load :	-	Max. Free height:	6.0	PGA for type 1:	0.39
		Type:	Barrel	Rise r:	4	t/s	21/74	Cross Section:	-	Euler Critical Load:	-	Equivalent thicness:	0.85	PGA for type 2:	
		Other,Specify:		Key t:	1.05			Slenderness:	-	Thickness/heigh:	-	Thickness/height(-):	1/7		

Structural Perfomance Form (Resume)

Ref.	Church	Vault in Main Space		Geometrical Data (m)				Columns in Main Space Data (m and kN)				Perimeter Walls Data (m)		Seismic Loading (m/s2	
SP11	Monastery of S. Cugat del Vallès	Yes		Span s:	8.4	r/s	2 1/7	Free height:	9.3	Vertical Load :	5793	Max. Free height:	15.25	PGA for type 1:	0.39
		Type:	Crossed	Rise r:	18	t/s	4/21	Cross Section:	2.35	Euler Critical Load:	854172	Equivalent thicness:	1.6	PGA for type 2:	
		Other,Specify:	-	Key t:	1.6			Slenderness:	16	Thickness/heigh:	24/95	Thickness/height(-):	1/9		
SP12	Monastery of S. María de Ripoll	Yes		Span s:	8.9	r/s	1 1/2	Free height:	5.95	Vertical Load :	1400	Max. Free height:	11.65	PGA for type 1:	0.98
		Type:	Barrel	Rise r:	13	t/s	10/89	Cross Section:	1.67	Euler Critical Load:	532196	Equivalent thicness:	1.5	PGA for type 2:	
		Other,Specify:	-	Key t:	1			Slenderness:	14	Thickness/heigh:	16/57	Thickness/height(-):	1/8		
SP13	S. María del Mar	Yes		Span s:	12	r/s	2 2/3	Free height:	16.5	Vertical Load :	4980	Max. Free height:	13.5	PGA for type 1:	0.39
		Type:	Crossed	Rise r:	32.3	t/s	5/48	Cross Section:	1.73	Euler Critical Load:	79700	Equivalent thicness:	0.85	PGA for type 2:	
		Other,Specify:	-	Key t:	1.25			Slenderness:	38	Thickness/heigh:	2/19	Thickness/height(-):	1/16		
SP14	Cathedral of Granada	Yes		Span s:	9.9	r/s	2 5/8	Free height:	17.6	Vertical Load :	5813	Max. Free height:	14	PGA for type 1:	2.26
		Type:	Crossed	Rise r:	26	t/s	6/41	Cross Section:	1.98	Euler Critical Load:	120192	Equivalent thicness:	0.9	PGA for type 2:	
		Other,Specify:	Sextipartite and quadripartite crossed vaults	Key t:	1.45			Slenderness:	36	Thickness/heigh:	9/80	Thickness/height(-):	2/31		
SP15	Cathedral of Sevilla	Yes		Span s:	16.25	r/s	2 2/7	Free height:	17.4	Vertical Load :	8730	Max. Free height:	14	PGA for type 1:	0.69
		Type:	Crossed	Rise r:	37.3	t/s	1/18	Cross Section:	2.4	Euler Critical Load:	265452	Equivalent thicness:	1	PGA for type 2:	
		Other,Specify:	-	Key t:	0.9			Slenderness:	29	Thickness/heigh:	4/29	Thickness/height(-):	1/14		

Title: **INDIAN INVENTORY AND**
STRUCTURAL PERFORMANCE FORMS

Asia-wide Programme: EU-INDIA ECONOMIC CROSS CULTURAL PROGRAMME

Project Title: IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE BUILDINGS

Project Contract N°: ALA/95/23/2003/077-122

Project Beneficiary: UNIVERSIDADE DO MINHO, PORTUGAL

Partners: TECHNICAL UNIVERSITY OF CATALONIA, SPAIN

CENTRAL BUILDING RESEARCH INSTITUTE, INDIA

UNIVERSITÁ DEGLI STUDI DI PADOVA, ITALY

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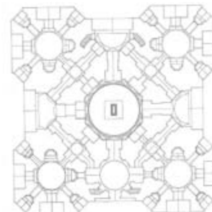
IN1: *Humayun's Tomb – New Delhi, India*

(a)



(b)

Figure A.1 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: World Heritage Series – Humayun's Tomb & Adjacent Monuments,ASI].

National Classification: World Heritage Monument (ASI Protected)

Construction period: 1565-72 AD

Description: It is the first mature example of Moghul architecture in India, which shows an unsurpassed skill and perfection of mason's craftsmanship. Meticulously symmetrical plan, symmetrical elevations with three emphatic arches on all four sides, bulbous double dome on a high drum, geometrically arranged coloured tilework and arch-netting in the vaults are the main features of Humayun's Tomb. Double-storeyed lofty mausoleum rises from a wide platform of 12000m^2 area and 6.5 m height with series of cells with arch openings, which in turn stands upon a podium of one meter height. The latter is the only feature of the mausoleum built of quartzite, the remainder being entirely built of random rubble masonry of red or yellowish sandstone with marble panels or outlines and marble-covered dome. The floor of the terrace is paved with red sandstone. The central octagonal chamber rises through two storeys is encompassed by octagonal chambers at the diagonals and arched lobbies on the sides, their openings closed with perforated screens. The central hall containing the cenotaph is roofed by a high emphatic dome carried on squinches, with plastered interlace in the spandrels. The high dome is achieved by use of a double shell – which appears to be first of its kind in India. Double dome gives an imposing exterior height to the structure but kept the ceiling of the central hall in proportion with the interior heights. It is supported by pavilions or chhattris above the wings and portals. These pavilions augmented by carefully graded pinnacles at all angles of the building, unite the soaring outline of the dome with the horizontal lines of the main structure and give strength and coherence of the design.

Previous Seismic Damage: No information on previous seismic damage. No structural strengthening measures has been used any where in the structure, while minor repair/renovation was on.

IN1: *Humayun's Tomb – New Delhi, India*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.2	0.05	1.5	1.5	1.7	1.6

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify:

GEOMETRICAL DATA (meters)

15.0 Span *s* **7.5** Rise *r* **0.8** Thickness at key *t* **1/2** *r* / *s* (-) **1/19** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[ ] Free height L [ ] Cross-section[1] [ ] lenderness $\lambda = L / (\text{Inertia} / \text{Area})^{0.5}$(-)

[ ] Vertical load [ ] Euler critical load **1/** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

22 Maximum free height **> 1** Equivalent thickness[2] **1/15** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

.25g PGA for Type 1 **0.25g** PGA for Type 2

[1] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[2] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN2: *Safdarjang's Tomb – New Delhi, India*

(a)
Figure A.1 – Geometry: (a) photo

National Classification: World Heritage Monument (ASI Protected)

Construction period: 1753-54 AD

Description:

One of the best-preserved examples of the late Mughal style at Delhi, rightly described as 'the last flicker in the lamp of Mughal architecture'. The double storeyed mausoleum is rises from a platform faced by a verandah broken by arched openings, leading to series of cells on the inside. The central chamber of the mausoleum is square with eight apartments around it, the corner apartments being octagonal and the others rectangular. The ceilings of different apartments are ornamented with incised and painted plaster-work. Large double-dome at the central chamber with its bulbous outline rises from a sixteen-sided drum. The corners of the mausoleum are occupied by polygonal towers picked with inlaid marble designs, and covered by chhatris. The arched entrances to the tomb-chamber from all the four sides are located within high recessed engrailed arches. Safdarjang tomb is layout is laid out on the pattern of Humayun's tomb, but the weakness of its proportions and its pronouncedly vertical elevation, lacking a pyramidal feeling, rob it of a balanced character.

Previous Seismic Damage:

No information on previous seismic damage

Cracks were seen in the walls and roof of verandah at many places.

IN2: *Safdarjan's Tomb – New Delhi, India*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
.3	.1	2.1	1.9	1.1	1.2

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify:

GEOMETRICAL DATA (meters)

[7.5] Span *s* [7.5] Rise *r* [0.7] Thickness at key *t* [1/1] *r* / *s* (-) [1/11] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[ ] Free height L [ ] Cross-section[3] [ ] nderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

[ ] Vertical load [ ] Euler critical load [1/] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[12.5] Maximum free height [> 1] Equivalent thickness[4] [1/6] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s²)

[.25g] PGA for Type 1 [0.25g] PGA for Type 2

[3] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[4] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN3: *Jami Masjid – New Delhi, India*

Figure A.1 – Geometry: (a) photo

National Classification: World Heritage Monument (ASI Protected)

Construction period: 1650-56 AD

Description:

It is the largest mosque of India, built on a high platform. It has a large rectangular prayer-hall, which is two-bay in depth. On eastern side prayer hall has a magnificent façade of eleven arches with central one being the higher. The western bay is pierced by seven arches only. The arches are decorated with marble frames, while above them run inscriptional panels in black and white marbles. The prayer-hall is surmounted by three shapely domes ornamented with alternating stripes of black and white marble and is flaked at the eastern corners by tall four storeyed tapering minarets (minars)

Previous Seismic Damage:

No signs of distress or damage have been noticed

From literature it is found that the mosque has undergone considerable repairs in the past

IN3: *Jami Masjid – New Delhi, India*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
.4	0.3	1.4	1.2	1.67	1.54

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify:

GEOMETRICAL DATA (meters)

[11] Span *s* [11] Rise *r* [0.5] Thickness at key *t* [1/1] *r* / *s* (-) [1/22] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[3.5] Free height L [0.6x0.6] Cross-section[5] [23] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$ (-)

[ ] Vertical load [ ] Euler critical load [1/] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[15] Maximum free height [~ 1] Equivalent thickness[6] [1/] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

[.25g] PGA for Type 1 [0.25g] PGA for Type 2

[5] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[6] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN4: *Diwan-i-am, Red Fort – New Delhi, India*

(a)
Figure A.1 – Geometry: (a) photo

National Classification: World Heritage Monument (ASI Protected)

Construction period: 1640-45 AD

Description:

Diwan-i-am (“hall of public audience”) is one of the building exists in very good condition within Red Fort. It is a magnificent hall have three-bays in depth, divided into 27 square bays on a system of columns which support the arches. The hall is open on three sides, backed by as set of rooms. It has an impressive façade of nine openings of engrailed arches, springing from pillars. The roof is spanned by beams of sandstones from four side arches. Chajja around the open sides is laid on cantilever brackets fixed and projected from the walls. The structure is stand on a podium of one meter height.

Previous Seismic Damage:

Some joints has been opened due to loosing of mortar. No information on previous seismic damage.

IN4: *Dewan-i-am, Red Fort– New Delhi, India*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
.8	0.8	1.8	1.7	2.4	2.3

Other Key Structural Features:

VAULT IN MAIN SPACE
☐ Yes ☐ No, Specify:
TYPE
☐ Barrel ☐ Crossed ☐ Domed ☐ Other, Specify:
GEOMETRICAL DATA (meters)
[ ] Span *s* [ ] Rise *r* [ ] Thickness at key *t* [1/] *r* / *s* (-) [1/] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
[3.0] Free height L [0.4ϕ] Cross-section[7] [30] nderness λ = L / (Inertia / Area)$^{0.5}$(-)
[ ] Vertical load [ ] Euler critical load [1/] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
[9] Maximum free height [0.4] Equivalent thickness[8] [1/23] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)
[.25g] PGA for Type 1 [0.25g] PGA for Type 2

[7] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[8] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN5: *Shish Gumand, Lodhi Garden – New Delhi, India*

(a)
Figure A.1 – Geometry: (a) photo

National Classification: ASI Protected

Construction period: 1491-1500 AD

Description:

It is a square shape gumbad with an imposing dome, turrets on corners and facades possessing a semblance of being double-storeyed stands on a podium of 1m height. The façades are divided horizontally by a string course and with series of sunk niches running above and below it. Its western wall contains a 'mihrab', which serves as a mosque, but the three sides have a central entrance set in a projecting frame. The mihrab-projection at the rear are portion of walls below the string-course are built with alternating narrow and wide course of stones. The square tomb consists of a single compartment covered with dome supported by frame work rises from a 16 sided drum. The niches are spanned by arches, the central openings by brackets and lintel beams.

Previous Seismic Damage:

Some of the stones has displaced from their position due to loosening of mortar.

No information on previous seismic damage.

IN5: *Shish Gumand, Lodhi Garden– New Delhi, India*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.05	0.05	1.8	1.9	2.3	2.4

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify:

GEOMETRICAL DATA (meters)

12 Span *s* **5** Rise *r* **0.6** Thickness at key *t* **1/2.4** *r* / *s* (-) **1/20** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

☐ Free height L ☐ Cross-section ☐ Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

☐ Vertical load ☐ Euler critical load **1/** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

15 Maximum free height **> 1** Equivalent thickness[10] **1/15** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

.25g PGA for Type 1 **0.25g** PGA for Type 2

[9] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[10] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN6: *Bhadra Gate (Lal Darwaja – Ahemdabad, Gujarat, India*

(a)

(b)

Figure A.1 – Geometry: (a) photo from top (b) photo with seismic damage

National Classification: World Heritage Monument (ASI Protected)

Construction period: 1411 AD

Description:

Built by Sultan Ahmad Shah (1411-1442) founder of Ahemdabad. Named as Bhadra Gate by first king of Gujarat state. It is two storeyed gate with two minarets at the end and clock tower in between. The minarets are circular in plan comprising of two shells with inner one of 6.6 m solid whereas the outer shell is 1.35m thick with 13 m diameter. Overall width of 40m with central opening in form of arch (gate) with 5m span, 2.5m rise and 8.4m deep. The walls are 2.2m thick on both sides of arch. The first floor height is 9.0 m, whereas the total structure's height is 17m.

Previous Seismic Damage:

Damaged severely during 2001 Bhuj Earthquake, collapse of outer walls of towers at corners due to torsional effects,

Repairing is under way, cracks are being filled with lime mortar comprising of sagoor, pulse, Jaggery, Cement & Surkhi.

Structural strengthening is missing.

IN6: *Bhadra Gate (Lal Darwaja – Ahemdabad, Gujarat, India*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
.04	0.04	.8	.7	.75	.89

Other Key Structural Features:

VAULT IN MAIN SPACE
☐ Yes ☑ No, Specify:
TYPE
☐ Barrel ☐ Crossed ☐ Domed ☐ Other, Specify: Arched
GEOMETRICAL DATA (meters)
5 Span *s* **2.5** Rise *r* **.55** Thickness at key *t* **1/2** *r* / *s* (-) **2/25** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
☐ Free height L ☐ Cross-section[11] ☐ Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)
☐ Vertical load ☐ Euler critical load **1/** Thickness / height, if applicable (-)

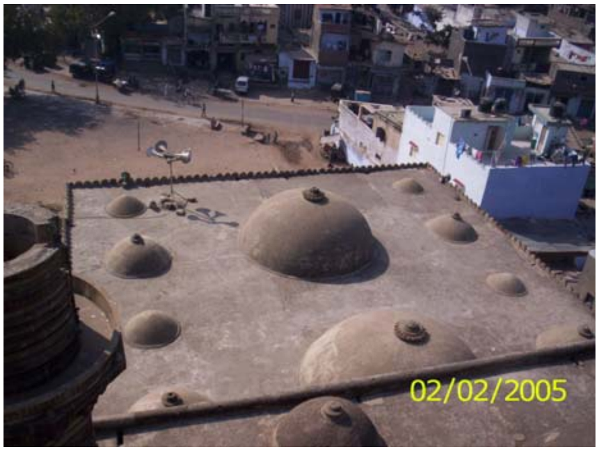
DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
8 Maximum free height **1.35** Equivalent thickness[12] **1/6** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)
.16g PGA for Type 1 **0.10g** PGA for Type 2

[11] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[12] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN7: *Mosque & Tomb of Bibiji's (Jumta Minar – Ahemdabad, Gujarat, India*



(a) (b)
Figure A.1 – Geometry: (a) front view of Minars (b) domes at the roof level of the mosque

National Classification: World Heritage Monument (ASI Protected)

Construction period: 1430 AD

Description:

The mosque located at Rajpur (Ahmedabad). The inscription appearing inside the central mihrab assigns the construction of the mosque in 1454 AD to Makhduma-I-Jahan, mother of Sultan Ahmad Shah. The combined conception is of immense size the site occupying 4598.70 sqm. The mosque is uqite rigid and ponderous but for its triple arched façade innovation. Its huge minar buttresses (14.50 m height) of which one was damaged upto the roof level by lightning, put on a commanding appearance and the usual spiral staircases are not let into them but taken through the thickness of the adjacent front walls, and re-enter the minars at a slightly higher level. The five mihrabs are decorated with rich ornament with rosettes, and chain-and-lamp carvings. The north end of the mosque has the Muluk-Khana or royal gallery with porched northern entrance. The roof at the landing of this entrance ahs remarkable carved dome descending in the center of its interior in a spiral pendentive.

Previous Seismic Damage:

Damaged severely during 2001 Bhuj Earthquake, collapse of one of the minarates and subsequently repaired by ASI. Structural strengtneing is missing and is required.

IN7: *Mosque & Tomb of Bibiji's (Jumta Minar – Ahemdabad, Gujarat, India*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.03	0.06	0.7	0.8	0.6	0.8

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify: Arched

GEOMETRICAL DATA (meters)

[6.2] Span *s* [2.5] Rise *r* [0.41] Thickness at key *t* [2/5] *r* / *s* (-) [1/6] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[5.0] Free height L [0.6x0.6] Cross-section[13] [0.36] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[230] Vertical load [976] Euler critical load [1/14] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[5.0] Maximum free height 1[14] [1.10] Equivalent thickness [2/9] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

[.16g] PGA for Type 1 [0.10g] PGA for Type 2

[13] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[14] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN8: *Mosque & Tomb of Bai Harir (Asarwa, Ahemdabad, Gujarat, India)*

(a) (b)

Figure A.1 – Geometry: (a) front view of Tomb (b) distressed walls of Tomb

National Classification: World Heritage Monument (ASI Protected)

Construction period: 1500 AD

Description:

The heritage building, comprising of *Mosque & Tomb of Bai Harir and step well* built by Bai Harir Sultani in 1500 AD, is in the suburb of Asarwa. The mosque is a simplified version of Bibi Achyut Kuki's or Miyan Khan Chisti's and has a rather cramped interior layout. The rauda is again a precursor of Rani Sipri's tomb in layout, but without screens in the lower storey.

Previous Seismic Damage:

Damaged severely during 2001 Bhuj Earthquake, collapse of one of the minarate and subsequently repaired by ASI.

IN8: *Mosque & Tomb of Bai Harir (Asarwa, Ahemdabad, Gujarat, India)*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.04	0.07	0.5	0.6	0.4	0.67

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify: -

GEOMETRICAL DATA (meters)

4.6 Span *s* 3.6 Rise *r* .30 Thickness at key *t* 7/9 *r* / *s* (-) 3/46 *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

3.85 Free height L 0.6x0.6 Cross-section[15] 43 Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

230 Vertical load 1647 Euler critical load 1/11 Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

3.85 Maximum free height 1 .60 Equivalent thickness 12/77 Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

.16g PGA for Type 1 0.10g PGA for Type 2

[15] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[16] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN9: *Mosque & Tomb of Sayyad Usman (Usmanpura, Gujarat, India)*

(a)

(b)

(c)

Figure A.1 – Geometry: (a) front view of Mosque (b) displaced column of mosque due to 2001 earthquake (c) repairing of periferal distress beam of tomb under progress by ASI

National Classification: World Heritage Monument (ASI Protected)

Construction period: 1460 AD

Description: The heritage structure is located in Usmanpur, situated between north and west of Ahmedabad was founded by Sayyid Uthman and his tomb in the same locality. This is one of the first monument that would fall within the time of Mahmud Begada being dated in about AD 1460. Complimentary in design and symmetrical in composition, both the mosque and rauda employ the hypostyle princile, and in the mosque which is of the open type. The rauda is a square structure with a square tomb chamber in the center of a double aisle of pillars, roofed by a dome, 10.97 m in diameter at center, whiel 8 domes of 2.6 m dia of 1.6 m height i.e. three on each face of the mosque. Thus, the mosque is 23.0x23.0m in plan, based on raised plateform of 60cm, with floor height of 4.8 m. The tomb is supported on 126 columns of 300x300mm size. The exceptional width of the dome has been met by introducing additional pillar in each angle of the central square hall, thus producing a twelve-sided figure on which the circular dome-base rests. The same method has been experimented upon in the dome of the tomb of Shaikh Ahmad Khattu (Ganj Bakhsh) at Sarkhej, but has been bettered in the tomb structure of Sayyid 'Uthman'. Another feature introduced at this time is an ariel window of artistic design brought in as an architectural motif and first attached to the sides of the mosque sanctuary but later given a place in the façade. It was fitted with a perforated screen also. The dargah of Sayyid 'Uthman' being that of a pir is frequented by many pious members of the faith, and is reputed with miraculous powers in restoring sanity to those suffering from hysteria and in exorcising evil from the mentally possessed.

Previous Seismic Damage: Damaged severely during 2001 Bhuj Earthquake, collapse of minarates while repairing of tomb domes and roofs are being repaired by ASI.

IN9: *Mosque & Tomb of Sayyad Usman (Usmanpura, Gujarat, India)*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.02	0.018	0.3	0.25	0.3	0.2

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify: Arched

GEOMETRICAL DATA (meters)

10.97 Span *s* **4.5** Rise *r* **0.60** Thickness at key *t* **2/5** *r* / *s* (-) **4/73** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

4.8 Free height L **0.6x0.6** Cross-section[17] **53** Slenderness $\lambda = L / (\text{Inertia} / \text{Area})^{0.5}$(-)

230 Vertical load **1060** Euler critical load **3/40** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

- Maximum free height 1[8] **-** Equivalent thickness **-** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

.16g PGA for Type 1 **0.10g** PGA for Type 2

[17] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[18] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN10: *Shiva Temple, Kotai (Tal.: Bhuj, Dist.: Kachha, Gujarat, India)*

(a)

(b)

Figure A.1 – Geometry: (a) View of Shiva temple (b) Roofing system (inside view) of temple

National Classification: World Heritage Monument (ASI Protected)

Construction period: 600 – 700 AD

Description: The heritage structure is located in Kotai, which has several ruined temples of earlier part of the 10th cent AD. The temple is dedicated to Lord Shiva, and built of the yellowish and red stone, and is roofed in a peculiar way. The aisles are covered by a sort of groins, like the side aisles in some Caitya-caves; the nave is roofed in the same way as at the Amarnatha temple – at Kalayan, the central area being covered with massive slabs holoed out in the center, in which a pendentive has been inserted. Outside it has a slanting roof divided into four sections of slightly different heights that next to the spire being the highest, and the remote end the lowest; each section is terminated by a neatly carved gable end. The door of the temple has been neatly carved with the nine grahas or patrons of the planets over the lintel; the jambs are also carefully sculptured. In the Mandapa, which is 5.1 m square, are four pillars measuring 2.9 m to the top of the bracket, and with a square block sculptured below the bracket, and six pillars apparently inserted for the sake of uniformity only, for they are not of any structural use. The shafts 2m high support a plinth 0.2m high, on which stands a block carved with colonnettes at the corners, and crowned with an amalasila-shaped member, the faces of the block being sculptured with figures of men and elephants. The total height is 2.6 m. Among the four armed figures on the brackets of the columns one is a female, and one has a face on the abdomen. In the window recesses are also pilasters with four armed figures in the bracket capitals. The pillars and pilasters all are of broken square form. The area behind the central one is roofed with large slabs carved with 16 female figures linked in one another's arms in a circle, with the legs crossed and turned towards the center.

Previous Seismic Damage: Totally damaged during 2001 Bhuj Earthquake, and subsequently being repaired by ASI.

IN10: *Shiva Temple, Kotai (Tal.: Bhuj, Dist.: Kachha, Gujarat, India)*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.05	0.07	.5	0.6	0.4	0.56

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify: Arched

GEOMETRICAL DATA (meters)

[2.5 .2] Span *s* [2.5] Rise *r* [0.4] Thickness at key *t* [1] *r* / *s* (-) [4/25] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[2.9] Free height L [0.36] Cross-section[19] [32] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$ (-)

[250] Vertical load [2903] Euler critical load [1/8] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[2.40] Maximum free height 1 [.6] Equivalent thickness[20] [1/4] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

[.36g] PGA for Type 1 [0.24g] PGA for Type 2

[19] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[20] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN11: *Rao Lakha Chhatri, Bhuj (Dist.: Kachha, Gujarat, India)*

(a) (b) (c) (d)

Figure A.1 – Geometry: (a) Rao Lakhaji Chhatri in Bhuj before the earthquake. The large structure on the left is the main chhatri built after the king, Rao Lakhaji, while that on the right was built after the queen. (b) Rao Lakhaji Chhatri was reduced to rubble (in the background), while the chhatri in the foreground sustained significant loosening of the masonry stones at both the sill and lintel levels. This chhatri, though still standing, is on the verge of a vertical split and complete collapse (c) Damage to stone column of the Royal Chhatri in Bhuj. (d) Close view of inner solid section of chhatri, which was damaged during 2001 earthquake.

National Classification: ASI protected monument

Construction period: 1710-1961 AD

Description:

A Royal Chhatri is the burial place of the royals of the Hindu religion. The Hindu rites of burning the mortal remains were performed here. The places were later decorated with the open column structures, and are architecturally the most significant buildings of the Kachchh region. It is a complex of sandstone structures near Hamirsar Lake, built in memory of Maharao Lakhpatji in the 18th century. These structures have pyramidal and domed roofs supported by decorative columns on a raised plinth. Some of these *chhatris* in Bhuj have completely collapsed. Others developed cracks in their domes. Stone pieces have fallen from the *chajjas* (awnings or the eaves of the building) in some. Most of the slender stone columns sustained structural damage due to the heavy roof load. These *chhatris* had been recently restored before the earthquake, their domes made watertight by an additional 100 mm thick plain cement concrete layer. This additional load on the already weak sandstone columns may have contributed to the development of longitudinal splitting cracks in them during the earthquake.

Previous Seismic Damage:

Totally damaged during 2001 Bhuj Earthquake, and subsequently being repaired by ASI.

IN11: *Rao Lakha Chhatri, Bhuj (Dist.: Kachha, Gujarat, India)*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0.03	0.03	0.5	0.5	0.4	0.4

Other Key Structural Features:

VAULT IN MAIN SPACE

☑ Yes ☐ No, Specify:

TYPE

☐ Barrel ☐ Crossed ☑ Domed ☐ Other, Specify: Arched

GEOMETRICAL DATA (meters)

10 Span *s* **4.25** Rise *r* **1.75** Thickness at key *t* **3/7** *r* / *s* (-) **7/40** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

4.25 Free height L **0.36** Cross-section[21] **47** Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

230 Vertical load **1352** Euler critical load **5/59** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

- Maximum free height 1 **-** Equivalent thickness **-** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

.36g PGA for Type 1 **0.24g** PGA for Type 2

[21] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[22] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

IN12: *Parag Mahal, Bhuj (Dist.: Kachha, Gujarat, India)*

(a)

(b)

(c)

Figure A.1 – Geometry: (a) Façade of the south building (b) Large cracks between masonry blocks (c) Heavy ornamented stones used in the parapet fell down at the Prag Mahal in Bhuj.

National Classification: Private Property, likely to be taken-up as heritage building

Construction period: 1865

Description:

Across the courtyard from the Old Palace, Aiyna Mahal, is the Prag Mahal (or new palace), designed by Henry St. Claire Wilkins, a British engineer, and built around 1865 by Rao Pragmalji. A grand Durbar Hall in the new Gothic style and the 45 m lofty clock tower command the skyline of the whole town of Bhuj. The tower is of 5 storey with 6.50m storey height. The plan dimension of clock tower is 6.15 x 6.15 m, with 1.5m thick wall at ground floor while 1.2m thick at top floor. The Italianate arches have alternating ornate marble and sandstone. Most of the structures, including the tall and slender clock tower, sustained severe damage. Joints between masonry blocks opened up, some arch stones dislodged or fell off, and some corner turrets and parapets partially collapsed.

Previous Seismic Damage:

Totally damaged during 2001 Bhuj Earthquake, and subsequently being repaired by ASI.

IN12: *Parag Mahal, Bhuj, Gujarat, India*

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction

Other Key Structural Features:

VAULT IN MAIN SPACE

☐ Yes ☑ No, Specify: flat arched roof

TYPE

☐ Barrel ☐ Crossed ☐ Domed ☐ Other, Specify: Arched

GEOMETRICAL DATA (meters)

[- .2] Span *s* [-] Rise *r* [-] Thickness at key *t* [ ] *r* / *s* (-) [ ] *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[-] Free height L [-] Cross-section[23] [-] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

[-] Vertical load [-] Euler critical load [-] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[6.15] Maximum free height 1[1.2] Equivalent thickness[24] [1/5] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

[.36g] PGA for Type 1 [0.24g] PGA for Type 2

[23] 0.50 x 1.25 or ϕ0.90 or I_x0.55 (for other shapes please provide lowest inertia)

[24] Take into account buttresses and opening to obtain the stiffness and calculate the equivalent thickness

Structural Perfomance Form (Resume)

Ref.	Monument	Vault in Main Space		Geometrical Data (m)				Columns in Main Space Data (m and kN)				Perimeter Walls Data (m)		eismic Loading (m/s	
India1	Humayun's Tomb	Yes		Span s:	15	r/s	1/2	Free height:	n/a	Vertical Load :	n/a	Max. Free height:	22	PGA for type 1:	2.5
		Type:	Domed	Rise r:	7.5	t/s	4/75	Cross Section:	n/a	Euler Critical Load:	n/a	Equivalent thicness:	1.5	PGA for type 2:	1.5
		Other,Specify:	-	Key t:	0.8			Slenderness:		Thickness/heigh:	n/a	Thickness/height(-):	0		
India2	Safdarjang's Tomb	Yes		Span s:	7.5	r/s	1	Free height:	-	Vertical Load :	-	Max. Free height:	12.5	PGA for type 1:	2.5
		Type:	Domed	Rise r:	7.5	t/s	0	Cross Section:	-	Euler Critical Load:	-	Equivalent thicness:	1.8	PGA for type 2:	1.5
		Other,Specify:	-	Key t:	0.7			Slenderness:	-	Thickness/heigh:	-	Thickness/height(-):	1/7		
India3	Jami Masjid	Yes		Span s:	11	r/s	1	Free height:	3.5	Vertical Load :	200	Max. Free height:	15	PGA for type 1:	2.5
		Type:	Domed	Rise r:	11	t/s	1/22	Cross Section:	0.36	Euler Critical Load:	1993	Equivalent thicness:	1	PGA for type 2:	1.5
		Other,Specify:	-	Key t:	0.5			Slenderness:	39	Thickness/heigh:	7/68	Thickness/height(-):	1/15		
India4	Diwan-i-am	No, Specify:		Span s:	n/a	r/s		Free height:	3	Vertical Load :	200	Max. Free height:	9	PGA for type 1:	2.5
		Type:		Rise r:	n/a	t/s		Cross Section:	0.13	Euler Critical Load:	46	Equivalent thicness:	0.4	PGA for type 2:	1.5
		Other,Specify:	-	Key t:	n/a			Slenderness:	92	Thickness/heigh:	1/23	Thickness/height(-):	2/45		
India5	Shish Gumand	Yes		Span s:	12	r/s	3/7	Free height:	-	Vertical Load :	-	Max. Free height:	15	PGA for type 1:	2.5
		Type:	Domed	Rise r:	5	t/s	1/20	Cross Section:	-	Euler Critical Load:	-	Equivalent thicness:	1.2	PGA for type 2:	1.5
		Other,Specify:	-	Key t:	0.6			Slenderness:	-	Thickness/heigh:	-	Thickness/height(-):	0		
India6	Bhadra Gate	No, Specify:		Span s:	5	r/s	1/2	Free height:	n/a	Vertical Load :	n/a	Max. Free height:	8	PGA for type 1:	1.6
		Type:		Rise r:	2.5	t/s	2/25	Cross Section:	n/a	Euler Critical Load:	n/a	Equivalent thicness:	1.35	PGA for type 2:	1
		Other,Specify:	Arched	Key t:	0.4			Slenderness:		Thickness/heigh:	n/a	Thickness/height(-):	1/6		
India7	Bibiji's Masjid	Yes		Span s:	6.2	r/s	2/5	Free height:	5	Vertical Load :	230	Max. Free height:	5	PGA for type 1:	1.6
		Type:	Domed	Rise r:	2.5	t/s	1/6	Cross Section:	0.36	Euler Critical Load:	976	Equivalent thicness:	1.1	PGA for type 2:	1
		Other,Specify:	-	Key t:	0.4			Slenderness:	56	Thickness/heigh:	1/14	Thickness/height(-):	2/9		
India8	Bai Harir Tomb	Yes		Span s:	4.6	r/s	7/9	Free height:	3.85	Vertical Load :	230	Max. Free height:	3.85	PGA for type 1:	1.6
		Type:	Domed	Rise r:	3.6	t/s	3/46	Cross Section:	0.36	Euler Critical Load:	1647	Equivalent thicness:	0.6	PGA for type 2:	1
		Other,Specify:	-	Key t:	0.3			Slenderness:	43	Thickness/heigh:	3/32	Thickness/height(-):	12/77		
India9	Sayyad Usman Tomb	Yes		Span s:	11	r/s	2/5	Free height:	4.8	Vertical Load :	230	Max. Free height:	n/a	PGA for type 1:	1.6
		Type:	Domed	Rise r:	4.5	t/s	4/73	Cross Section:	0.36	Euler Critical Load:	1060	Equivalent thicness:	n/a	PGA for type 2:	1
		Other,Specify:	-	Key t:	0.6			Slenderness:	53	Thickness/heigh:	3/40	Thickness/height(-):	n/a		
India10	Shiva Temple, Kotai, Bhuj	Yes		Span s:	2.5	r/s	1	Free height:	2.9	Vertical Load :	250	Max. Free height:	2.4	PGA for type 1:	3.6
		Type:	Domed	Rise r:	2.5	t/s	4/25	Cross Section:	0.36	Euler Critical Load:	2903	Equivalent thicness:	0.6	PGA for type 2:	2.4
		Other,Specify:	-	Key t:	0.4			Slenderness:	32	Thickness/heigh:	1/8	Thickness/height(-):	1/4		
India11	Rao Lakha Chattri	Yes		Span s:	10	r/s	3/7	Free height:	4.25	Vertical Load :	230	Max. Free height:	n/a	PGA for type 1:	3.6
		Type:	Domed	Rise r:	4.25	t/s	7/40	Cross Section:	0.36	Euler Critical Load:	1352	Equivalent thicness:	n/a	PGA for type 2:	2.4
		Other,Specify:		Key t:	1.75			Slenderness:	47	Thickness/heigh:	5/59	Thickness/height(-):	n/a		
India12	Parag Mahal	No, Specify:		Span s:	n/a	r/s	n/a	Free height:	n/a	Vertical Load :	n/a	Max. Free height:	6.15	PGA for type 1:	3.6
		Type:		Rise r:	n/a	t/s	n/a	Cross Section:	n/a	Euler Critical Load:	n/a	Equivalent thicness:	1.2	PGA for type 2:	2.4
		Other,Specify:	-	Key t:	n/a			Slenderness:	n/a	Thickness/heigh:	n/a	Thickness/height(-):	1/5		

Title: **ITALIAN INVENTORY AND STRUCTURAL PERFORMANCE FORMS**

Asia-wide Programme:	EU-INDIA ECONOMIC CROSS CULTURAL PROGRAMME
Project Title:	IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE BUILDINGS
Project Contract N°:	ALA/95/23/2003/077-122
Project Beneficiary:	UNIVERSIDADE DO MINHO, PORTUGAL
Partners:	TECHNICAL UNIVERSITY OF CATALONIA, SPAIN
	CENTRAL BUILDING RESEARCH INSTITUTE, INDIA
	UNIVERSITÁ DEGLI STUDI DI PADOVA, ITALY

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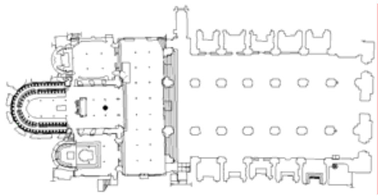
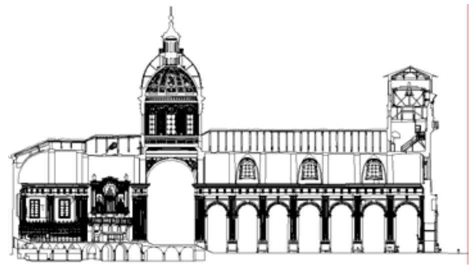
IT1 - Reggio Emilia Cathedral, Reggio nell'Emilia, Italy

(a)



(b)



(c)

Figure A.1 – Geometry: (a) photo; (b) plan; (c) longitudinal section [Source: Studio Severi, Reggio Emilia]

National Classification: Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

Construction period: Built on a previous roman construction around A.D. 857, underwent several Romanesque style remodelling. During the XVI, XVII and XVIII centuries, the church style was renewed and converted to the mannerist period canons.

Description: Latin cross plan with three naves and transept; the crypt is placed below the presbytery, presenting a ceiling composed by crossed vaults sustained by 42 columns. The Cathedral ends in three semicircular apses, the central longer than the two lateral.
The ceiling of the naves, cross vaulted until the restoration of 1777, is composed by barrelled vaults. The façade in gable wall presents three openings; above these a central "serliana" and two rose windows. An octagonal lantern is positioned above the entrance and at the crossing between central nave and transept a high dome takes place (44,60 m high). The double sloping roof is sustained by wooden trusses. The length of the church is 77,40 m, the width is 33,80 m, the span of the main nave is 10,15 m, the span of the two lateral naves is 6,50 m. The height of the front lantern is 33,80 m and the height of the roof above the central nave is 22,25 m.

Previous Seismic Damage: The major seismic event related to the structure of the Cathedral, reported by historical notes, is referred to the reconstruction of the wall of the façade lantern, damaged by the earthquake of 1832.

IT1- Reggio Emilia Cathedral, Reggio nell'Emilia, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio (m^2/MN)		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,07	**0,09**	**2,77**	**3,44**	**1,15**	**1,42**

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [X] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

9,08 Span *s* **5,50** Rise *r* **0,18** Thickness at key *t* **1/1,65** *r* / *s* (-) **1/50** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

8,0 Free height L **1,60x2,0** Cross-section **17,36** Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

3673 Vertical load **315674** Euler critical load **1/5** Thickness / height, if applicable (-)

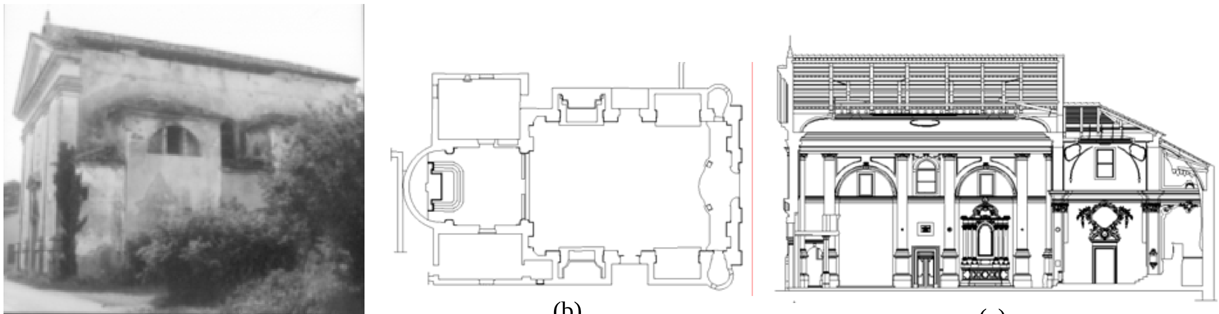
DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

17,15 Maximum free height **1,26** Equivalent thickness **1/13,61** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

1,47 PGA for Type 1 [ ] PGA for Type 2

IT2 - SS. Lucia and Vittore church, Biadene, Treviso, Italy



(a) (b) (c)

Figure A.2 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: SM engineering, Padua]

<u>National Classification:</u> Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

<u>Construction period:</u> 18th century. The construction of the "SS. Lucia e Vittore di Biadene" church started in 1714, taking the place of the pre-existing rural church of San Vittore; in 1719 the building was completed.

<u>Description</u>: Single nave plan with four lateral rectangular chapels, ending in a long presbytery with a semicircular apse. At both sides of this last, two sacristies take place. Ionic column strips, positioned on high bases, give the rhythm of the lateral walls. The roof is composed by four "palladiane" wooden trusses.
The presbytery, closed by column strips, is lightened by two "thermal" windows; on the ceiling, a fresco by Giambattista Tiepolo is closed by an octagonal cornice, and the roof is sustained by wooden trusses. The Neoclassic façade presents column strips in Doric roman style, on a high base, and is crowned by a simple tympanum.

The main changes on the original structure are the widening of the west sacristy, carried out between 1719 and 1745, and the construction (likely in the years 1768-1782) of two external semicircular volumes, close by the external column stripes of the façade (stairwell and baptistery).

<u>Previous Seismic Damage</u>: No historical documents describe damages or repairs on the building caused by an earthquake. It is likely that the crack pattern visible in many part of the church is related to minor seismic events, documented from the years of the construction. In 1976 a major earthquake struck the north eastern part of Italy, but still no information about damages on the structure of the church.

IT2 - SS. Lucia and Vittore church, Biadene, Treviso, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio (m^2/MN)		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,10	**0,11**	**2,65**	**2,85**	**0,62**	**0,66**

Other Key Structural Features:

VAULT IN MAIN SPACE
[X] Yes [ ] No, Specify:
TYPE
[X] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:
GEOMETRICAL DATA (meters)
5,60 Span *s* **2,64** Rise *r* **0,31** Thickness at key *t* **1/2,13** *r* / *s* (-) **1/18,0** *t* / *s* (-)

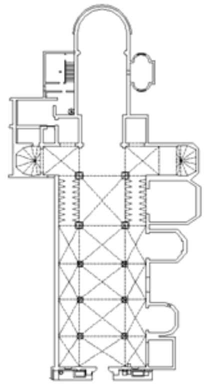
DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
3,5 Free height L **0,6x0,6** Cross-section **20,21** Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)
1467 Vertical load **26079** Euler critical load **1/5,8** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
11,26 Maximum free height **0,60** Equivalent thickness **1/18,76** Thickness / height (-)

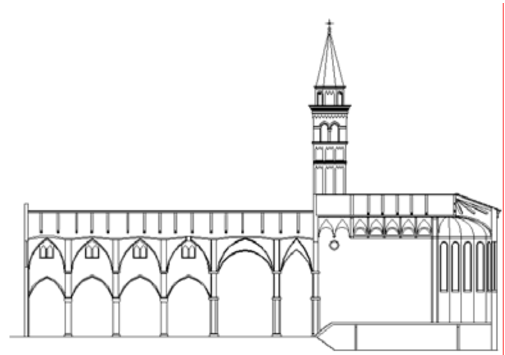
MAGNITUDE OF SEISMIC LOADING (m/s^2)
2,45 PGA for Type 1 [ ] PGA for Type 2

IT3 - Santa Corona Church, Vicenza, Italy

(a)



(b)



(c)

Figure A.3 – Geometry: (a) photo; (b) plan; (c) longitudinal section [Source: SM engineering, Padua].

National Classification: Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

Construction period: from the 13th to the 15th century. The church was built by will of the dominican bishop Bartolomeo da Breganze and the construction started in 1260. At the end of 15th century (1480) the presbytery was extended.

Description: For the construction of the church, built in Romanesque style, red bricks masonry was used in main part of the structure (façade, perimeter walls and bell-tower). The presbytery, originally rectangular shaped, in the year 1480 was widened and a semicircular apse was added.
Many repair interventions were performed during the years, and the most significant was the one performed by the architect Luigi Tognato, in the second half of the XIX century, consisting in the reconstruction of the façade. The interior, in Cistercians gothic style, is composed by three naves with an emerging and subtle transept. The central nave is divided into six bays, progressively increasing toward the long presbytery. The fifth bay is squared and is sustained, instead of circular columns, by octagonal piles. On the right side some lateral chapels are positioned, while the left altars are set against the perimeter wall that separate the church to the cloister. The ratio between the span of the lateral naves and the central is 1:2. The bell tower was built in the XIII century, until the belfry; the octagonal upper part was built during the restoration works of the end of the XIV century. Each external façade is subdivided horizontally by column stripes with small arches.

Previous Seismic Damage: Unknown.

IT3 - Santa Corona Church, Vicenza, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio (m^2/MN)		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,08	**0,06**	**3,44**	**2,56**	**3,98**	**2.95**

Other Key Structural Features:

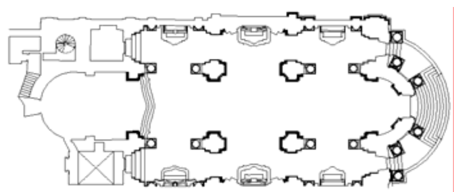
VAULT IN MAIN SPACE
[X] Yes [ ] No, Specify:
TYPE
[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:
GEOMETRICAL DATA (meters)
8,10 Span *s* **5,07** Rise *r* **0,11** Thickness at key *t* **1/1,6** *r* / *s* (-) **1/73,64** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
6,14 Free height L **ϕ 1,06** Cross-section **23,17** Slenderness $\lambda = L / (Inertia / Area)^{0.5}$ (-)
2770 Vertical load **48647** Euler critical load **1/5.79** Thickness / height, if applicable (-)

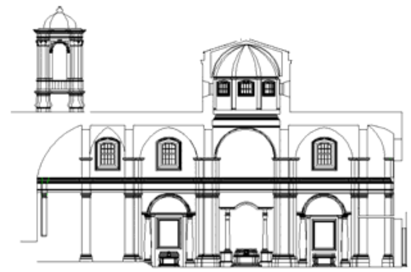
DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
22,83 Maximum free height **0,74** Equivalent thickness **1/30,85** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)
0,49 PGA for Type 1 [ ] PGA for Type 2

IT4 - San Domenico church, Noto, Syracuse, Italy



(b)



(c)

(

a)

Figure A.4 – Geometry: (a) photo; (b) plan; (c) longitudinal section [Source: Studio Tringali, Ragusa].

National Classification: Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

Construction period: 18th century. The church was built by Rosario Galiardi in 1737.

Description: The church is one of the best example of Noto Baroque, mainly for its convex façade with 6 elegant superimposed columns that articulate the two front orders, separated by a high cornice. The façade is marked by three portals (the ones at the sides are two times smaller than the central one), a sequence of niches, the cornice that underlines the two orders and then, in the upper and conclusive roof, a big central window with a little balustrade. The church is based on a central plan, a greek extended cross, and it culminates in five domes.

The two lateral naves are composed by rectangular chapels that contain marble altars. The main dome is sustained by four pillars, each of them connected to a column that helps to sustain its relating side-dome.

At the end of the side-naves there are two sacristies.

Previous Seismic Damage: Unknown.

IT4 - San Domenico church, Noto, Syracuse, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio (m^2/MN)		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,10	**0,16**	**1,66**	**2,58**	**0,52**	**0,81**

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[ ] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

5,6 Span *s* **2,95** Rise *r* **0,20** Thickness at key *t* **1/1,9** *r* / *s* (-) **1/28** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

7,2 Free height L **2,55x2,1** Cross-section **13,63** Slenderness $\lambda = L / (Inertia / Area)^{0.5}$(-)

1940 Vertical load **1312300** Euler critical load **1/3,43** Thickness / height, if applicable (-)

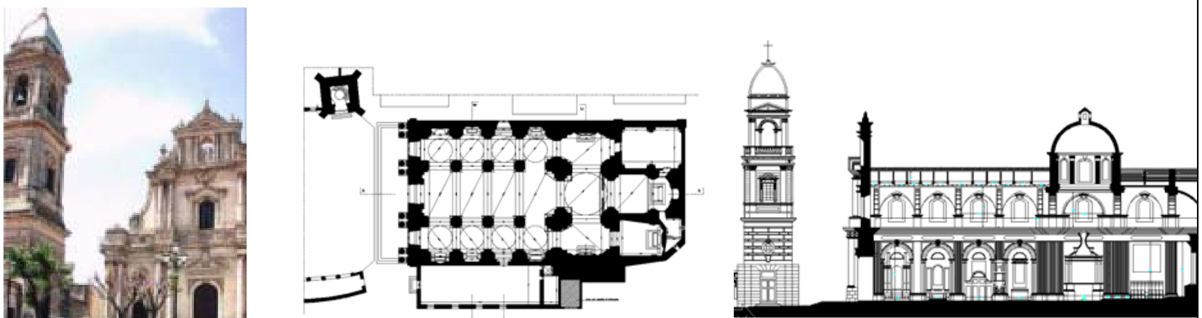
DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

--- Maximum free height **---** Equivalent thickness **1/** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

2,45 PGA for Type 1 [ ] PGA for Type 2

IT5 - Santissima Annunziata church, Cava di Ispica, Ragusa, Italy



(a) (b) (c)

Figure A.5 – Geometry: (a) photo; (b) plan; (c) longitudinal section
[Source: Studio Tringali, Ragusa].

National Classification: Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

Construction period: The marquis Statela started the construction in the 17th century. The works were carried to an end during the 18th century.

Description: The Santissima Annunziata Basilica, due to its impressing facade and its artistic value, represents the most significant religious construction of the Ragusa province. Prior to the earthquake of 1693, the church was included in the defensive walls of the marquis Statela. Under the dominion of the Statela family, from half the XVI century, the building was widened and took the name of “Chiesa dell’Annunziata”, with latin cross plan and the apse positioned toward east. The plan of the church is longitudinal, with 3 naves divided by massive pillars, decorated by channelled strips, with corinthian capitals.

The central nave is defined by four arches, the roof is barrel-vaulted; at the crossing with the transept, a central massive dome rises, leaning on an octagonal tambour sustained by four pillars.

Previous Seismic Damage: In 1704, 10 years after being struck by the earthquake, the church was reconstructed in its definitive shape, except the main arch, rebuilt after the 1727 earthquake, and the façade, collapsed in 1869 because of decay and incautious repair interventions.

IT5 - Santissima Annunziata church, Cava di Ispica, Ragusa, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio (m^2/MN)		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,14	**0,18**	**1,96**	**2,39**	**0,57**	**0,70**

Other Key Structural Features:

VAULT IN MAIN SPACE
[X] Yes [ ] No, Specify:
TYPE
[X] Barrel [ ] Crossed [X] Domed [ ] Other, Specify:
GEOMETRICAL DATA (meters)
9,13 Span *s* **4,2** Rise *r* **0,10** Thickness at key *t* **1/ 2,17** *r* / *s* (-) **1/91,30** *t* / *s* (-)

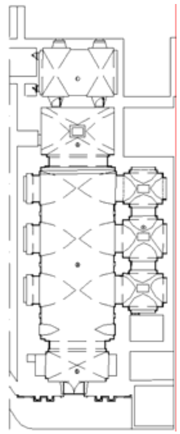
DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
7,8 m Free height L **2,05x2,05** Cross-section **18,92** Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
3655,4 Vertical load **46099,6** Euler critical load **1/3,8** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
16,85 Maximum free height **1,33** Equivalent thickness **1/12,67** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)
2,45 PGA for Type 1 [ ] PGA for Type 2

IT6- Santa Maria Gesù church, Scicli, Ragusa, Italy


(a)


(b)

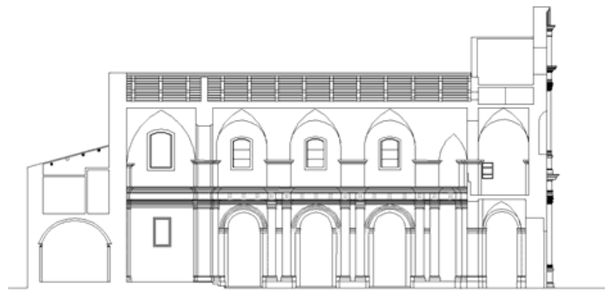

(c)

Figure A.6 – Geometry: (a) photo; (b) plan; (c) cross-section
[Source: Studio Tringali, Ragusa].

<u>National Classification:</u> Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

<u>Construction period</u>: The convent and the church were built starting in 1639 using recycled materials from the abandoned castle of Ragusa. Unlike the convent, the church was damaged by the 1693 earthquake and then almost completely rebuilt in 1700.

<u>Description:</u> Longitudinal plan with rectangular nave; the right nave is composed by the procession of three lateral chapels. Small niches are positioned on the left side. At the end of the nave the presbytery takes place, with rectangular plan as the following rectory, positioned aligned with the longitudinal axis of the church. The front façade is taller than the building, with two orders of columns and a single opening. The ceiling of the main nave is composed by a sequence of crossed and barrelled vaults, while the lateral nave, the presbytery and the rectory present a cross-vaulted ceiling. The vertical structures are massive and composed by masonry.
The roof above the main nave is double-sloping with a timber structure, the one insisting above the lateral nave and the rectory is lower than the first and single-sloping.

<u>Previous Seismic Damage:</u> The actual church was rebuilt in the XVIII century, being collapsed after the 1693 earthquake.

IT6- Santa Maria Gesù church, Scicli, Ragusa, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio (m^2/MN)		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,15	**0,15**	**1,26**	**1,28**	**0,53**	**0,54**

Other Key Structural Features:

VAULT IN MAIN SPACE

[X] Yes [ ] No, Specify:

TYPE

[X] Barrel [X] Crossed [ ] Domed [ ] Other, Specify:

GEOMETRICAL DATA (meters)

7,97 Span *s* | **1,4** Rise *r* | **0,30** Thickness at key *t* | **1/5,68** *r* / *s* (-) | **1/26,57** *t* / *s* (-)

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

5,00 Free height L | **1,63x1,35** Cross-section | **12,8** Slenderness $\lambda = L / (Inertia / Area)^{0.5}$ (-)

345,35 Vertical load | **395426** Euler critical load | **1/3,7** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

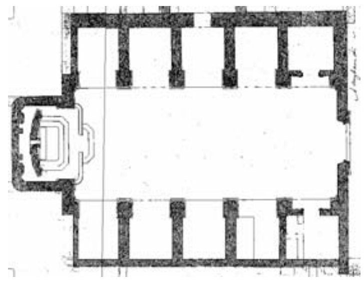
12,78 Maximum free height | **0,97** Equivalent thickness | **1/13,17** Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

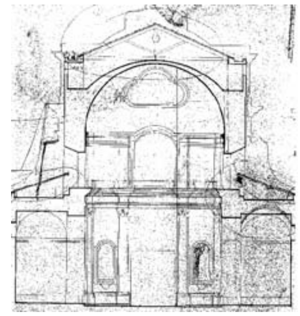
2,45 PGA for Type 1 | [ ] PGA for Type 2

IT7 - SS. Severino and Sossio church, Naples, Italy

(a)



(b)



(c)

Figure A.7 – Geometry: (a) photo; (b) plan; (c) cross-section [Source: Studio Izzo, Naples].

<u>National Classification:</u> Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

<u>Construction period:</u> The church and the adjacent monastery were built in the IX century by the Benedictines that, in 902, transferred there the relics of the Saints Severino and Sossio. The monastic complex was restored by the Angevins.

<u>Description:</u> Longitudinal plan, single nave with seven side chapels; the church is part of a monastic complex and is connected to this by transversal walls. The ceiling of the central nave is composed by barrelled vaults and the double-sloping roof is sustained by wooden trusses.
The façade presents a single opening and two big central windows. External buttresses, positioned above the transversal walls that separate the lateral chapels, reach the height of the starting of the central barrelled-vaults. The presbytery is raised respect the height of the church’s floor.

<u>Previous Seismic Damage:</u> The earthquake of 1731 damaged the structures of the church; some repair works were carried out.

IT7 - SS. Severino and Sossio church, Naples, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio (m^2/MN)		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,11	**0,13**	**2,87**	**3,26**	**0,78**	**0,88**

Other Key Structural Features:

VAULT IN MAIN SPACE
[X] Yes [ ] No, Specify:
TYPE
[X] Barrel [ ] Crossed [ ] Domed [ ] Other, Specify:
GEOMETRICAL DATA (meters)
10,7 Span *s* **4,8** Rise *r* **0,30** Thickness at key *t* **1/2,23** *r* / *s* (-) **1/35,7** *t* / *s* (-)

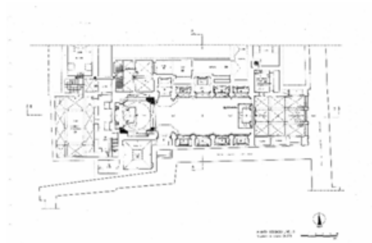
DATA FOR COLUMNS IN MAIN SPACE (meters and kN)
--- Free height L **---** Cross-section **---** Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)
--- Vertical load **---** Euler critical load **---** Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)
16,30 Maximum free height **1,00** Equivalent thickness **1/16.30** Thickness / height (-)

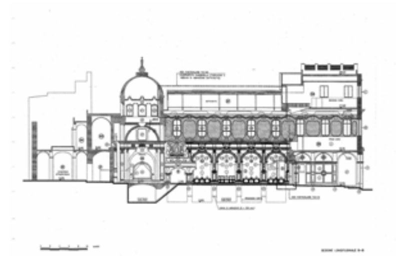
MAGNITUDE OF SEISMIC LOADING (m/s^2)
2,45 PGA for Type 1 [ ] PGA for Type 2

IT8 - S Gregorio Armeno Church, Naples, Italy

(a)



(b)



(c)

Figure A.8 – Geometry: (a) photo (courtyard); (b) plan; (c) longitudinal section [Source: Studio Izzo, Naples].

National Classification: Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

Construction period: The construction began in 1574 by a donation of the abbess Donna Giulia Caracciolo. The church was terminated in 1579 and , in the next year, dedicated to St. Gregorio Armeno.

Description: The church of St. Gregorio Armeno is situated on the street with the same name. The façade shows three arches in piperno stone; the entrance to the church happens through a hall covered by crossed vaults, with four central pillars, sustaining the 1^{st} and 2^{nd} order choirs.

The church is composed by a single nave surrounded by four rectangular chapels on the left side and five on the right. The presbytery is positioned below the central dome and there are no apses; at the sides of the altar there are the rectory and a side access room to the other structures of the religious complex. The lacunar ceiling is covered by a double-sloping roof composed by wooden trusses.

The interior, except the chapels, was painted by Luca Giordano in 1679 to celebrate the first centenary of the church.

Previous Seismic Damage: Unknown.

IT8 - S Gregorio Armeno Church, Naples, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,13	**0,13**	**2,41**	**2,49**	**0,86**	**0,89**

Other Key Structural Features:

VAULT IN MAIN SPACE

Yes [X] No, Specify: [ ]

TYPE

Barrel [ ] Crossed [ ] Domed [X] Other, Specify [ ]

GEOMETRICAL DATA (meters)

Span *s* [---] Rise *r* [---] Thickness at key *t* [---] *r* / *s* (-) [---] *t* / *s* (-) [---]

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[---] Free height L [---] Cross-section [---] Slenderness λ = L / (Inertia / Area)$^{0.5}$(-)

[---] Vertical load [---] Euler critical load [---] Thickness / height, if applicable (-)

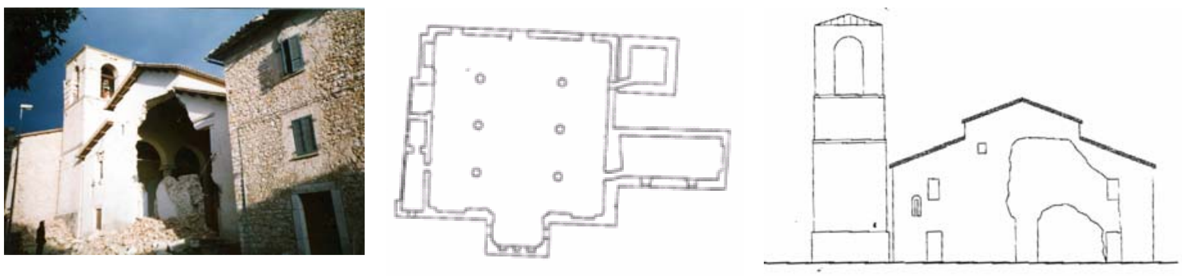
DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[15,50] Maximum free height [1,07] Equivalent thickness [1/14.50] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

[2,45] PGA for Type 1 [ ] PGA for Type 2

IT9 - S. Maria Assunta Church, Montesanto, Italy



(a) (b) (c)

Figure A.9 – Geometry: (a) photo (after the 1997 Umbria earthquake); (b) plan; (c) elevation

[Source:]. Umbria Superintendence for the Architectural Heritage

National Classification: Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

Construction period: From the 13th to the 14th century.

Description: The S. Maria Assunta a Montesanto church is positioned inside the defensive walls of the Montesanto castle, and all around lies the small town. The religious complex is composed by the church, the rectory and the bell tower. The church is composed by three naves, after the widening of 1545, separated by Ionic order columns. The central nave ends in a rectangular apse, this last presenting three niches in the head wall.

The façade is marked by a XVI century stone masonry portal, surmounted by a triangular tympanum, and at the sides, two moulded windows are sustained by corbels. The access to the bell tower and to the rectory, whose walls are entirely frescoed, happens from the right nave. The complex underwent different repair works since 1970, when the roof was renewed, until 1997, before the last earthquake struck the region.

Previous Seismic Damage: The building was heavily damaged by the 1997 umbria-marche seism, presenting remarkable disarrangements in all the external masonry walls and partial collapse of the façade, falling of the stone cornices, expulsion of material from the external layers of the walls.

The columns presented disarrangement of the ashlars.

IT9 - S. Maria Assunta Church, Montesanto, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,08	**0,09**	**2,86**	**3,28**	**0,43**	**0,49**

Other Key Structural Features:

VAULT IN MAIN SPACE

Yes [ ] No, Specify: [X]

TYPE

Barrel [ ] Crossed [ ] Domed [ ] Other, Specify [ ]

GEOMETRICAL DATA (meters)

Span *s* [ ] Rise *r* [ ] Thickness at key *t* [ ] *r* / *s* (-) [1/] *t* / *s* (-) [1/]

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[4,7 m] Free height L [ϕ 0,70] Cross-section [26,86] Slenderness λ = L / (Inertia /Area)$^{0.5}$(-)

[351] Vertical load [15774] Euler critical load [1/6,72] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

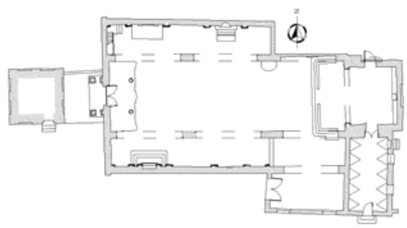
[11,2] Maximum free height [0,70] Equivalent thickness [1/16] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

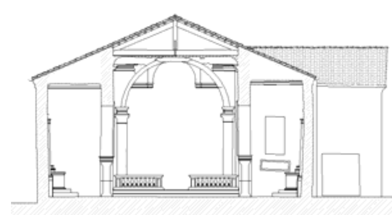
[3,43] PGA for Type 1 [ ] PGA for Type 2

IT10 –San Prosdocimo church, Villanova di Camposampiero, Padova, Italy

(a)



(b)



(c)

Figure A.10 – Geometry: (a) photo; (b) plan; (c) cross section.
[Fonte: SM engineering, Padua].

National Classification: Building of historical and artistic interest (D. LGS. 29 ottobre 1999 n° 490 L. 1939 n°1089)

Construction period: Its origins date back, according to some historical sources, to the pre-Lombard period, even if the first documents related to the church are more recent. The Lombards invaded the Veneto region through the North eastern part of Italy in 568 a.D., and in 602 a.D. they devastated and burnt Padua. The first mention of the Villanova parish church can be found on a document of 1085, when the Benedictine monastery of saints Eufemia and Pietro is named for the first time.

Description: The church, with the façade towards west and the bell tower just in front of it, seems to be built on the structures of a pre-existing middle age castle tower. It also seems that the "older" church was narrower, being evident the difference in terms of materials between some central and lateral parts of the building. Three naves, plan asymmetry, the church presents a hut-shaped and quite bare façade. The two lateral naves are separated from the central by two rectangular pillars per side, supporting big and round longitudinal arches. The right nave meets, at its end and in correspondence of the presbytery, the sacristy.
The length of the church is approximately 27,90 m, the width 14,50 m and the maximum height, reached in correspondence of the façade, is about 11,00 m.

Previous Seismic Damage : unknown

IT10 – San Prosdocimo church, Villanova di Camposampiero,Padova, Italy

Simplified Methods:

In- plan area ratio		Area to weight ratio		Base shear ratio	
X direction	Y direction	X direction	Y direction	X direction	Y direction
0,06	**0,08**	**3,06**	**4,53**	**1,00**	**1,48**

Other Key Structural Features:

VAULT IN MAIN SPACE

Yes [ ] No, Specify: [X]

TYPE

Barrel [ ] Crossed [ ] Domed [ ] Other, Specify [ ]

GEOMETRICAL DATA (meters)

Span *s* [ ] Rise *r* [ ] Thickness at key *t* [ ] *r* / *s* (-) [1/] *t* / *s* (-) [1/]

DATA FOR COLUMNS IN MAIN SPACE (meters and kN)

[2,28] Free height L [0,64x2,03] Cross-section [12,34] Slenderness $\lambda = L / (Inertia / Area)^{0.5}$ (-)

[295] Vertical load [252328] Euler critical load [1/3,56] Thickness / height, if applicable (-)

DATA FOR PERIMETER WALLS IN MAIN SPACE (meters)

[7,6 m] Maximum free height [0,40] Equivalent thickness [1/19] Thickness / height (-)

MAGNITUDE OF SEISMIC LOADING (m/s^2)

[1,47] PGA for Type 1 [ ] PGA for Type 2

Structural Perfomance Form (Resume)

Ref.	Church	Vault in Main Space		Geometrical Data (m)				Columns in Main Space Data (m and kN)				Perimeter Walls Data (m)		eismic Loading (m/s	
IT1	Reggio Emilia	Yes		Span s:	9.08	r/s	3/5	Free height:	8	Vertical Load :	3673	Max. Free height:	17.15	PGA for type 1:	1.47
		Type:	Crossed	Rise r:	5.5	t/s	1/50	Cross Section:	1.6	Euler Critical Load:	315674	Equivalent thickness:	1.26	PGA for type 2:	-
		Other,Specify:	-	Key t:	0.18			Slenderness:	17	Thickness/heigh:	1/5	Thickness/height(-):	5/68		
IT2	Ss. Lucia and Vittore	Yes		Span s:	5.6	r/s	1/2	Free height:	3.5	Vertical Load :	1476	Max. Free height:	11.26	PGA for type 1:	2.45
		Type:	Barrel	Rise r:	2.64	t/s	1/18	Cross Section:	0.6	Euler Critical Load:	26079	Equivalent thickness:	0.6	PGA for type 2:	-
		Other,Specify:	-	Key t:	0.31			Slenderness:	20	Thickness/heigh:	6/35	Thickness/height(-):	4/75		
IT3	S. Corona	Yes		Span s:	8.1	r/s	5/8	Free height:	6.14	Vertical Load :	2770	Max. Free height:	22.83	PGA for type 1:	0.49
		Type:	Crossed	Rise r:	5.07	t/s	1/74	Cross Section:	1.06	Euler Critical Load:	48672	Equivalent thickness:	0.74	PGA for type 2:	-
		Other,Specify:	-	Key t:	0.11			Slenderness:	23	Thickness/heigh:	5/29	Thickness/height(-):	1/31		
IT4	S. Domenico	Yes		Span s:	5.6	r/s	1/2	Free height:	7.2	Vertical Load :	1940	Max. Free height:	-	PGA for type 1:	2.45
		Type:	Crossed	Rise r:	2.95	t/s	1/28	Cross Section:	2.1	Euler Critical Load:	1312300	Equivalent thickness:	-	PGA for type 2:	-
		Other,Specify:	-	Key t:	0.2			Slenderness:	14	Thickness/heigh:	7/24	Thickness/height(-):	-		
IT5	S. Annunziata	Yes		Span s:	9.13	r/s	1/2	Free height:	7.8	Vertical Load :	3655	Max. Free height:	16.85	PGA for type 1:	2.45
		Type:	Barrel	Rise r:	4.2	t/s	1/91	Cross Section:	2.05	Euler Critical Load:	46100	Equivalent thickness:	1.33	PGA for type 2:	-
		Other,Specify:	-	Key t:	0.1			Slenderness:	19	Thickness/heigh:	5/19	Thickness/height(-):	3/38		
IT6	S. Maria Gesù	Yes		Span s:	7.97	r/s	1/6	Free height:	5	Vertical Load :	345	Max. Free height:	12.78	PGA for type 1:	2.45
		Type:	Barrel	Rise r:	1.4	t/s	2/53	Cross Section:	1.35	Euler Critical Load:	395426	Equivalent thickness:	0.97	PGA for type 2:	-
		Other,Specify:		Key t:	0.3			Slenderness:	12.8	Thickness/heigh:	10/37	Thickness/height(-):	6/79		
IT7	SS. Severino and Sossio	Yes		Span s:	10.7	r/s	4/9	Free height:	-	Vertical Load :	-	Max. Free height:	16.3	PGA for type 1:	2.45
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		Type:	Domed	Rise r:	-	t/s	-	Cross Section:	-	Euler Critical Load:	-	Equivalent thickness:	1.07	PGA for type 2:	-
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		Other,Specify:	-	Key t:	-			Slenderness:	12	Thickness/heigh:	16/57	Thickness/height(-):	1/19		

Title: **DETAILED DESCRIPTION OF THE MONASTERY OF JERÓNIMOS**

Asia-wide Programme: EU-INDIA ECONOMIC CROSS CULTURAL PROGRAMME
Project Title: IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE BUILDINGS
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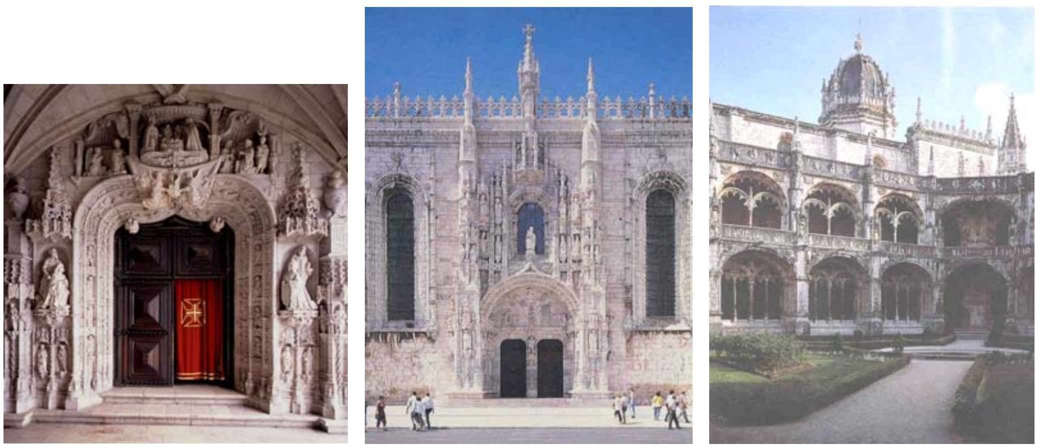
1. INTRODUCTION

The Santa Maria of Belém Monastery, commonly called Monastery of Jerónimos, is an architectural and functional compound which has articulated public service components like cult place, monastery, palace and mausoleum.

It exhibits an extensive façade of more than three hundred meters, with a horizontality evolution that gives it a calm physiognomy. The monastery is structured around two blocks. At the west zone, the largest one is defined by a long arcade, of two floors, where now is the Ethnographic Archaeology Museum, with a higher central body, and the Navy Museum. The smallest block is defined by the cloister together with the Entrance, the Dining hall, the Sacristy, the Chapter Room and the Church (Figure 1 to Figure 3).

Figure 1 - General view of the Monastery of Jerónimos and the Empire Square.



(a) (b) (c)

Figure 2 - Monastery of Jerónimos: (a) Main Portal of the Church; (b) South Portal of the Church; (c) View of the main cloister (Source: DGEMN).

The Monastery is located in an urban area, in front of the Tagus river, implanted where it existed an old beach and harbour. Rectangular volumes horizontally articulated, distinct coverings, roofs, terraces and spires characterize the Monastery.

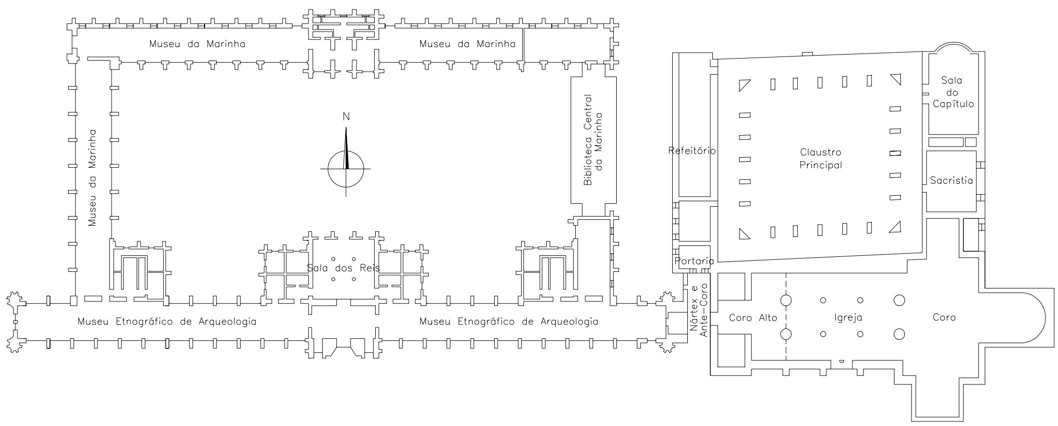


Figure 3 - Monastery of Jerónimos Plan View (actual).

2. HISTORY OF MONASTERY OF JERÓNIMOS

The first ships, for the Portuguese marine enterprises, namely for India and Brazil leaved from this harbour. There, the trade activity was extensive, constantly visited by sailors. The population that lived there didn't dispose neither of a cemetery nor a cult place. So, Infante D. Henrique ordered the construction of a church and a small monastery of Christ's Order, to render spiritual attendance for sailors and for the population.

In 1495, 46 years after Infante D. Henrique's death, the king D. Manuel I, immediately after his crown, ordered the construction of a monastery on this same place. Christ's Order gave up the church, the houses and lands to the Hieronymites Congregation. The Hieronymites would celebrate daily mass in vote for Infant D. Henrique, and then, for king D. Manuel I and their successors. Also, D. Manuel I wanted to be buried in the monastic church. Besides the church, called Santa Maria of Belém Church, D. Manuel I and D. João III (1521-1616) would increase new houses to expand the Monastery of Jerónimos.

The Hieronymites Order was an institution which had been founded in the XIV century, in Italy. The Hieronymites' Friars were known for their extraordinary cultural labour, remembering our history names of great masters of this Order in several fields.

In 1499, D. Manuel I donated to the monastery the bulky benefit, the twentieth part of the collection of the gold came from Guinea and the spices from India. That flow would sustain not only the community and their cultural and meritorious initiatives, but also to hire the best masters and to finance the whole construction expenses.

D. Manuel I, however, was changing the original work program, wanting to join to the monastery an occasional royal residence. The king's death in 1521 moved away that idea. Another function, of business kind, would be the grocery store for ships provision, to be installed in west zone, at the ground floor of its extensive gallery with arches open to South. D. Manuel I also wanted to use the church as real pantheon, for himself and for his successors.

Subsequent works came to modify the building. D. Catarina, widow of D. João III, ordered the demolition of the original chancel, for being small, and the construction of the current one. After that, D. Sebastião, the Filipes of Spain, D. Pedro II and D. João V introduced new modernization elements, especially ornamental ones.

In 1584, Filipe II removed the mentioned monastery income. It was the beginning of the financial difficulties. These difficulties would continue in the period of D. João V, declining the importance of the monastery and increasing the lack of material means. The conflicting problems became worse with the government of Marquês de Pombal.

Extinct by the liberal government in 1833, the monastery was incorporated in the royal crown, becoming the new installation of the educational institute founded by Pina Manique, called "Casa Pia". The monastery church would be parish headquarters. The valuable stuffing of the monastery was disappearing and a great part was destroyed. Declared National Monument in 1904, it was considered "Cultural Heritage of All Humanity" in 1984 by UNESCO.

3. THE MONASTERY HISTORY CONSTRUCTION

In 1499, or 1500, excavations were started and in 6 January of 1501, or 1502, was seated the first stone of the new Monastic Building. Between 1496 and 1502 the preparatory technical studies must had been elaborated, such as soil surveys, the shipyards installation and the supply of construction materials (stone, whitewash, building sand, etc.). The columnists frequently refer the existence of an archetype or plan, of the original project, that now is missing, although it had stayed in the monastery registry office up to 1833.

As that project, planned out by architect Diogo Boytac (or Boitaca), it was delineated a much vaster monastery than it would be built. The area to build would be four times larger than the one that was built in fact. Four monasteries were foreseen, with different sizes and functions, although just one had been built but not concluded. A second monastery would have been initiate, called "jónico", but its construction was abandoned soon. They were still foreseen four dormitories but just one had been built. The global dimension in plant and the proportion for the height ceilings was defined at the beginning of construction of the monastery. It would be built in limestone (Lioz) that would be removed very close from its implantation place.

The monastery was drawn in "Manuelino" style, which is a Gothic's art evolution, representing the first Portuguese chill for the subjection to a strange art. However, its expression would be modified when Boytac, starting to drive other royal works, was substituted by his collaborator João de Castilho.

Between 1502 and 1516, that is, during fourteen years, Boytac led the construction works of the Monastery of Jerónimos. He had elaborated the plan of the church and was also responsible for the magnificent first floor of the cloister, full of "Manuelino" decoration and in which were used lowered arches. With the magnificence of the project several construction task works were happened. The Boytac successor was João de Castilho (1475-1552), Diogo de Torralva (1500-1566) and Jerónimo de Ruão (1530-1601). All of them left their indelible marks and they are some of the names who the Monastery remembers today. Within the XVI century, the monastery construction presents three essential work periods. However, the works had not been accomplished neither in sequence nor in uniform rhythm, undergoing periods of great and smaller intensity. So, the monument is like a combination of arts and styles, even in ways, denouncing pauses, but it results rarely dissonant. The construction phases were finished by the end of XVI century.

The XVII and XVIII century works were merely ornamental, liturgical or of circumstance; the ones of the century XIX were of summary restore, but not always right, and the last ones, in 1940, were to correct improper interventions and to reinstate the primitive monument features.

The Henriquine Foundation

The Monastery of Jerónimos would have been ordered to be built over the place of the Henriquine chapel. In fact, the implantation place of the church coincides with part of the actual Museum of Ethnography. Actually, very little remains of the Henriquine church. The walls of the chapel either were radically destroyed, or are integrated in the monumental church of the monastery.

The Monastery of Jerónimos and D. Manuel I Reign

By the ends of 1516, on Boytac's period, the following works were executed: the arcades or porch of the ground floor, the top gallery, the primitive chancel, the outlying walls of the church, the windows, the octagonal columns in the naves, decorated later by Castilho, the arches of the transept and four ground floors of the cloister covered with cross ribbed vaults.

In 1521, when D. Manuel died, the following works were ended: the body of the church, excepting the vault of the cruise (transept), the sacristy, the dining hall, the South portal, the portal west or axial, and the main cloister, except the gallery of the second floor. The third floor in this monastery, where it would be place the lodge, was not executed. The Chapter Room was unfinished: it just was done the portal, the walls and the apse, not being executed the vault. The secondary cloister was not built. However the foundations of the second cloister, the "jónico", were done at the North of the main cloister.

The construction of the dormitories would have been begun on the second monastery, referred above. The third period of the construction of the monastery ranged from 1521 to 1601. This phase of the construction was under the order of João de Castilho, Diogo de Torralva and Jerónimo de Ruão. The columns, cruise and naves vault's were ended; the second floor of the main cloister was completed; the chairs of the high-choir were executed; the actual chancel was built, the chapels of the transept and the garden of the main cloister were internally modified, according to Renaissance style, see Figure 4.

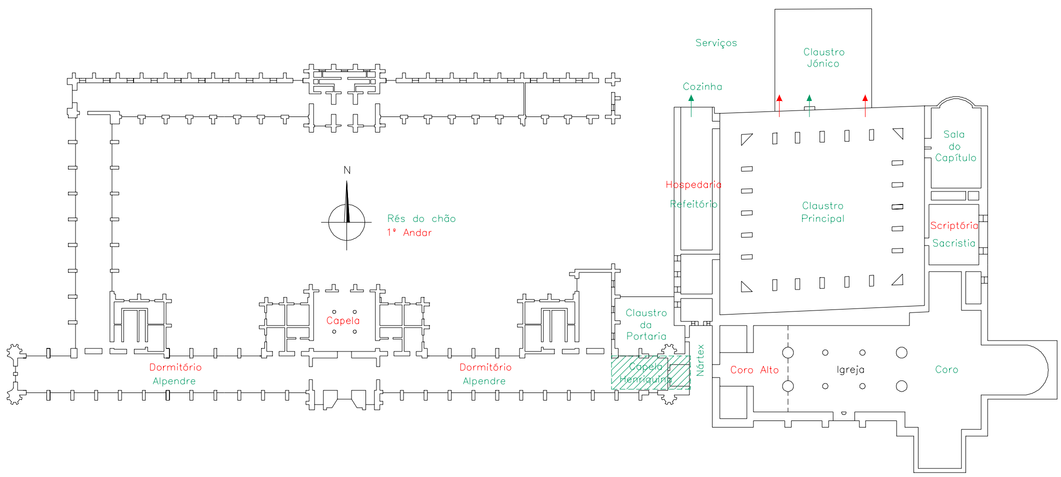


Figure 4 - Monastery facilities in the reign of D. Manuel I.

The Monastery of Jerónimos from XVII up to XIX Century

The construction phases were finished by the end of XVI century. Afterwards, minor constructions and punctual arrangements were executed, having enriched its artistic stuffing. In 1625, it was built the conventual's staircase and the room that gives access to the gallery of the monastery. Also, it was initiate the process of secularization of the monastery.

In 1684, a fire occurred in the existent grocery stores under the arcades, which caused ruin to part of it. The arcades were already transformed into rental grocery stores. In 1707, accommodations were made, under the arcades, for the English army cavalry, filling all of the arches with brick masonry walls. In 1723 part of the arcades were occupied by the Real Cooper and in 1756, the Customs of Lisbon were settled there.

The earthquake of 1st November 1755 became known in Europe as the "Great Earthquake of Lisbon". For the assumption of its devastating effects, it was contributed the total disappearance of the downtown city, not only due to the earthquake and its effects, like fires, but also by the demolition of buildings, ordered by Marquês de Pombal, in order to rebuild the new blocks (or uptowns). From the twenty thousand Lisbon buildings, only three thousand could be inhabited. Several reminiscences of this earthquake had been felt until September of the following year. Constructions that suffered minor damage were the Lisbon Aqueduct, built in 1731 (it remained intact after the earthquake), the Monastery of Jerónimos and the Tower of Belém.

The Monastery resisted well to the earthquake. Its structure just suffered few damage, forcing to limited reparation works. In spite of that, because the repairing was not convenient, in December of 1756, a church's column fell during a new earthquake, felling also part of the vault. In that period, the center vault, under the high choir, also collapsed.

In 1808-1813 the British army installed the British Military Hospital at the Monastery, staying there for five years. They occupied the superior galleries of the cloister and filled the arches facing the terrace.

The monastic life was losing quality and the number of friars was decreasing. In 1833 they were just thirteen or fourteen friars in the Monastery.

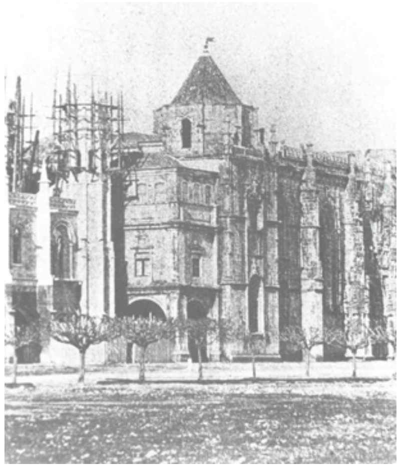
The Monastery of Jerónimos during the XIX Century

During the XIX century, the disfiguration and destruction of the building took place, as well as dismantling, dispersion and extravagance of its artistic stuffing. The interventions in this period were quite disastrous, not only for the undone works but also for the alteration works. Firstly, it was destroyed the Monastic Community. On 28th December 1833 it was done the Ordinance to secularize immediately the Monastery of Nossa Senhora of Belém. A Ordinance of 28th May 1834 defined the extinction of convents, monasteries, schools, hospices and any houses of religious orders in Portugal.

Consequently, the friars' domestic accommodations were destroyed: the bedrooms, the dining hall, the workshops, the barns, the wine cellar and the lodges, with all its artistic stuffing, as tiles, cuts, paintings, relics and jewellery pieces. Additionally, it was dismantled the library and its eight thousand volumes, the altars of the choir and of the cloister, the monumental coral shelf was lost and the hall as well as the narthex were demolished, destroying the existent mozarabic tiles.

The destruction continued during the XVIII century, promoted by the pleasure of intervening in monuments, on behalf of a "original purity". Designs to follow the new-manuelino were made. The octagonal tower of the church was substituted (Figure 5a) and the arcades were restored, not respecting its original function. A design to the homage tower, with clock among minarets, destroyed the horizontal rhythm of the old dormitory (Figure 6), and the King's Room was also destroyed. Finally, an exotic mitral form bell-tower was implanted in the church, the prismatic spires on the South façade were swelled (Figure 5) and the vault of the Chapter´s House was ended.

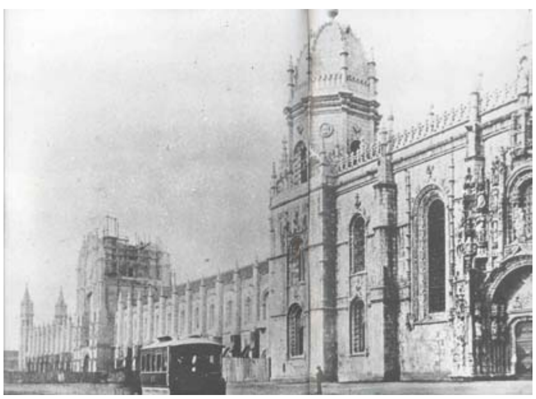
In 1878, the works on the homage tower collapsed due to its weak connections to the structural elements (Figure 6b). The interventions performed during the XIX century in the monastery caused worse damage than all historic earthquakes (including the 1755 earthquake).



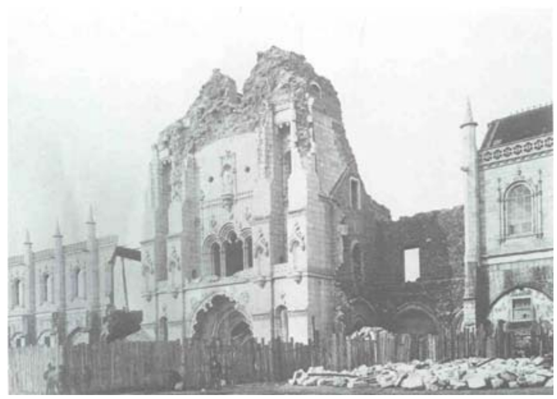
(a)

(b)

Figure 5 - (a) Old octagonal tower and Hall, XIX century; (b) New aspect of the bell-tower and of the spires (Marques de Carvalho, 1984).



(a)



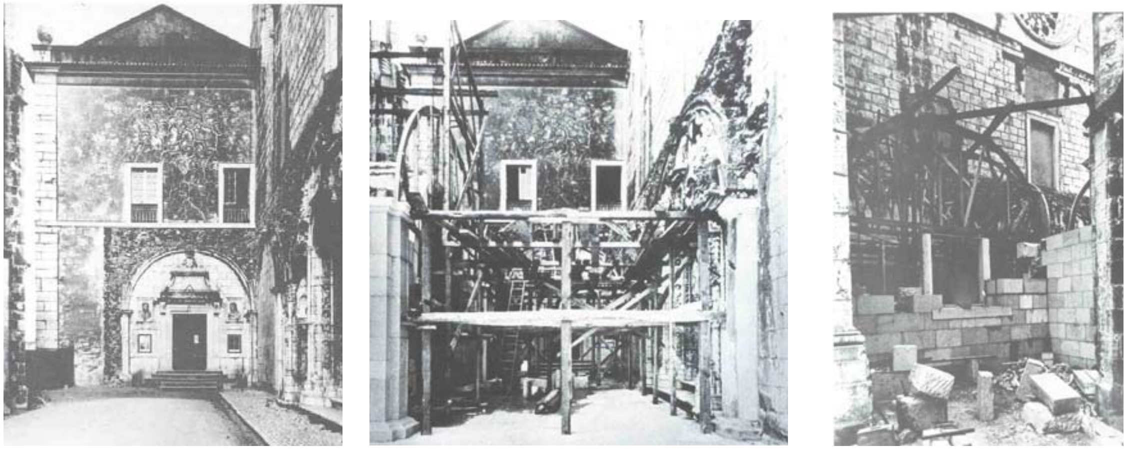
(b)

Figure 6 - Homage Tower: (a) the construction; (b) aspect of its collapse (Marques de Carvalho, 1984).

The Monastery and the XX Century

Since 1910, the interventions in the Monastery have been oriented to appeasement and arrangement, trying to reinstate the monument in its original purity, without radicalisms and to impede its degeneration. The aesthetic criteria have been improved progressively.

The old arcades and dormitory became totally autonomous and without interferences with the monastery. Today the Ethnographic Archaeology Museum and the Navy Museum are installed there. In the same way, the "Casa Pia of Lisbon" became totally autonomous, without any interference with the Monastery. To correct the hall demolition (narthex), a new one was built, like a terrace (Figure 7 to Figure 9), and the South façade was recomposed (Figure 10).



(a) (b) (c)

Figure 7 - Narthex construction; (a) the site; (b) and (c) vault braces assembly (Marques de Carvalho, 1984).

(a) (b)

(c) (d)

Figure 8 - The vault ceiling of the narthex: (a), (b), (c) and (d) Construction details of the vault (Marques de Carvalho, 1984).

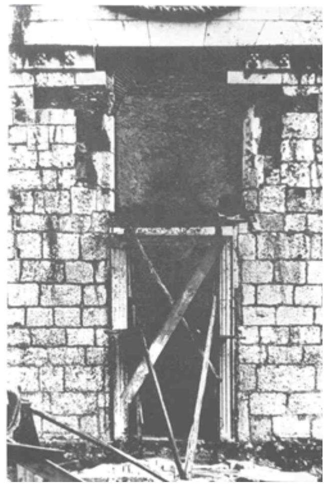
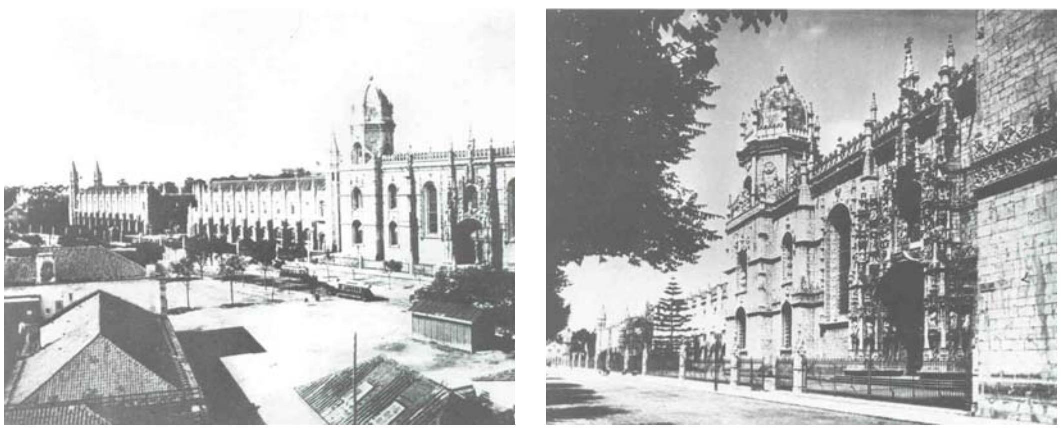


Figure 9 - Construction of the door access between elevated choir and narthex (Marques de Carvalho, 1984).



(a) (b)

Figure 10 - (a) Façade reconstruction; (b) Current view of the monastery (Marques de Carvalho, 1984).

At the South façade and at the East wall of the cruise, coloured stained glass windows were put on the biggest window openings. In 1940, for the Exhibition of the Portuguese World, a square garden in front of the monastery was made. The actual aspect of the monastery is due to the preparation of this Exhibition.

4. STRUCTURAL ANALYSIS OF THE MONASTERY CHURCH

4.1 Historical analysis

A brief chronological summary of the constructive phases of the church and the most important structural interventions along its history are now presented.

XVI century

1501-1502 (?): placement of the first stone;

1516- .. : columns and the outlying walls of the church were concluded (Boitaca);

1516-1522 (?): the vault of the naves were concluded (João de Castilho);

1522- .. : built the vault and columns of the transept (João de Castilho);

1557-1572 (?): the chancel (shrine) assumes its current volume;

By the end of the XVI century the great works in the monastery were finished.

XVII century

Construction of the connection body between the church and the dormitory (narthex).

XVIII century

1755: A great earthquake hit the monastery, causing small damages to it;

1756: Collapse of part of the vault over the choir and fell of the central arch and its associated vault, under the elevated choir.

XIX century

The connection body between the church and dormitory was demolished; the communication door with the high choir was closed;

1877-1878: Construction of a rose-window opening at the high choir (main façade). Modification of the bell-tower;

1883: Reconstruction of the central vault under the choir and its baluster.

XX century

1920-1932:	The roofs and vaults were repaired;
1939-1942:	The South façade suffered a general simplification (balcony, pinnacles and central body). At the main entrance a new narthex was built, with a ribbed vault ceiling;
1947-1949:	Restoration of the church's cover; construction of brick masonry wallets over the vaults, parallel with the outlying church's walls, to seat the timber structure roofs'.
1963:	Minor maintenance and consolidation works were done on the vaults (refill the bed joints and brief evaluation of the state of degradation of the stones).
1999-2001:	An historical-artistic study of the Monastery and a scientific-technical study of the stone's pathologies were done.
since 1949:	Several historical documents refer the falls of stone fragments from the vault ceilings church (naves, transept, choir and chancel).

4.2 Structural Survey

4.2.1 Geometry and structure of the church

Dimensions in plant (interior):

Length: 51 meters

Width: 22.7 meters [6.25 m + 10.30 m+ 6.15 m]

Heights (interior):

Maximum height of the nave vault's (from the ground floor): 21.5 / 24 meters

Maximum height of the transept vault's: 21.5 / 27 meters

Height of the columns: 15.5 meters

In plant, on the transverse direction, the columns of the church are not aligned with the external buttresses in the South façade, especially in the first span (Figure 11). This can intensify the idea that the vault's design (attributed to João de Castillo) is subsequent and different from its original conception (attributed to Boitaca).

The partial obstruction of two window openings, on the South façade, by the elevated choir vault's, has denounced its latter construction.

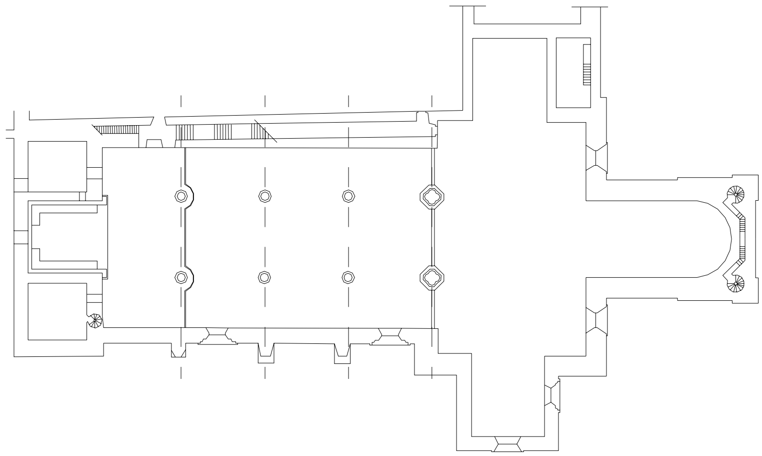


Figure 11 - Church's plan view.

From the architectural and structural point of view, the church's cover vault represents, for the knowledge, judged for its time, an innovative solution. It's a lowered barrel vault, with a complex triangular net ribs, straights (liernes and tiercerons) and curves where, overcoming the constructive techniques of that time, were suppressed the traditional arches (longitudinal and transversal). In this way, the vault's supports (abutments) with the columns and brackets, are of "fan vault" type, which gives a continuous aspect to the church's ceilings (Figure 12).

Figure 12 - "Fan vault" appearance for the church's ceilings (Source: IPPAR).

The ribs net define the vault shape and carry out a main structural function. The vaults are then faced by staves of concave stones directly seated on ribs. To assure the rib's staves assembly, especially close to the vault crowns (where the vault is lowered), metallic (iron) connections were used.

In a recent study of the vault (Monteiro, 1995), it was verified that:

- The expected thickness of the vault's stone staves is about 10 centimetres (measurements were done in existent holes that are associated with the scaffolds' strings manoeuvre during the construction);
- There are different mortars' shades on the bed joints of the vault (repairing interventions? different materials? interruptions in the construction?);
- The vault's staves distribution present smaller stones in the last span before the transept (interruption in the construction? material shortage? repairing interventions?).

It is supposed that the Monastery was not raised at the same time as the church because there are two resistant walls, juxtaposed but no parallel, among which there is a staircase that ascends to the high choir. Under the staircase, there are open up the "confessionals", separated by traverse walls that bring together the walls. This hypothesis is not defended by some authors (see Monteiro, 1995).

During the demolitions and excavations accomplished for the construction of the Cultural Center of Belém, implanted at the same elevation of the monastery, it was verified that the margin line of the old beach of Belém defines the separation among the constructions supported on soil or rock. Consequently, it's expected that the foundations of the Monastery of Jerónimos were seated on rock (Monteiro, 1995).

4.2.2 Cracks

At the interior North façade, over the door of the choir, that gives access to the cloister, is visible one important fissure that spreads about vertically and along all the thickness of the wall, being visible from inside the choir. This fissure is associated with historical damages that the church suffered in the 1755 earthquake and subsequent earthquakes. On the other façades there aren't observable significant fissures, neither interior nor exterior.

4.2.3 Deformations

Recently, studies to evaluate the verticality of the walls and columns were made (Monteiro, 1995). Longitudinally the columns' deformation has minor importance; in obliquely direction, were measured deformations with 30 centimetres of maximum relative distance (Figure 13). It's likely that the horizontal vault's thrusts are concentrated, above all, on the columns due to the lowered profile of the vault and the largest span of the central nave. Consequently, it is expected that the thrusts over the outlying walls will be, above all, vertical. In fact, these walls exhibit transverse deformations with light tendency to the interior (between 3 and 8 cm, values with a minor importance). So, supposedly, the South façade buttresses just have an apparent structural function.

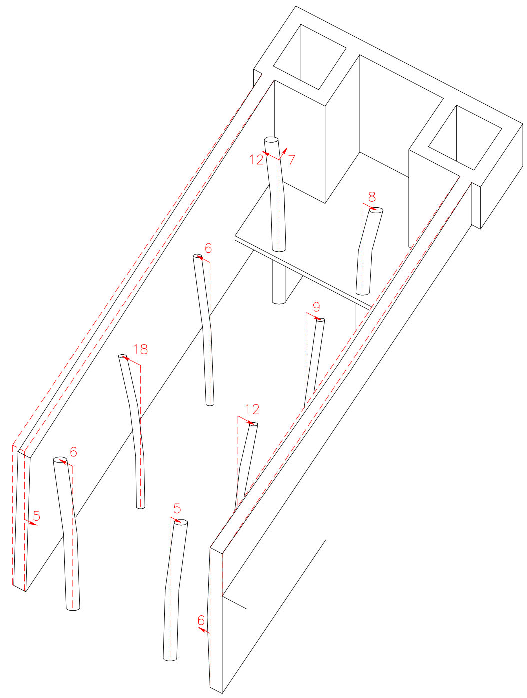


Figure 13 - Deformations, in centimetres, measured over the walls and columns of the Church (Monteiro, 1995).

The South and North façades present, in their upper edge alignments before the transept, close to the cornices, vertical depression and deformations.

4.2.4 Pathologies

Besides deformations and a single fissure referred above, it has been verified that stone fragments fall from the vault ceilings. However, it doesn't exist yet an explanation for that phenomenon, which can be related with: stone degradation (?), bad quality of the stone (?), water infiltrations (?), oxidation of the metallic (iron) connections (?), mortars aging (?), excessive stresses (?), etc.

5. REFERENCES

DGEMN, General Directorate for Buildings and Sites (also available at www.monumentos.pt).

IPPAR, Portuguese Institute for Architectural Heritage (also available at www.ippar.pt).

MONTEIRO, Soraya, Etude Descriptive de la Voute de L'Eglise du Monastere Santa Maria de Belém a Lisbonne, Center d' Etudes de la Conservation du Patrimoine Architectural et Urbain, R. Lemaire, Katholieke Universiteit Leuven, 1995.

MOURÃO, Sara, Study of the Seismic Behavior for Monumental Jeronimos Monastery, MSc Thesis, Universidade do Minho, Guimarães, Portugal, 2001.

Title: **DETAILED DESCRIPTION OF MALLORCA CATHEDRAL**

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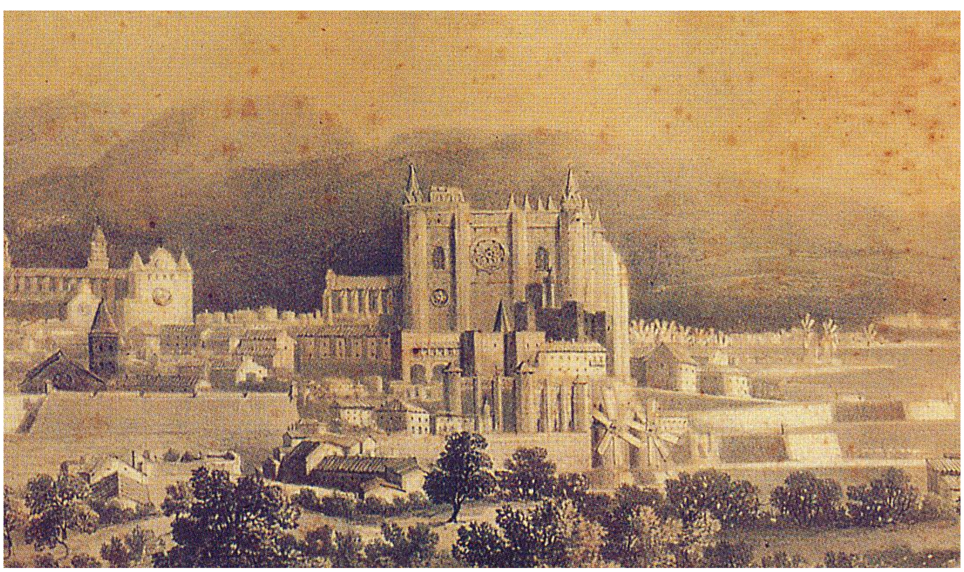


1. DESCRIPTION OF THE BUILDING

1.1 General

The place where Mallorca cathedral is located - the elevation close to the seaside where the quarter of the Almudaina spreads, in Palma - is full of history. The references available on the place and surrounding territory provide sufficient data to trace a historical sequence that goes from prehistory to the present time. The elevation, within the bay of Palm and limited by a cliff at west, facing the Mediterranean, makes of this place a convenient emplacement to be occupied by man and allowing control of the space that surroundings, both marine and terrestrial. Before the cathedral, the location hosted other buildings erected by the Romans and the Muslims. Roman pedestals of possible statues possible belonging to a Roman forum have been found in the cloister of the cathedral. The existence of a Mosque before the construction of the Cathedral is very well documented as well, although no attempt has been made, for the moment, to undercover possible archeological remains. The presence of a reused paleo-Christian capital as part of a base of the present altar in the Real Chapel may be demonstrating that, the location constituted a religious place long before the Muslim conquest. The cathedral itself is surrounded today by other important historical buildings such as the Palace of the Bishop or the Palace of the Almudaina, former Royal Palace of the Kings of Mallorca.

It is well known that the location of the Arab Mosque is the same that is now occupied by the cathedral; in principle it seems that the cathedral was constructed around the Islamic building and that the latter was not destroyed until Christian church was finished.

The Cathedral of Mallorca is, to a large extent, a Gothic cathedral, although it has some Renaissance characteristic, because, as it is explained later, the works began about the year 1300 and they finalized in the heat of the Renaissance period.

Mallorca Cathedral (figures 1-7)) is one of the most imposing medieval constructions thanks to the immensity of its interior space and the extraordinary dimensions and the extreme slenderness of its structural elements. However, the historical process leading to its final lay-out and dimensions is not very well known. The plant and the longitudinal section (figures 6 and 7) clearly shows two distinct parts or bodies, one formed by the main nave (at west) and a second composed by the choir and surrounding elements (at east: Capella of the Trinitat, Capella Reial, Capella of the Corpus Christi, Capella de Sant Pere). The first body the Cathedral includes a central nave and two lateral ones, flanked as well by eight powerful abutments which lodge between the lateral chapels. The second body, built in a previous historical stage, includes the so-called Capella Reial (Royal Chapel), a single nave imposing Gothic construction by itself, and the smaller, but even older, Capella de la Trinitat (Trinity Chapel), the first element of the complex to be built. It is not known with certainty –although opinions exist in all directions- weather the complex was laid-out in accordance to its final configuration (as the combination of the mentioned distinct spaces), or weather the construction of the imposing three-nave body, with its large dimensions, resulted as a decision taken after the older bodies where already built. Remains of unused capitals and nervure springings at the end of the Royal Chapel suggest that the decision of building an imposing body of larger dimensions was actually taken after the completion of the eastern part of the building.

The proportions of the Gothic lateral facades of the cathedral are of great verticality and slenderness, contrasting with the heavy neo-Gothic body constructed at the end of 19th c. to strengthen the old renaissance façade. The neo-Gothic façade designed by Peyronnet has been criticized very much not because of its wide proportions and little adaptation to the original structure and architectural concept.

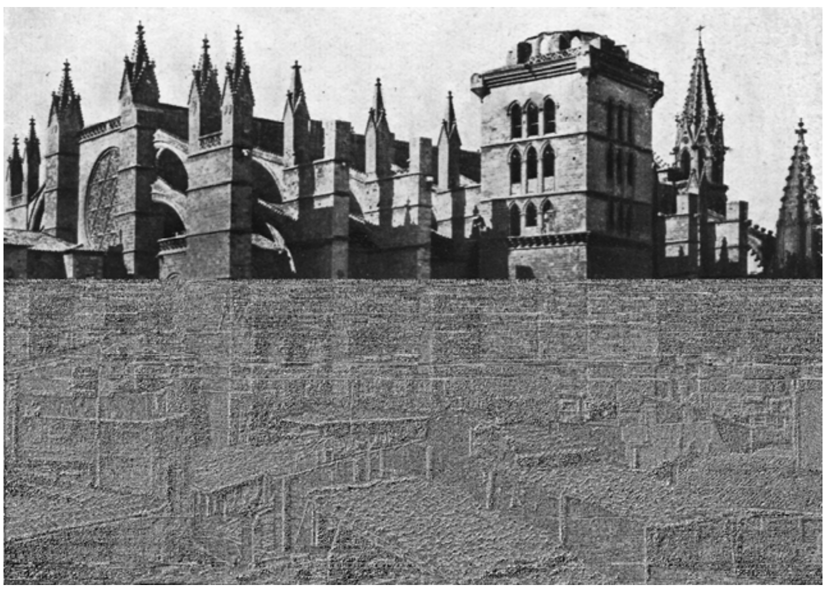


Figure 1- View of the exterior of the cathedral and clock-tower from old Palma

1.2 Architectural arrangement and structure

The length of the nave of the main body is of 77m and is distributed across seven bays. The width covered by the naves is of 35.3 m, of which 8.75x2 m are spanned by the lateral naves and 19,8 m by the central nave. The lateral naves are covered by pointed vaults of simple square plan; however, in the central nave they are of double square plan.

This scheme is repeated both in all the bays of the naves except in the 5th one (from the choir), due to the presence of lateral doors (door of the Mirador and door of the Almoina) which provide it the role of a transept. In this bay, the longitudinal span of the vaults is slightly longer.

The height reached by the vaults in their highest point (the key of the transverse arches) is of 43.95 m, surpassed solely with 44m by the Cathedral of Milan (with tied springings) and by the Cathedral of Beauveais with 46.30m.

The Cathedral of Mallorca also is unique in being the Gothic cathedral with the highest lateral naves (29,4m). This means that the height if the octogonal piers, with circunscribed diameter of 1.6 and 1.7m, is of 22.7, showing their extreme slenderness.

Figure 2 – View of the interior

The singularity of the building becomes more patent when its cross-sectional section is compared with the one of other Gothic cathedrals (table 1).

Another aspect to note is the double battery of almost identical flying buttresses. The role of the upper battery of flying arches is not clear since the building has never had a high pitched roof (causing lateral thrust due to wind pressure), but just a terrace over the vaults until the construction, in 18th c., of the existing traditional tile roof.

The transverse arches of both the lateral and central naves are diaphragmatic, meaning that they are provided with masonry wall spandrels filling all the space to the height of the key. The vaults are not filled or backed with rubble masonry, but just with a light structure composed of slender stone wallets and slabs.

The structure of the cross section is complemented with significant overload, in the shape of triangular masonry masses placed upon the transverse arches and the keys of the vaults of the central nave. On the transverse arches, as it is possible to appreciate in figure 4, a symmetrical triangular wall exists reaching its maximum depth at the key of the arch. On the keys of the vaults, the overload appears as a pyramid of square base, figure 5. According to Rubió (1912), these overloads are "hidden artifices to assure the stability of the building".

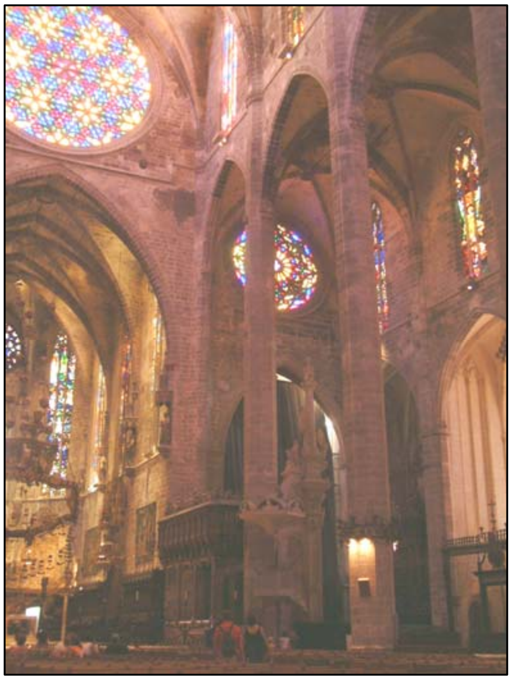
As mentioned, the slenderness of the piers, reaching a ratio of 14.6 between diameter and height, constitutes the more unique and audacious aspect of the building and contributes largely to a sense of internal great spaciousness. The diaphanous interior space is made possible, in fact, by the very robust external buttressing system provided to the construction. The base of the main buttresses is 7.7 m long and 1.5 m wide; its maximum dimension represents a 44% of the span of the central nave.

Recent historical research has provided light on the original quarries from which the stones where taken from. All of them are local quarries located at the sea-side allowing easy transportation of the material to the cathedral works by ship. Two main different types of stones were used to build the masonries of the cathedral. On one hand, most of the volume of the walls and buttresses is build by a bloc masonry composed of the so-called Marés stone, a well-known local type of limestone characterized by its very low strength and very easy workability. Laboratory mechanical tests have allowed the measurement of a very low compression strength for this type of stone, of only about 2 MPa. For the piers, by far more delicate and more intensely structurally solicited elements, another type of limestone, of better quality, was used, for which a higher compression strength, about 20 MPa, has been measured.

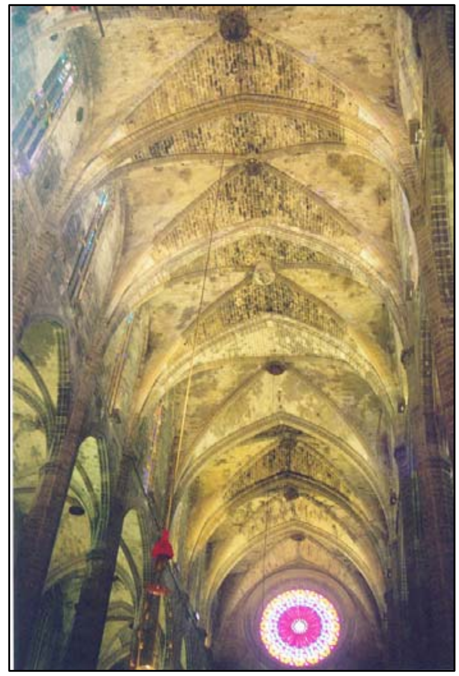
The studies suggest that not only the external leaves of the walls and buttresses, but also their interior, is composed of large blocks of thus type of stone. Similarly, the piers are solid, their section being composed of a large square inner stone and four pentagonal perimeter stones, all in the higher quality sandstone. No rubble seems to have been used to fill the core of the piers, buttresses and walls, all of them being composed of block masonry made of the mentioned types of stone.

Table 2.1. Comparison of magnitudes in different Gothic cathedrals

Catedral	Nave central		Nave Lateral		Piers	
	span	height	span	height	diameter/span	height / span
Girona	21,8	34,2	(single nave)		(no piers)	
Mallorca	17,8	43,95	8,75	29,4	0,08	14,6
Milán	16,4	44	7	29	0,17	9
Beauveais	13,4	46,3	5	21	0,16	7,1
Amiens	12,4	41,5	6,4	18,7	0,14	7,5
Reims	12	36,4	5,3	16	0,15	5
París	11,85	31,4	4,6	10,2	0,11	4,5
Salamanca	11	34	7,3	22,4	0,25	3,5
Barcelona	11	25,6	5,5	20,5	0,16	8,5



(a)



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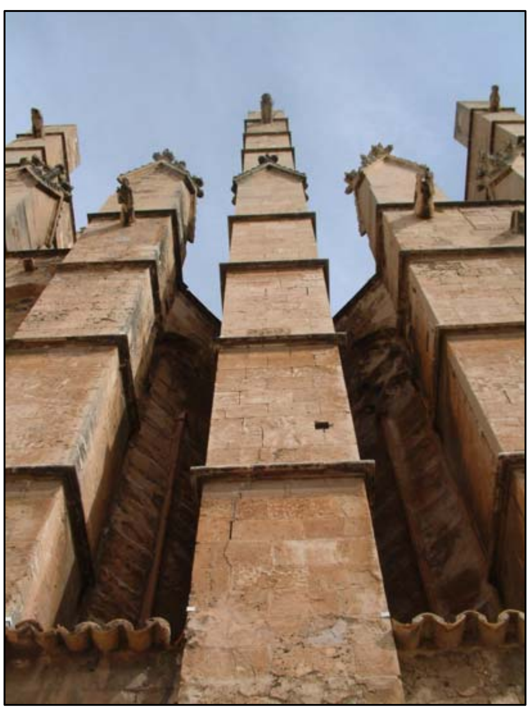

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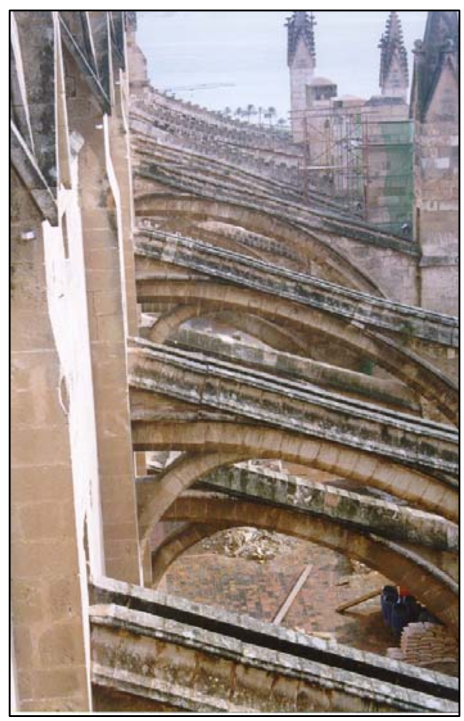


(d)

Figure 3- Different elements of Mallorca Cathedral: (a) triumphal arch and piers; (b) vaults of the central nave ; (c) main and secondary buttresses; (d) flying arches

Figure 4 - Masonry Pyramid over the key of a transverse arch

Figure 5- Masonry pyramid over the key of a vault

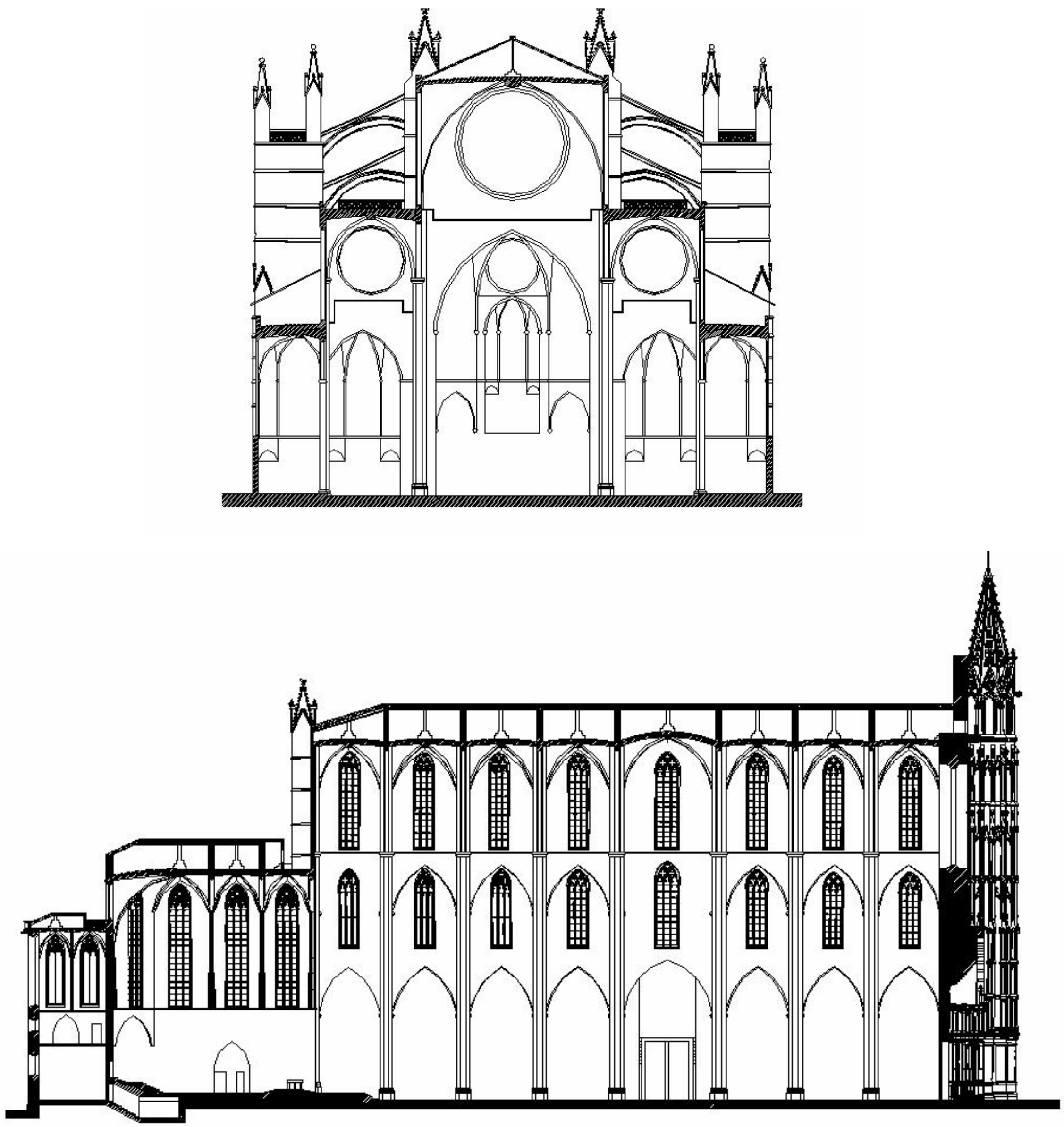


Figure 6 – Transverse (above) and longitudinal section (below) of Mallorca Cathedral.
Source: Director Plan of Mallorca Cathedral.

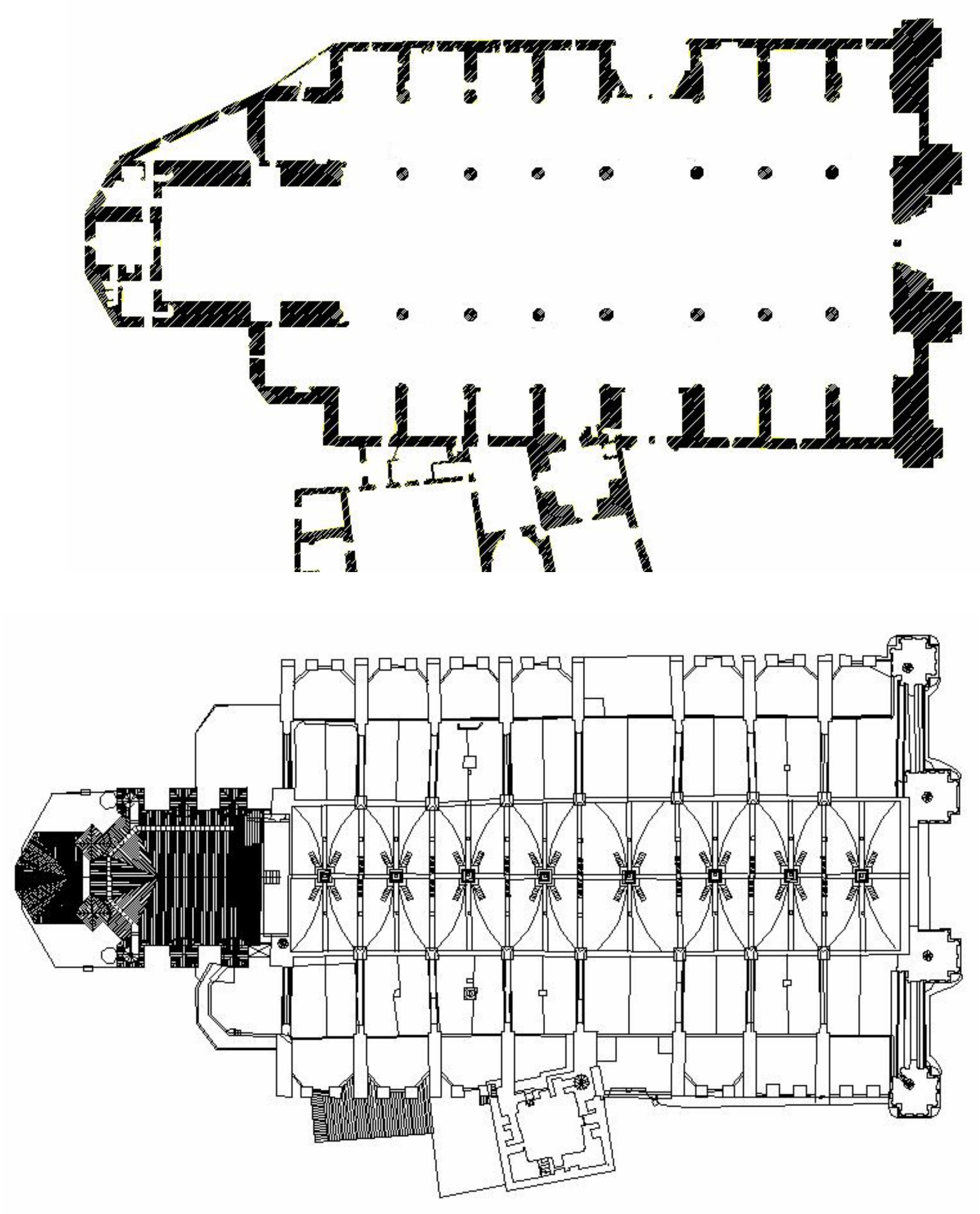


Figure 7 – Plan indicating the distribution of piers (above) and vaults (below) of the main nave. Source: Director Plan of Mallorca Cathedral.

2. HISTORICAL ISSUES

The more relevant aspects of the history of the construction as well as later significant events experienced by the building are here presented based research carried out by some authors. A more detailed and updated research, with more comprehensive information on the construction process and historical repairs, obtained after a close investigation on the historical files of the cathedral, can be found González and Roca (2003-2004). Five different periods are distinguished:

First stage: The royal construction (1300-1368)

The construction began during the first reign of the insular dynasty, about year 1300, after king Jaume II (1276-1311) leaved an important legacy in his testament (1306) to support the cost of the Chapel of the Trinity. This first body had the mission of lodging the tombs of the royal family in its crypt. In the year 1311, the works of the following body of the apse began, namely the presbistery known as the Real Chapel. This phase concludes with the completion of the Real Chapel by 1370.

Second phase: The naves (1368-1601)

According to Llompart (1995), the architect who conceived the three great naves which constitute the main body of the Cathedral was Jaume Mates, who in year 1368 is known to be choosing in the quarries of Santanyí (Mallorca) the stone that was going to be used in the construction of the seven pairs of octogonal piers. In Domenge (1995), many reasons are suggested to justify the drastic change in the construction of the building, but no hints are placed about the reasons or the rationale followed the architect to devise and to construct a cathedral of such dimensions and so structurally audacious.

By the year the 1400 the works of the Cathedral concentrate in the door of the Mirador and by 1601, with a noticeable Renaissance style, the west, main façade is finished, with which the construction sites of the Cathedral are finalized.

During this phase, and according to Domenge (1997), making reference to the article of Llompart (1995), an arc of the central nave fell in April of 1490 causing serious deterioration.

Third period: 1601-1851

This it is the period spanning from the conclusion of the West facade to the beginning of its substitution. Diverse episodes related to problems in the vaults are known. In order to allow a better understanding of such episodes, they are exposed in chronological order (regardless of the date in which they are mentioned by the different authors)

1639.- Giving specific dates, Jovellanos (1832) affirms: "the 10th of July of 1639, a series of experts gathered to find a remedial for the major vault close to the façade, whose masonry were full of cracks. They concluded that, unfortunately, the vault was to be completely dismantled and rebuilt to avoid possible disgraces". It is the first historical reference that speaks of bad condition of the vault of the central nave.

1655.- According to Durliat (1960) research,"...,1655, it was necessary to remake the greater arc of the main nave and the first northern flying buttress.....".

1659.- Mentioning Jovellanos (1832), who is in turn mentioning articles to newspapers by Jaume Fiol, Domenge (1997) mentions that the night of the 20th of May of 1659, an arch fell, without specifying which one.

1660.- Fontseré (1970) comments that at the end of March of the year 1660, Palma de Mallorca undergoes an earthquake of degree VII and Pau Bouvygives gives the dates of end of March (18, 19, 26) for an earthquake of degree VII. Apparently, it caused the failure of two arcs near the façade. This could be also in the origin of the out-of-plumb of the façade. A first report on the problems of the façade, written 19 years later, mentions a deviation of the vertical of four handpsans (80 cm).

1679.- Cantarellas (1975) mentions a report, dated in 1679, that notifies that the facade the west displays an out-of-plumb of four handspans (80 cm). The author also speaks of a second report, dated in 1803, where an out-of-plumb of the facade of four and a half handspans (90cm) is mentioned.

1698.- According to Durliat (1960), in 1698 the vault of the second bay collapsed, and so it did again after the reconstruction in 1699. The13th of May of that year, the architect recommended a reconstruction of the set of the vaults of the nave, which was indeed carried out during the 18th c. The vaults of the North lateral nave were also reconstructed during the 18th c.

1706 and subsequent. Coll (1977) refers three new collapses of vaults in 1706,1717 and1743. Although the source of this information is not mentioned, it agrees with the previously facts described by Durliat (1960).

1739.- On the 4 of October of 1739 it is issued the order to prop up 6 flying buttresses (from Taltabull, 1999) (figure 8).

1803-1851.- Numerous voices of alarm were raised declaring the precarious condition of the western façade. After two new reports on the condition of the west façade, dated in 1817 and 1841 respectively, it was the 28 of March of 1851 when a definitive report proposes to demolish the façade, the out-of-plumbing of it being already of 6 handspans (1,3 m) for an overall height of about 300 handspans (60 m).

The 15 of May from 1851 at 1:45 a.m. Palma de Mallorca was whipped by an earthquake of intensity between VII and VIII, causing probably the destruction of some part of already deteriorated main façade. Apparently, The movement did not have greater effect on the rest of the building.

Fourth Period: The reconstruction (1851-1888)

In the summer of 1851 the works of disassembling of the façade began under the direction of architect Antoni Sureda (figure 11); they lasted six months. In August of the following year architect Juan Peyronnet Baptist was committed with the design and the reconstruction of the new façade.

The restoration project is presented in 1854 (figure 10). Preyroned laid-out a very different, flamboyant neo-Gothic façade completely strange to the neat design of the old façade (figure 9) and the rest of the building. The section of the buttresses of the new façade are significantly increased with respect of those of the former one. The works finish in 1888.

Fifth Period: Reforms 1888-2002

This last stage it includes a series of interventions, among which the liturgical reform carried out by the Catalan architect Antoni Gaudí between 1904 and 1914 with the collaboration of other architects (Joan Rubió i Bellver, Josep M. Jujol, J. Towers Garcia and Guillem Reynés).

During last decades, the building has been subjected to continuous repair and maintenance works. The West façade and its towers have been very recently restored.

Figure 8 - Flying arch propped on a masonry pillar

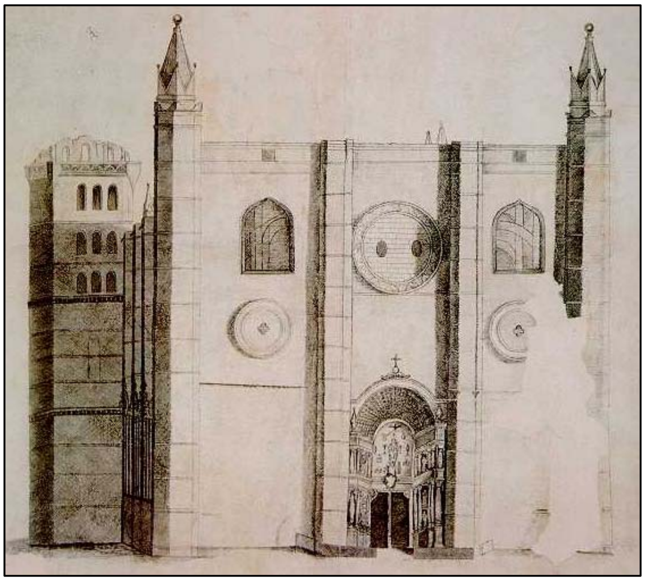


Figure 9- Original western façade

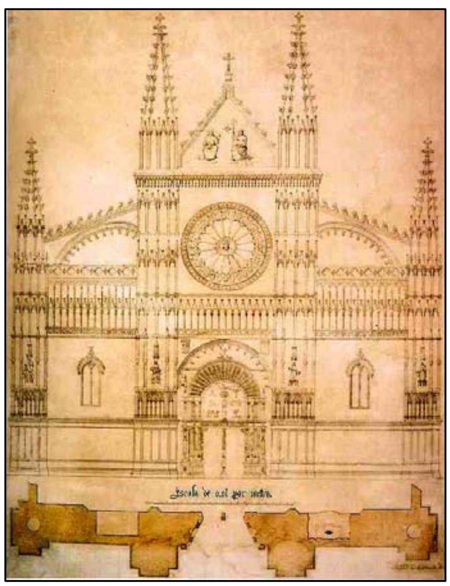


Figure 10 - New façade from the original project by Peyronnet

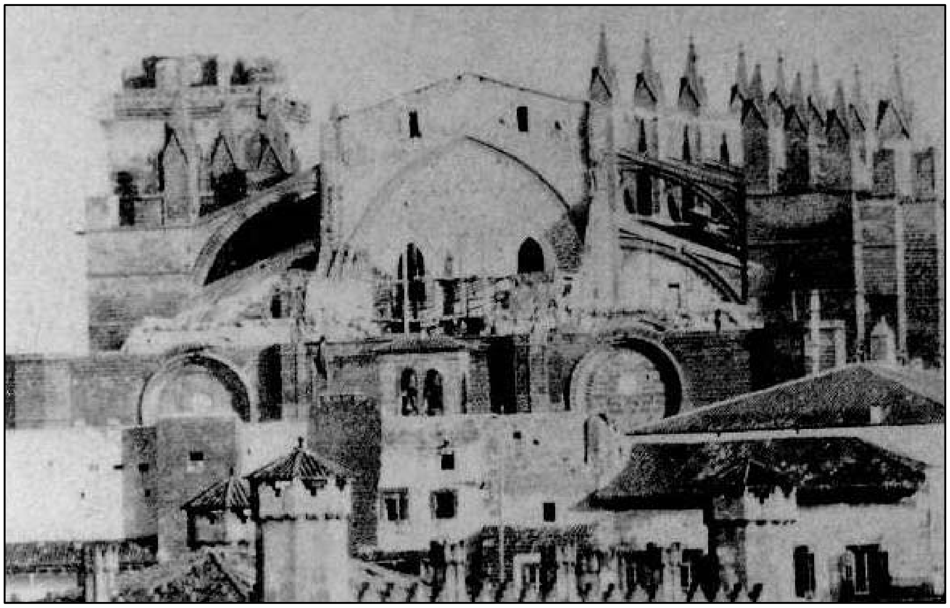


Figure 11- Dismantling of the western façade by 1855

3 NOTICE ON MAIN STRUCTURAL ALTERATIONS

The building is showing today a certain number of structural anomalies (large deformations and structural cracks) which significance is still subject to discussion. The main observed structural irregularities are (figures 12-13):

- Significant deformations affecting the piers, which show a remarkable curvature and lateral displacement both in the longitudinal and transverse direction of the nave.

- Vertical cracks at the base of some of the piers; eventually, these cracks shape surface wedges partially expelled from the core of the pier (figure 12).

- Significant deformations affecting the flying arches –in special, those corresponding to the upper battery. Apparently, a few flying arches were, at some time, propped by means of masonry columns and walls to prevent their possible failure.

- The vaults of the central nave and the main transverse arches are separated by wide cracks developed throughout their contact lines.

-The western façade seems to have experienced anew a certain out-of-plumb after its reconstruction, causing, in turn, some cracking in the panels of the clerestory wall close to it.

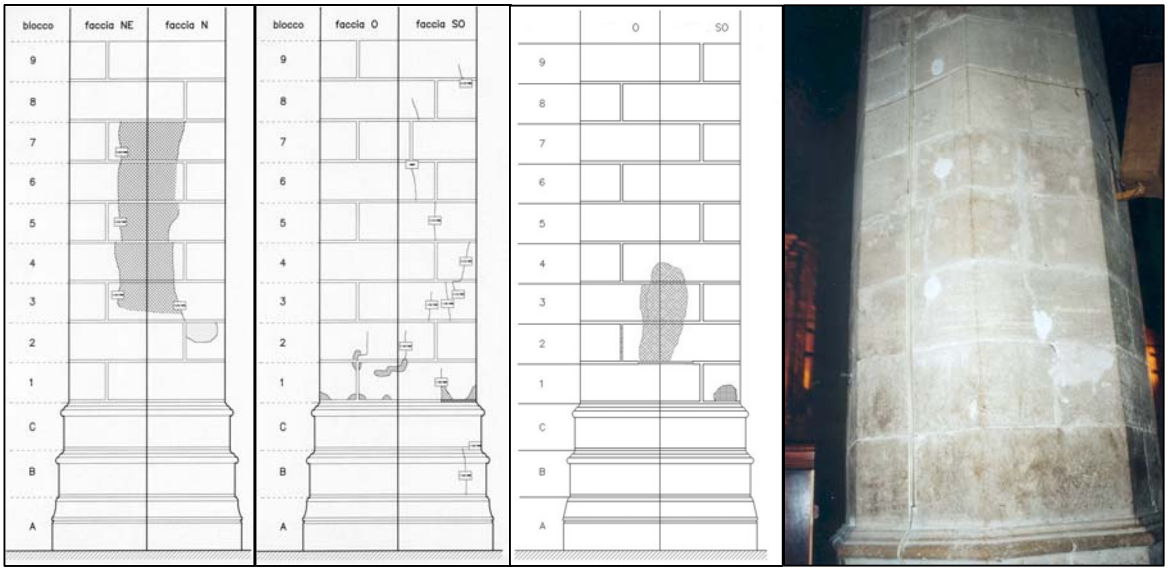


Figure 12 – Examples of cracking in pier faces. The photograph corresponds to the wedge developed in the pier face sketched at the left

Figure 13 – Examples of cracking in (left, above) the clerestory, (right, above) between vault and transverse arch and (below) in the vaults of the central

-Cracking is abundant at the clerestory walls, specially (as mentioned) close to the western façade and also on the walls corresponding to the transept.

-Cracking is also observed in other structural components (as in buttresses, caused by existing openings or false windows between lateral chapels, and also in lateral vaults).

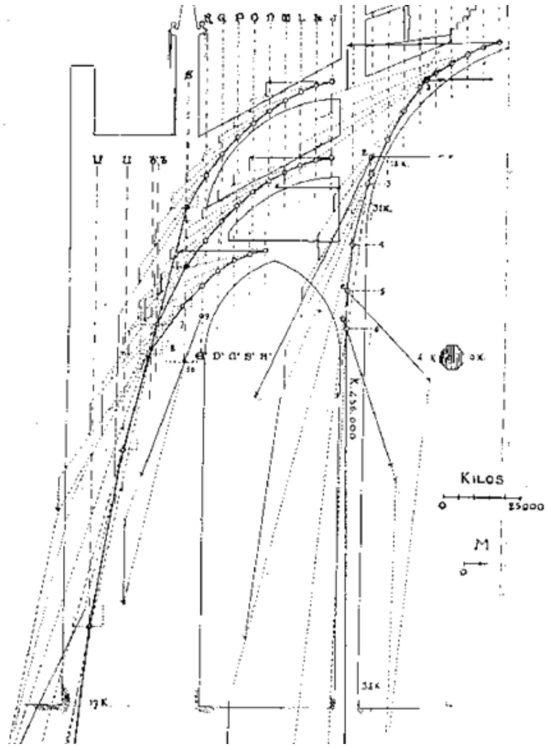
Because of the concern caused by these observed anomalies –and, in particular, by the cracks and deformations affecting the piers of the central nave- a detailed assessment has been lay-out devising comprehensive historical investigation, inspection, monitoring and structural analysis (González and Roca, 2000, 2003-2004).

4 PREVIOUS STRUCTURAL STUDIES

Previous structural analyses are available thanks to the pioneering studies carried out by architect Josep Rubió (1912), consisting of a detailed static analysis, and Robert Mark (1984), by means of photo-elasticity (figure 14). Additionally, preliminary analyses are also being carried out by means of the numerical techniques already mentioned (Continuous damage model and GMF).

Rubió's analysis, based on graphic- statics, was actually pioneering at its time. Although the concept was not new, very few attempts had been carried before to apply it to a large and complex structure. Rubió succeed in applying it, in a very accurate way, to the case of Mallorca Cahtedral. After much elaboration, Rubió was able to find an equilibrated solution for which the thrust line kept fully contained within the volume of the elements. As explained by the author, fitting the descending thrust line within the volume of the pier revealed extremely difficult. In his solution, the thrust line becomes almost tangent to the perimeter of the pier at the level of the springing of the lateral vault (figure 14). Rubió noted that this solution was consistent with the curvature shown by the pier. According to Rubió, attaining stability in the real construction should have required the inclusion of artifices such as the dead loads (in the form of masonry pyramids) placed over the vaults and main arches; at least, his calculation showed that such contribution was required to obtain the equilibrium solution.

The pioneering studies on the structure of Gothic Cathedrals carried out in the 70's by Robert Mark (1982) included the analysis by photo-elastic modeling of many emblematic Gothic constructions. Given its structural interest, the case of Mallorca Cathedral was also considered and analyzed using the same technique (figure 14). The analysis permitted to draw interesting conclusions about its structural features and response subject to gravity loading and wind. Interestingly, some of the conclusions reached by Mark are not in agreement with those drawn by Rubió. According to Mark (1982), the photo-elastic study predicts a very uniform state of compression in the piers under dead-weight, indicating that the amount of bending is so negligible as to be unique among the many Gothic churches discussed by the author.



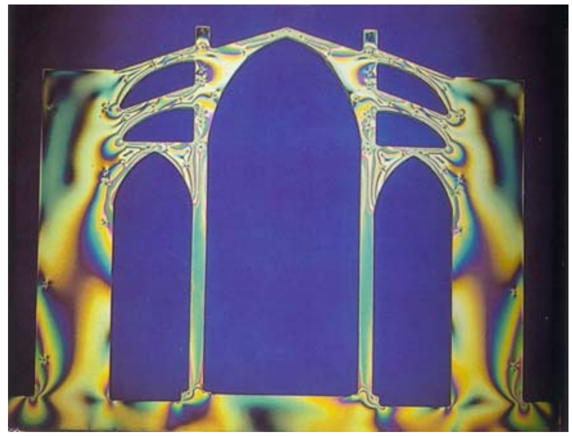


Figure 14- Limit analysis by Rubió (1912) (left) and photoleastic analysis by Mark (1982) (right)

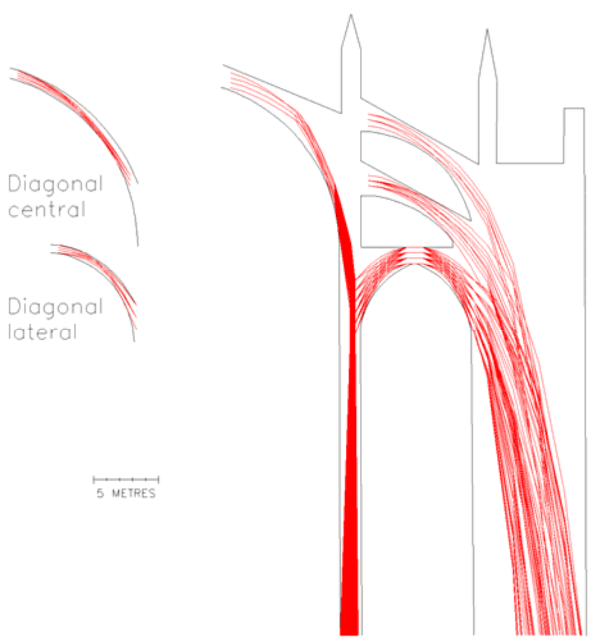


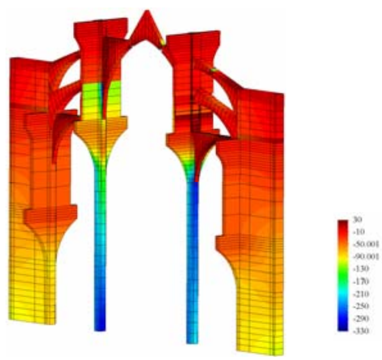
Figure 15 - Computer-aided limit analysis by Maynou (2001) showing that many equilibrium solutions alternative to that obtained by Rubió (1912) are possible

More recently, additional structural analyses have been carried out using modern computer calculation techniques using different numerical approaches. Limit analysis –similar to that manually applied by Rubió- has been carried out, using computer techniques, Maynou (2001) (figure 15). Finite element calculations based on a damage model in the frame of the finite element formulation have been undertaken by Filippo (2001) and Sales. The Generalized Matrix Calculation –another approach for non-linear analysis alternative to the finite element method- has been also applied by Salas (2002) To the typical bay of the building. The more significant results obtained in this latter analysis are here mentioned (while the reader is referred to the aforementioned references for more information on the other approaches). More information on the Generalized Matrix Calculation for the non-linear analysis of masonry framed structures can be found in Salas (2002) or in Molins and Roca (1998).

Figure 16,c shows the distribution of normal stresses (always parallel to the main axis of each structural component) for dead loading applied on a (theoretically) undeformed geometry. Cracking (and deep cracking associated to plastic hinges) predicted by the formulation is shown in white. At the base of the piers, the reaction is applied with significant eccentricity (in contradiction with Rubio's assumption and Mark's appreciation), causing a significant increase of the maximum compression. The maximum compression at the base of the pier reaches 3 MPa (the average compression being 2.5 MPa). Complementary analysis show that if the dead load is applied on the current deformed geometry, the maximum compression may increase about a 15%. The superior flying buttress experiences two hinges which indicate the exact place where the line of thrust is located. Similarly, the transverse arch of the central nave also shows the formation of two symmetrical hinges at the edges of the upper pyramid. These hinges may be produced by the need to make compatible the different movements of the pier and the abutment. This is patent in figure 16,b, corresponding to the deformed transverse section amplified by a factor 2000. it must be also noted that the displacements predicted for the dead load are 2 orders the magnitude smaller than the deformations actually observed in the building, although the deformed shapes are qualitatively similar.

Further increasing of the dead load, above 100%, is also simulated to obtain a qualitative understanding of the safety of the structure (figure 17). A relatively low value of 1.7 is obtained for the maximum multiplier of the dead load leading to full collapse. Higher values, beyond 2 or even 2.5 would be expected for most masonry buildings and have been actually obtained by the authors in the study of other Gothic Cathedrals such as Barcelona's (Roca and Molins, 2000). Interestingly, this value decreases significantly if either the upper flying arch or the pyramidal dead loads are removed form the model, but keeps similar if both elements are simultaneously eliminated.

A complementary parametric study (figure 18) shows that the maximum multiplier is not influenced by the compression strength considered for the masonry except for values lesser than 5 MPa. The masonry actually existing in the piers, made of a stone having compression strength larger than 20 MPa, can be assumed to actually provide an average compression strength above this limit.



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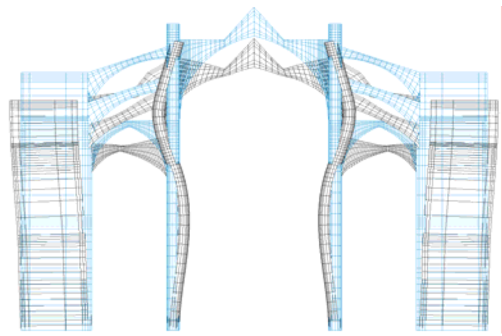

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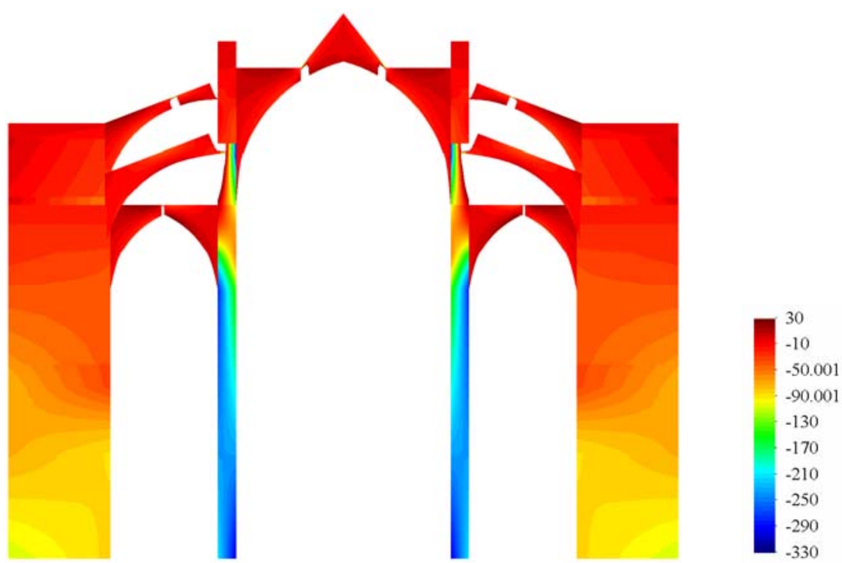

(c)

Figure 16 - (a) Model, (b) Deformation (x2000) and (c) distribution of normal stresses in chromatic scale (10*MPa) and cracking (in white) for dead loading.

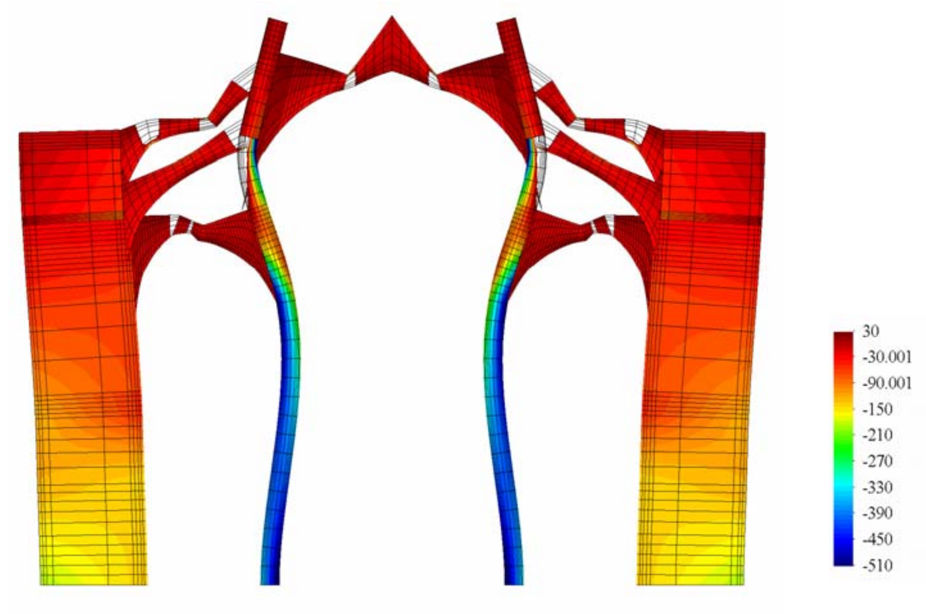

Figure 17- Distribution of stresses (20xMPa) and cracking at failure, occurring at 1.7x the dead load and deformed shape x 1000

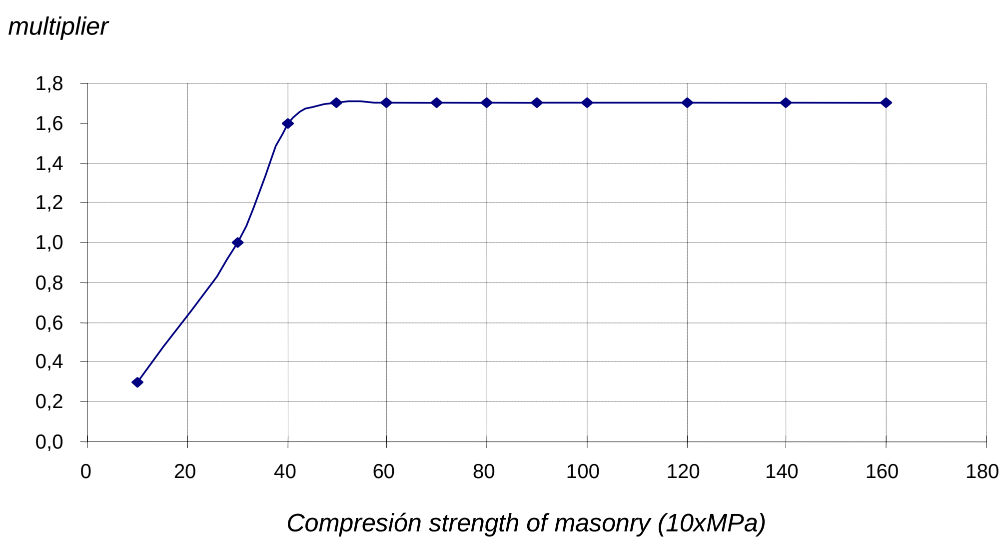

Figure 19 - Influence of the compression strength of masonry on the maximum dead load multiplier resisted by the structure

The effect of wind or earthquake corresponding to very long (historical) return periods has been also assessed by means of simplified static equivalent analysis. The wind pressure and the seismic factor, corresponding to return periods of 1000 years, have been estimated from the Spanish codes on actions (NBE-AE-88) and the Spanish seismic code (NCSR-94). According to the analysis, the structure manages to resist both the actions of wind (w = 1.45 KN/m^2) and earthquake ($a_c/g=0.12$) considered, but to the cost of very intense damage. The resulting condition seems to be not far from possible collapse. Figure 19 shows the resulting distribution of cracking (and hinges) resulting for wind, the one corresponding to earthquake being similar. The need for most accurate dynamic analysis – and, also, for a more accurate estimation of such actions in historical periods- is clear and should lead to further assessment in the immediate future. Additional analysis are indeed planned within the frame of the project of studies funded by the Spanish Ministry of Culture, now in progress under the leadership of the Technical University of Catalonia.

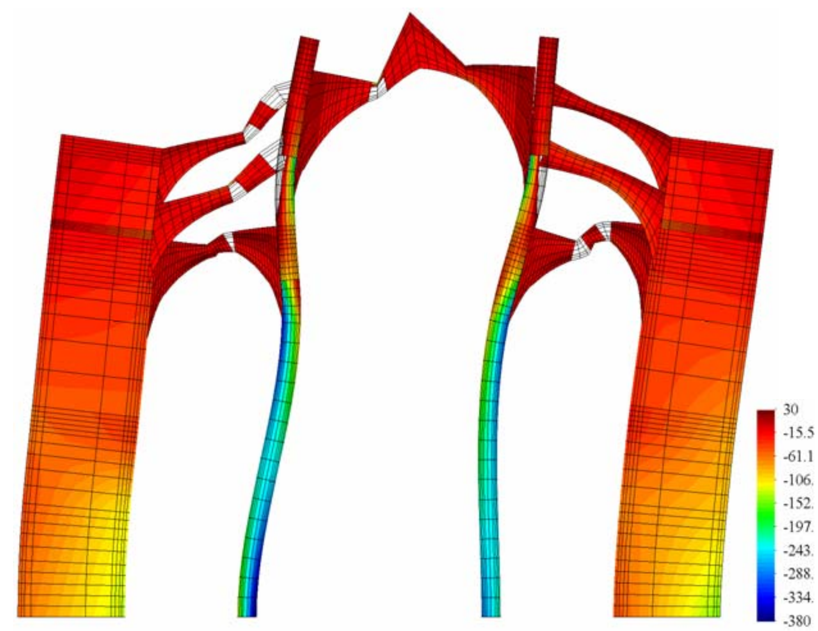

Figure 19 - Distribution of normal stresses (100xMPa), cracking and deformation x 1000 for the structure subjected to a wind pressure corresponding to a return period of 1000 years

REFERENCES

Cantarellas , C.(1975) *La intervención del arquitecto Peyronnet en la Catedral de Palma*. Mayurca. Palma.

Casarin, F., Magagna, E. (2001) *Analisi strutturale della Catedrale di Palma de Mallorca*. Graduation Thesis.. University of Padua, Padua.

Coll , B.(1977) *Cathedrale de Mallorca*, Palma.

Domenge, J. (1995) *Trazas de una fortuna historiográfica,* en Pascual, A. (coord.) . Palma.

Domenge , J. (1995)*Tres siglos de obras en la catedral* (ss. XIV-XVI), en Pascual A. (coord.) Palma.

Domenge, J. (1997*) L'obra de la Seu. El procés de construcció de la catedral de Mallorca en el tres-cents* .Palma .

Durliat, M.(1960) *Le portail del Mirador de la Cathédrale de Palma de Majorque*. Pallas (Toulouse, 1960 *).L'Art en el Regne de Mallorca*. Palma.

Fontseré, E. (1971) *Recopilació de dades sísmiques de les terres catalanes entre 1100 i 1906.* Generalitat de Catalunya, Barcelona.

González, J. L., Roca, P.(2000) *Plan de estudios constructivos-estructurales de la catedral de Palma de Mallorca* . Universitat Politècnica de Catalunya, Barcelona.

González, J. L., Roca, (2003-2004) *Estudio del comportamiento constructivo-estructural de la catedral de Santa María, en la ciudad de Palma, isla de Mallorca (Baleares)*. *Primera Fase*. Parts I. (2003), Part II (2003), Part III (2004), Part IV (2004). Universitat Politècnica de Catalunya, Barcelona.

Jovellanos, G. M. (1832) *Carta histórico-artística sobre el edificio de la Iglesia Catedral de Palma de Mallorca*, Palma.

Llompart, G., (1995) El Coro , *La catedral de Mallorca*. Pascual, A. (coord.) .Palma

Mark, R.(1982) *Experiments in Gothic Structure* . The Massachusetts Institute of Technology Press, Massachusetts and London.

Maynou, J., (2001) *Estudi estructural del pòrtic tipus de la Catedral de Mallorca mitjançan l'estàtica gràfica*. Graduation Thesis. Universitat Politècnica de Catalunya, Barcelona.

Molins, C., Roca, P. (1998) *Capacity of masonry arches and spatial frames*. ASCE Journal of Structural Engineering vol. 124, nº 6,

Roca, P., Molins, C., (2000) *Análisis de Construcciones de Obra de Fábrica mediante Técnicas Computacionales*. Monografía CIMNE Nº 53, CIMNE, Barcelona.

Rubió, J. (1912) *Conferencia acerca de los conceptos orgánicos, mecánicos y constructivos de la catedral de Mallorca*, Anuario de la Asociación de Arquitectos de Cataluña, Barcelona, 1912.

Salas, J. (2002) *Estudio estructrural de los porticos tipo de la Catedral de Mallorca*. Graduation Thesis. Universistat Politècnica de Catalunya.

Taltabull, E. (1999). *Plan director de la Catedral de Mallorca*. Chapter of Mallorca Cathedral, Palma.

Title: **DETAILED DESCRIPTION OF THE QUTUB MINAR**

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1. GENERAL STATUS OF HERITAGE STRUCTURES

India is dotted with plethora of monuments, which include temples, Buddhist stupas, churches, mosques, rock-cut caves, minarets, palaces and forts. Many of these monuments are of considerable antiquity dating back to 1000 years or more. Since the time immortal, these rich heritage buildings of India have been facing the wrath of man made cultural invasions, natural disasters and environmental degradation. However, they are the physical evidences of rich cultural values of our glorious past, which we inherit from our ancestors and are to be preserved in their authenticity i.e. aesthetic and historical values ensuring structural safety against external actions.

The tragedy of the 2001 Bhuj earthquake in Gujarat, India took its toll on the rich architectural heritage and culture of the region. The earthquake indiscriminately affected the historic and the new, the rich and the poor, the religious and the secular. It is estimated that about 10,000 heritage structures of the state were either destroyed or extensively damaged during this earthquake. The composite character of the structures in India results in poor performance of the historic structures during earthquakes. A combination of factors, namely geometry and dimensions, the large mass, the use of structure, the choice of building materials, the lack of adequate interlocking mechanisms in the masonry work, and the type of lateral load-resisting system adopted, normally determines the overall behaviour of the historic structures. For the conservation of these historic buildings, interventions are required for their re-use and technical inputs are required for their proper restoration and retrofitting. Special building code provisions for repair, seismic strengthening/restoration of heritage structures are generally required for their long-term protection. Available knowledge on the seismic behaviour of these structures is also very limited. Detailed studies and research will help to better understand the repair, strengthening, and restoration processes. Maintenance and monitoring also have to be carefully understood and worked out to prevent inflicting further damage during restoration. Reconstruction and preparation of development plans and guidelines should incorporate earthquake resistant technologies. Long-term strategies are necessary for managing the existing heritage structures and areas.

2. QUTUB MINAR

Heritage structures are being protected by Archeological survey of India. There are about 16 world heritage monuments in India and Qutub and its complex falls into that as shown in Figure 1. The minar is situated in Delhi, which has following seismic status:

- Delhi, Capital of India, well known to be seismically active;
- MSK Seismic Intensity VIII;
- As per Indian Code IS:1893-2002, Zone-IV (PGA : 0.25 g);
- Might face an earthquake of Magnitude 6.0 in a period of 50 yrs;
- 80% probability of Magnitude of 7.0 in the region;

- In a 50 Year window (1983-2033), Delhi would experience PGA=0.2g with 10% probability of exceedance.

Figure 1 - World Heritage Monuments of India.

The Qutub Minar is located 15 km south of New Delhi and is a majestic monument and is the tallest tower of India. It is minar in perfection, known to have no parallel in the world. The tower was named after Qutbud-Din to herald the victory of the slave dynasty in the 13th century. The construction of this monument was started in 1200 A.D. but was completed by Iltumitsh. Originally, it was built as a minar for calling the faithful to the mosque for prayer but later it was known as a victory tower, see Figure 2.

Spearing its way proudly into the sky, Qutub Minar with a height of 72.5 meters commands a panoramic view of the green fields extending into a sprawling city. The Qutub Minar was built as a victory memorial by the Muslims who captured Delhi. Minar is the root of the English word "minaret" meaning "Little Minar" or pillar.

Qutb-u'd-Din Aibak laid the foundation of Qutub Minar in 1199 A.D. for the use of Mu'azzin (crier) to give calls for prayer and raised the first storey, to which were added three more storeys by his successor and son-in-law, Shamsu'd-Din Iltutmish. All the storeys are surrounded by a projected balcony encircling the Minar and supported by stone brackets, which are decorated with honeycomb design, more conspicuously in the first storey. The beautiful calligraphy on the bands of Qutub adds to its grandeur, see Figure 3.

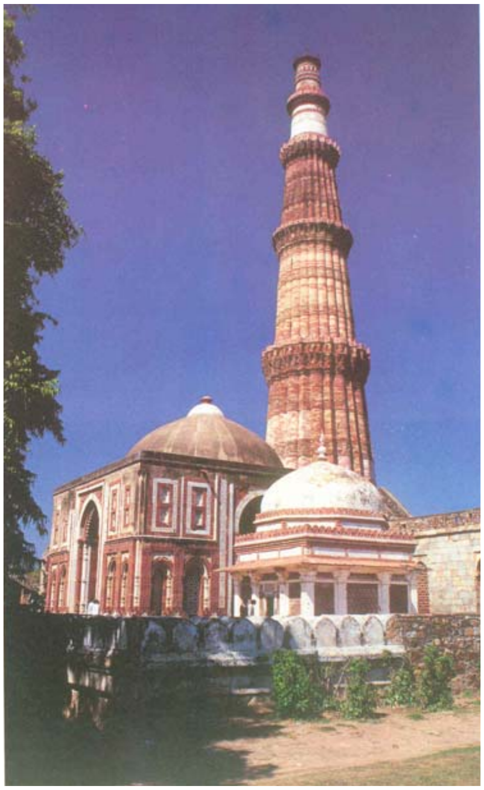

Figure 2 - The Qutub Minar.

Qutub Minar is 72.5 m high with 379 steps and it has a diameter of 14.3 m at the base and 2.8 m at the apex. The magnificent monument has five storeys at present, which can be easily distinguished from the outside by the projecting balconies with stalactitic brackets. Initially, it was a four storeyed tower. The topmost tower was damaged in 1368 when two more storeys were added (see Figure 4). The architecture of the Qutub is of Islamic style. The lower most storey has alternate angular and circular flutings, the second storey with rounded and the third with angular ones, the alignment of the flutings remaining in the same line. The ornamentation of the varied styles in the different storeys adds to the grandeur.

Figure 3 - Ornamentation of the Qutub Minar.

The lower three storeys of the Qutub are made mainly of buff colored quartzite. But the upper two storeys, which were damaged and reconstructed, are made mainly of marble with a subordinate amount of quartzite; Quartzite of the Alwar Series of Delhi system (Pre-Cambrian) is available locally. The marble was brought from different parts of Rajasthan, India. Sculptured Vindhyan sandstone is reported to be brought after destroying the Hindu temples, was also used in the construction of the Qutub. From the Nagari and Persian inscriptions on the minar, it is evident that it was partially damaged in 1326 and 1368 by lighting and was promptly repaired by the Muslim rulers. While on the subject of the repairs executed to the minar, it is recorded that "On the first of August 1803, the old cupola of the Qutub Minar was thrown down and the whole pillar seriously injured by an earthquake." About two years later, the governor-General authorized the necessary repairs to be begun, and the work was entrusted to Major Robert Smith of the Engineers, who completed it by the beginning of the year 1828, at a cost of Rs. 17,000. All the forms of the mouldings were carefully preserved, but the rich ornamentation omitted.

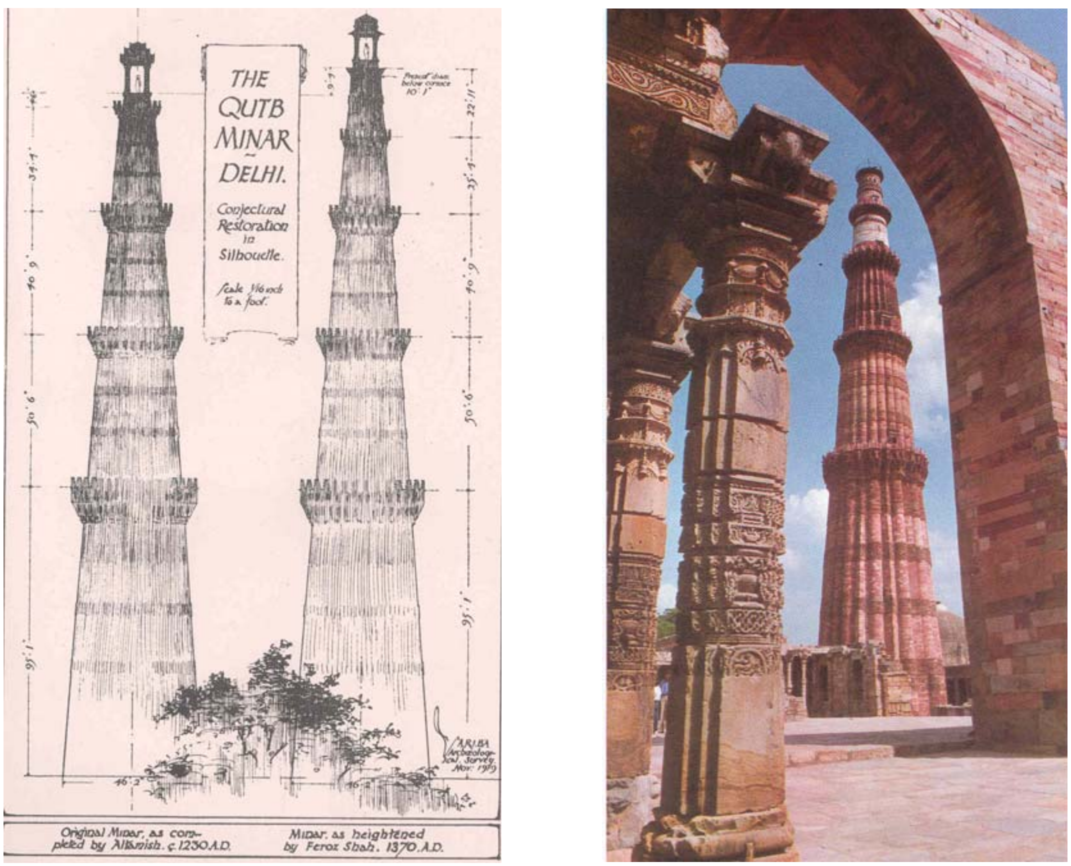

Figure 4 - The Qutub Minar before and after restoration.

Qutbu'd-Din Aibak laid the foundation of Minar in AD 1199 for the use of mu'azzin (crier) to give calls for prayer and raised the first storey, to which were added three more storeys by his successor and son-in-law, Shamsu'd-Din IItutmish (AD 1211-36). All the storeys are surrounded by a projected balcony encircling the minar and supported by stone brackets, which are decorated with honey-comb design, more conspicuously in the first storey. Numerous inscriptions in Arabic and Nagari characters in different places of the minar reveal the history of Qutb. According to the inscriptions on its surface it was repaired by Firuz Shah Tughlaq (AD 1351-88) and Sikandar Lodi (AD 1489-1517). Major R. Smith also repaired and restored the minar in 1829.

In the Qutub Complex, there is one unfinished minar called Alai Minar, which was later made, see Figure 5. The ides was to make a talled and more magnificent minar than the Qutub but it failed. However, the unfinished minar gives an excellent opportunity to look into the constructions practices and material being used. It was the intention of Ala-ud-din Khalji (1296-1316) to construct a minar, double both in diameter and height of the existing one, under the name Alai Minar. Its construction was begun, and a rough unfinished stump is insitu at Qutub complex, but the minar did not seem to have reached any stage of completion.

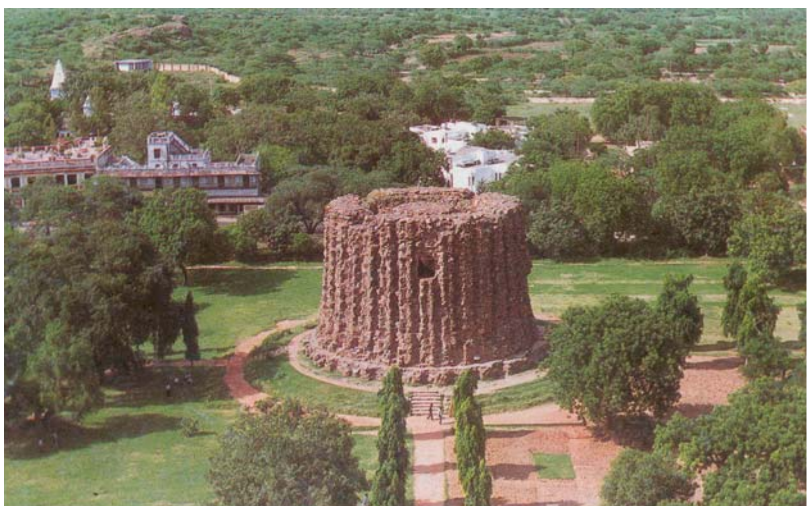

Figure 5 - Unfinished Alai Minar.

Without any information, if the empirical relations as given in the Indian codes are to be used for estimation of time period of the minar, the calculations are as follows.

Basic Parameters for Qutub-Minar:

- H = 72.5 m
- Base dia (d) = 14.6 m
- Top dia (d1) = 2.74 m

The various empirical formulae given in BIS: 1893 - 2002 (Indian code for earthquake) are:

$$T = \begin{cases} 0.1n \\ \dfrac{0.09\,H}{\sqrt{d}} \end{cases} \qquad T = 0.075H^{0.75}$$

Thus, natural period comes out to be T = 1.70 – 1.90 sec. The minar structure looks fragile and flexible from empirical relations, however, in appearance it is not so and standing tall and strong. Apart from this, mathematical modeling of Qutub-Minar using NISA-II (a finite element analysis software) has been started. The each storey is being modeled separately. Material properties are being compiled through literature.

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1. DETAILED DESCRIPTION OF S. MARIA ASSUNTA CATHEDRAL, REGGIO EMILIA, ITALY

1.1. Introduction

The “Santa Maria Assunta” Cathedral, in Reggio Emilia, is the main religious centre of the city. The structure of the church is connected with the buildings of the Bishop’s Palace and the rectory.

Built on an ancient roman construction around A.D. 857, underwent several Romanesque style remodelling. During the XVI and XVII centuries, the church style is renewed and converted to mannerist period canons.

The crypt, dating back to XIII century, is placed inside the Cathedral, below the presbytery. The ceiling of the crypt is composed by crossed vaults, sustained by 42 columns with capitals.

The oldest part of the crypt is the altar area, containing the tomb of the Saints Crisanto and Daria. The crypt underwent a general restoration in 1923. During the repair works, valuable roman mosaic fragments were found (III, IV century); descending a stairway, from the crypt’s level, is it possible to reach a lower room.

Figure 1 - View of the Cathedral’s façade.

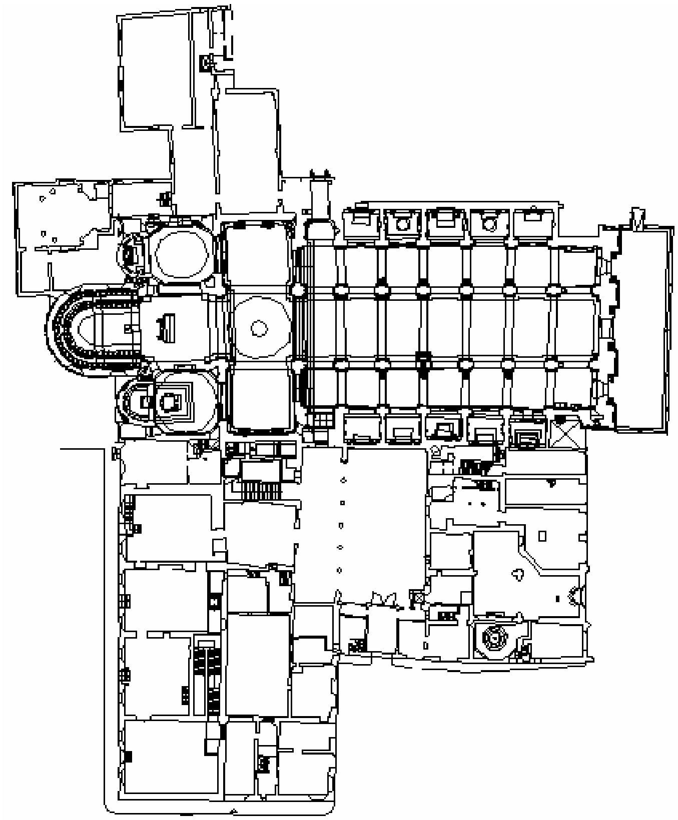


Figure 2 - The religious complex (Cathedral, Bishop's Palace, rectory)

(a) (b)

Figure 3 - (a) The front of the Cathedral; (b) the main nave

The plan of the church is Latin cross shaped, with three naves and transept; the crypt is placed below the presbytery.

The length of the church is 77,40 m, the width is 33,80 m, the span of the main nave is 10,15 m, the span of the two lateral naves is 6,50 m. The maximum height is reached at the top of the dome, with 44,60 m; the height of the front lantern is 33,80 m and the height of the roof above the central nave is 22,25 m.

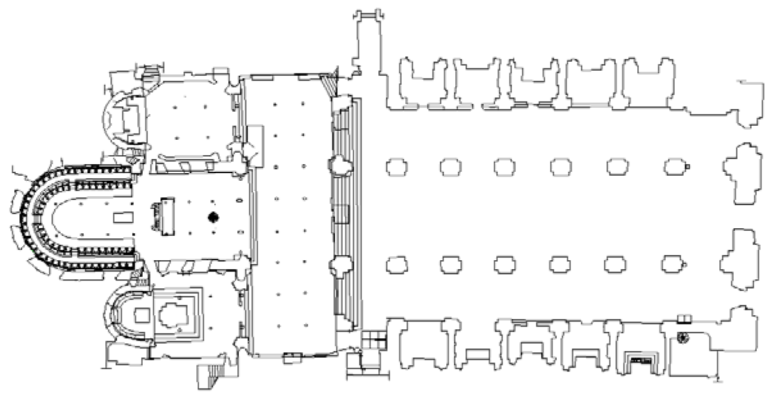
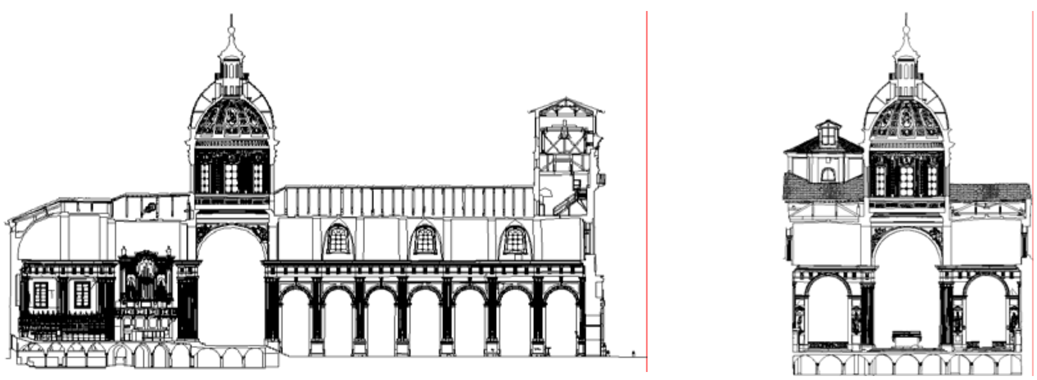


Figure 4 - Plan of the Cathedral



(a) (b)

Figure 5 - (a) Longitudinal section – (b) cross section

2. HISTORY OF THE CATHEDRAL

2.1. The Romanesque church (before 1269)

Historical documents attest, since A.D. 451, the presence of a Bishop in Reggio Emilia, although the description of the "Cathedral" is found in far following historical notes.

After the longobard occupation (about A.D. 569) a religious centre outside the defence walls was created (S. Apollinare church, at the present time called S.Agostino church); after the conversion to the catholic religion of the castrum regiense (VII c.), it is likely that the Bishop moved his Episcopium (seat) inside the town.

During the Frank domination (VII c.), because of the new relations between the Church and the Carolingian Empire, the Episcopium is once again moved outside the town, not far from the centre and toward north, where today the S. Prospero church is placed.

The origins of the Reggio Emilia Cathedral are to be found, according to some historical sources, at the beginning of the IX century, (particularly the year 857 A.D.), when the Bishop Sigifredo established a Saint Mary rectory, when the Ecclesia Sancti Prosperi extra moenia (S. Prospero church outside the walls) was already built.

It is possible that the will to set up a religious centre inside the perimeter of the castrum was decided by the Bishop, as feudal landlord, because of the heavy incursions of the Hungarians (about 900 a.D.) and the following need to erect a stronghold in the heart of the city, to better defend his church.

Starting from A.D. 942, is in fact documented, inside the castle, the existence of the St. Mary church, that shares those days the title of Cathedral with the church of S. Prospero outside the walls.

Yet, a document of A.D. 1135 describes the St. Mary church as the "Ecclesia Maior", appellative that since the XIV century evolved in "Cathedralis" (Cathedral), conserved up to present.

The original plan of the church is to be found in the "Latin cross" plan typology, with three naves and transept (this last datable between the X and the XI century).

Probably based on roman pre-existences, this fact being confirmed by the discovery of a mosaic of the roman period between the last three bays of the central nave before the crossing with the transept, the cross section of the church had to be similar to the "proto-Romanesque style" cross section, with lateral naves with depressed cross vaults, on which the women's gallery was placed, opening this last on the central nave with three mullioned windows.

Since the XIII century the central nave of the church was subdivided into two bays, when the lateral ones into six; the third span of the central nave was shared between the intersection with the transept and the rectangular plan based presbytery.

For this reason, before the main conversion that concerned the church during the XVII century, the main nave had to be scanned by three big arches. The first two of them should necessarily have been positioned one above the last couple of pillars, at the intersection with the transept, to sustain the lantern that is supposed to take the place of the existing dome, the other nearby the fourth couple of pillars. The third arch, built later than the year 1269 and after the construction of the façade's lantern, corresponded to the first couple of pillars.

The cross-shaped plan was visible from the exterior because of the projection of the arms of the transept out of the longitudinal body, and the hierarchy of the internal spaces was outlined outside by conforming the façade with the probable shape of a hut, with the two minor wings corresponding to the lateral naves.

Some internal and external architectural traces are to be found in the Romanesque period: Outside, hanging arches positioned above the Romanesque arch vaulted doubly splayed windows, inside, again hanging arches on the lateral walls above the vault of the main nave.

2.2. The Malaguzzi repair

One of the most important modifications of the Cathedral during the restoration decided by Alberico Malaguzzi (1269), following the collapse of the north tower, is without any doubt the erection of the lantern positioned above the façade.

To the original edifice, an atrium is adjoined, corresponding to a narthex, adding a new space to the façade and defining the new perimeter of the building. The original XIII century façade disappeared, and concurring with the renovation of the façade assuming now the shape of a hut, the church took its definitive plan with six bays in the lateral naves, two in the central one and the atrium in façade.

Above this entrance space, common for all of the three naves, from which by lateral stairwells the access to the choir is granted, a lantern is positioned, supported by the new façade and the first two pillars of the actual central nave.

The lantern, based on a rectangular plan, in the elevation takes the shape of an octagon; it is likely that the original height of the lantern was remarkably lower than the height of the actual belfry.

To this period date back the hanging arches, similar to those of the external walls, disposed inside the lantern, on the lateral walls of the rectangular base. Such arches have a sustaining action for the upper structures, being connected to the wall itself.

It is also believed that the two longitudinal walls of the nave were pre-existing respect the actual lantern, and, consequently to the realization of its foundations, underwent an intervention that forced to the closing of the ancient windows and entailed the positioning of the hanging arches.

Above the first bay of the left lateral nave, is it possible to perceive on the internal splay of the fifteenth century rose-window, a fresco perfectly similar to those discovered on the splay of the left rose-window, demonstrating in this way that also on this side had to exist a symmetric (by shape and decoration) opening.

It can be hypothesized that two walls were separating, at least at the level of the women's gallery, each of these openings from the rest of the church.

Strictly connected to the erection of the lantern is the construction of the façade, even if the whole intervention and modifications that changed the Cathedral since this period up to the XVII century, allowed to establish with a certain degree of certitude the original shape of the principal front of the building.

To this period date back the cornice, laying down along the pitches of the tympanum, and the projecting fillet, closing the lowest part of the tympanum, composed by a row of columns outlining a fake loggia. the capitals of this last decorative element, passing through the entire width of the façade, disappeared, but some stone blocks and traces of the above positioned architrave still remain.

Such columns leaned on a massive offset that is still perceivable below, in correspondence of which a series of semicircular hanging arches lay horizontally, interrupted by a central serliana.

Traces of the ancient trufina or fake loggia still remain on the façade, positioned on the lower part of it, of which remain some capitals and almost all of the original stone blocks, immediately above the decorative XVI century marble facing, witnessing one of the oldest decorative apparatus of the front.

Also the widening of the crypt was carried out in this period. The oldest document stating the existence of the crypt inside the Cathedral date back to 1282: it is a decree of the Bishop ordering that

> (…) a San Crisanto e Daria, nella chiesa di sotto, le porte dovessero essere chiuse nelle ore nelle quali non c'era officiatura

meaning that in the lower church (crypt) the doors had to be closed during the hours when there were no services or ceremonies.

The pre-existing structure placed below the main chapel (dated back to the first years of the thirteenth century) is widened during the last twenty years of the XIII century, opening below the transept, with the same floor level, but lower height of the ceiling respect to the older part.

This last is hence supposed being the one placed below the apsidal area that surrounds the altar with the bodies of the two saints, in which however some more recent columns are placed, belonging likely to the XVI century restoration, respect other columns placed in the widening of the crypt below the transept.

It's worth stressing that in these years the church had, in addition to the main front and the apsidal one on "via del Carbone", also the two laterals freed from other constructions; the left one, confining with the "plathea parva" and connected to the Bishop's Palace just by the body of the transept, and the right one sided by the back-gardens, the original cloister and the cemetery of the Cathedral.

2.3. XV-XVI centuries

The final plan disposition is mainly due to the widening interventions, providing the erection of the chapels along the lateral naves, carried out between half the XV century and the end of the XVI, and the transformation of the apsidal front of the church with the widening of main chapel and the construction of the two side chapels (1505).

Is in this period that the church looses its original external Latin cross plan: the right wing of the transept is aligned to the noble's chapels close by the back-garden (Fiordibelli chapel, 1450; Malaguzzi and Ruggeri chapels, end of the XV century), while on the left wing, beside the newly constructed chapels (S. Girolamo chapel, first years of ‘500; the Notary’s board chapel, 1483; SS. Giovanni e Paolo chapel, 1462; S. Sebastiano chapel, 1518), the Bishop’s Palace takes the main place of the “plathea parva”, closing the left front, once clear from other constructions, of the church, and conforming this way the shape of the actual square.

The first chapels, placed on the right side of the church, surely had a lower foundations height respect to the actual; for this it is likely that they were placed below the former fourth side of the gallery of the rectories, nowadays existing on just three sides.

It is in this period that starts the process of enrichment of the Cathedral that hosts, inside the noble’s chapels, many artworks. Between the end of the XV century and the beginning of the XVI, hence, some important repair work take place, also aimed to adorn the church, also thanks to the patronage of the Bishop Bonfrancesco Arlotti.

The main works of this period are the construction of the new apses, built between 1502 and 1508; moreover the church is subjected to further transformation interventions, such as the erection of the lantern (1451), the elevation of 53 cm of the church’s floor, the lowering of the crypt’s floor below the transept and the construction, on this last, of the two lateral apsidal chapels.

The almost final planimetric disposition is reached in any case only after 1559, by raising the lateral nave’s vaults and the elimination of the Romanesque women’s gallery (1551-1559).

In fact to this period dates back the construction of cross vaults higher than those which had to sustain the floor of the women’s gallery: such cross vaults still exist all along the left nave just above the actual barrelled vault, while on the right nave there is no trace of them.

This fact leads to think that these vaults were realized just on the left side of the church; moreover, just above them it is still possible to perceive the traces of a corridor gallery which had to pertain to the Bishop’s Palace.

The elimination of the left women’s gallery is hence justified both because of the exigency of the realization of this corridor and because of the subsequent need to raise the height of the lateral nave. Also the right side of the Cathedral should have had the same arrangement, but meanwhile the new dispositions of 1599 stopped the finishing of that partial intervention.

Other interventions of a certain importance on the church, contribute to the defining of the definitive aspect (by then) of the building.

Between these the new mannerist disposition of the central nave, from the floor to the trabeation, due to an intervention carried out from 1559 to 1623, directed by Cosimo Pugliani, and the raising of the right side chapels, become too low to be placed side by side with the right nave, at the beginning of the XVII century.

Is then in this period that the original Romanesque pillars are included inside the new structural elements: it is interesting to notice how the several studies that attempted to define the morphology of the original vertical structures sustaining the vaults, gave different results, depicting different typologies existing at that time.

Concerning this last issue, it is useful to remind some of the more interesting studies carried out until now. The first of them was Gaetano Chierici's, examining the cross section of the pillars, hypothesizing that all of them had a cross-shaped section, composed by a central rectangular pillar and by four lateral half-columns. Other historians think that it would be more probable that just some of the pillars had such cross section, namely the first, the fourth and the seventh of each row, that is to say the ones sustaining the main arches, while the others should have a "T" shaped cross section, being lacking of the semi-column toward the central nave, this fact being due to functional reasons.

This last suppositions is supported by the presence of an image of the "Our Lady of the Pillar" painted on the second pillar of the right side (XV century): the fresco on the pillar should have had a plain surface to contain it.

Of the original conformation of the pillars does not exist any visible trace today, even if the XVII century intervention (inclusion of the pillars inside the new structures) was not able to remedy to the irregularities of the distance from a pillar to the other. In fact, it is possible to notice that the distance between the Romanesque pillars does not match the one of the XVII century structures; on the contrary there is a remarkable irregularity on the second and the third span, with a slight tendency to increase the difference gradually when distancing from the entrance.

To this period date back also the reconstruction works of the vault of the choir and the lantern's sustaining arch, dividing the narthex structure from the main nave, and the facing intervention of the façade, made by Prospero Spani, also known as "il Clemente". Close to the half of the XVI century, start the intervention on the façade; after different vicissitudes, the works were not carried to an end (1586), except for the placing of the last statues, in 1621.

2.4. XVII – XIX centuries

The main interventions that regard the constructive transformations of the church in these years, besides the works of decorative completion and external outlining, are the substitution with a dome (1624-1626) of the ancient lantern positioned at the main nave/transept crossing, and the complete substitution of the pre-existing cross-vaulted structures, both in the central than in the lateral naves, with the construction of barrelled vaults (1777).

The Cathedral assumed by then a definitive configuration, slightly partially altered by the reconstruction of the wall of the lantern, damaged by the earthquake of 1832.

3. THE STRUCTURES OF THE CATHEDRAL

3.1. Naves and transept:

It is necessary to make an important distinction between the vertical sustaining structures (walls) and the system of covering mainly composed by vaults. These last had construction phases very diversified and only at the end of the XVIII century were subjected to an organic intervention of structural modification.

The actual disposition of the naves and transept walls is to be found in 1599, when the architect Cosimo Pugliani drafts an arranging intervention for the internal part of the church, aimed to regularize the Romanesque structure, that includes the substitution of the original columns (slightly different the ones from the others) that in some cases are included in the actual pillars. The new entablature, in Doric order, terminates with a moulded cornice, above which remained the XV century cross-vaults, both on the central than on the lateral naves.

On the two arms of the transept remained the big XV century cross-vaults, while, after few years, the ceiling of the main chapel was reconverted by using barrelled vaults. Some historical documents (1600's agreements of Reggio Emilia master-masons, concerning the commitment to bring the structural and decorative works to an end) have interesting notices concerning the construction phases and the materials used. For example, from one of these agreements, it is possible to know that all the decorations, and in particular the cornice, were built by using plaster, probably cast on site on suitable mouldings.

In 1601 the lateral naves underwent the same type of intervention, followed by the reconstruction of the lateral chapels, carried to an end around the year 1608.

The actual vaults of the main nave and of the two arms of the transept result from the intervention of the architect Giuseppe Barlam Vergnani, started in 1777, after the evaluation of different covering arrangements, that had to substitute the XV century cross-vaults.

It was only in 1878 that the newly reconstructed barrelled vaults were decorated by using lacunars, still existing, according to the design of the architect Pio Casoli.

During the same intervention also the paintings underwent a cleaning; due to the lack of any document stating the real entity of the intervention on the paintings, it is supposed that it was a renewal of the pink paintings of the XVIII century.

The actual barrelled vaults of the two lateral naves were realized both with the XVIII century intervention of Vergnani, but their roofing structures followed, in the centuries, very different destinies.

It is likely that the structures of the Romanesque Cathedral, containing the women's galleries, presented the lateral naves with a height remarkably lower than the actual. It is however not clear if the XV century intervention dealing with the construction of the cross-vaults, financed by Giroldo Fiordibelli, regarded just the central nave or implied also the elimination of the women's galleries.

The raising of the lateral naves, involving the construction of new cross-vaults, certainly happened in the north side of the Cathedral. Such vaults stand in fact above the actual barrelled vault that, for this reason, is positioned 40 cm below the analogous vaulting system present on the south side, above which there are no other structures.

3.2. Structures of the Narthex:

The construction of the “pronaos” is to be connected to the 1269 restoration made by Alberico Malaguzzi, when the new façade was renewed. There are no many information about the masonry walls of this part of the structure, even if it is known that until the period of the repair works of Pugliani (1600), on the internal part of the façade, a choir was placed, lately moved to the main chapel.

3.3. Presbytery and choir:

The actual main chapel and the apse find their construction phase during the interventions of 1502-1508. This arrangement is however not visible, because the walls were subjected to following finishing, and the original windows of the apse, whose original conformation is traceable on the north apse, were closed and deprived of the elegant masonry arched lintel.

The actual arrangement of the walls is to be find in the late XIV century intervention carried out by the architect Pio Casoli, who completed the vaults of the church with the fake painted lacunars, used also in the vault of the apse.

Below this decoration, on the walls of the apse, a dark ochre painting takes place, with some portions on which a gilding was proposed, imitating the mosaic technique. Below the upper choirs, built in 1763 by the architect Giovanni Battista Cattani, some decorations on the walls imitate a marble facing.

3.4. The north nave chapels

The actual disposition of the north nave chapels, at least relatively to the structure, can be considered finished around the years ’20 of the XVII century, following the intervention on the three naves, according to Cosimo Pugliani drawings.

Notary’s board chapel

Where the Notary’s board chapel stand, a previous chapel was built between the XV and XVI centuries, by the Archdeacon Simone Calcagni, dedicated to S. Girolamo. The Notary’s board chapel was, at that time, on the following bay. The change happened in 1608, following the decision of the Bishop Claudio Rangone to find a place where to transfer the fresco of Our Lady of the Pillar, that at the end was placed in the Rangone chapel.

Calcagni chapel

The transfer of the Notary’s board chapel caused the change of place between this last and the Calcagni chapel, that took the place of the first.

The Calcagni chapel was built starting from 1483. The arrangement of the chapel by the Calcagni family seemed finished in 1614, when the religious decided to move into it a painted table, coming from the baptistery, representing Our Lady with the saints Girolamo and Caterina from Alexandria.
The chapel underwent to not better defined repair works in 1739, by demand of the chapter.

Estense chapel

The Estense chapel is the last to be built in the Cathedral. A former stair, linking directly the Bishop's Palace to the church, was previously there. The new chapel was built in 1621, and Paolo Messori (architect of the dome) was committed to transfer into it the S. Michele altar, that was previously positioned close to one of the pillars of the presbytery.

Fiordibelli chapel

This is the fourth chapel of the left nave of the Cathedral. Built from 1613, substituting the original of the right nave, his construction phase speeds up in 1624, when, still working on the masonry structure, Guercino was committed to paint the altar-piece, still in the same place, representing the "Assunta" with the Saints Pietro and Girolamo.

San Sebastiano chapel

The last chapel of the left nave still maintains the dedication to S. Sebastiano since the year of construction (1518), when the works started on the drawings of Bartolomeo Spani. The reconstruction (partial, at least) took place in 1622 to adapt it to the general conformation of the church.

3.5. The transept chapels

SS. Sacramento chapel

The construction of the chapel was decided by the bishop Bonfrancesco Arlotti, dating back to 1502, as seat of his own mausoleum.
The chapel underwent several modifications, firstly due to its use as SS. Sacramento chapel, with the insertion of the huge marble ciborium sculptured by Prospero Clemente, and then because of a substantial renovation, carried out by the architect Giuseppe Barlam Vergnani. The new disposition of Vergnani modified both the plan and the elevation of the chapel: the plan, from squared becomes octagonal, to sustain a luminous dome, entirely contained inside the big lantern that rises up on the left apse of the Cathedral.
The chapel underwent recently a general renewal for what concerns the paintings, following the underlying decoration of the XVIII century.

Rangoni chapel

As for the SS. Sacramento chapel, the Rangoni chapel was built in the period of the Bishop Bonfrancesco Arlotti, those days named Canonicals chapel. Also this chapel presented a squared plan, with semicircular apse covered by a wide cross-vault, whose keystone with the coat of arms of the canonicals and the date 1506 is still preserved.

Some modifications to the chapel were carried out by will of the Bishop Claudio Rangone, by consequence of the transfer into it of the image of Our Lady of the Pillar. Some repair works are documented in 1679, after the 1666 reconstruction of the altar.

In any case the definitive transformation was carried out in 1774, following the design of Prospero Zilocchi that implied the reduction of the plan to an octagon, covered by a vault with the shape of a depressed ellipsis

3.6. The south nave chapels

Santa Lucia chapel

The oldest information concerning the first chapel of the right nave, date back to 1440, when Simone Canossa obtained the permission to built a chapel for his family. The construction was not lead to an end, and the heirs, in spite of the presence of Simone’s tomb, lost all of the rights on the chapel.

Madonna Pellegrina chapel

The third chapel of the right nave is also known as Malaguzzi chapel, from the noble family that financed the construction at the end of the XV century.

In 1498 Valerio Malaguzzi died, and Bartolomeo Spani was charged to realize the marbled sepulchre that was finished in 1515.

Crucifix chapel

The last chapel of the right nave was built by Girolamo della Fossa and his brother Nicolò in 1489, taking the place of an ancient stairway. The stone-cutter Andrea de’Bisi was committed to realize the structure; by the agreement it is possible to know that he used “Canossa” stone, and decorated it with pillars, columns and half columns.

The actual morphology of the chapel is to be found in the renewal and unification of the architectural style, following the restoration interventions inside the Cathedral, by the hand of the architect Cosimo Pugliani, starting from 1600.

4. TECHNICAL REPORT ON THE STATIC MONITORING

4.1. Introduction

The following report regards the results of the diagnostic survey performed on the masonry structures of the S. Maria Assunta Cathedral of Reggio Emilia by the R.teknos s.r.l. company (Bergamo, Italy), on behalf of the Reggio Emilia-Guastalla diocese (committee for the restoration of the S. Maria Assunta Cathedral of Reggio Emilia). A static monitoring system was also positioned on the structures of the Cathedral.

The investigation regards the morphology and the consistency of the masonry of the crypt's two main pillars, of a lateral pillar (by performing 3 horizontal core samples), and of the masonry of the crypt's underlying room, where the roman mosaic is placed (by performing 2 horizontal and 1 vertical core samples on the foundation structure).

The samples have been taken by using thin wall core barrels with diamonded crown wheel (76 mm external diameter), and the hole, once extracted the sample, has been inspected with a video endoscope. In addition, a monitoring system (aimed to detect the behaviour of the principal load-bearing structures) was placed, focused on:

- measurement of the relative displacements between the vertical structures (pillars, columns and perimeter walls).
- measurement of the width of the main fissures;
- measurement of the settlements of the foundation soils below the two main pillars of the crypt;
- measurement of the air temperature;

The monitoring system chosen is "semiautomatic", based on fixed measurement devices equipped with electric transducers connected to a multi-switch panel, and by a removable electronic read-out unit.

4.2. Description of the inspection techniques

Core samples

The core samples allow to analyze the morphology and the texture of the masonry and to extract samples of the materials constituting the structure. The core samples performed on the structures of the foundations are mainly aimed to determine the depth of the foot of the foundation system, whilst for what concerns the elevation structures of the walls, the most important information arising from the test are the composition of the inner part of the masonry, e.g. presence of voids, multi leaf walls, thickness of the external layers and the internal infill, existence of masonry with different composition.

The samples extracted are disposed in boxes, marked with the indication of the serial number of the test and the depth of the drilling, and photographed directly on site. The material extracted is described by detailed stratigraphies, distinguishing the presence of mortars, pieces of stones and brick elements.

Video Endoscopy

The video endoscopy allows to examine in detail the lateral surface of the boring, where the masonry keeps its morphological structure, and may integrate the information obtained by the sample extracted, giving the possibility to individuate and to measure the internal cavities.

To perform the prospecting inside the core sample borings (diameter 76 mm), a camera of small diameter (24 mm, sensitivity 1 Lux) is used, connected to a video digitizer connected to a laptop, allowing to effect digitalized shootings at different depths.

Positioning of the inspections

In the following scheme, at the level of the crypt, the positioning and the number of the inspections are shown:

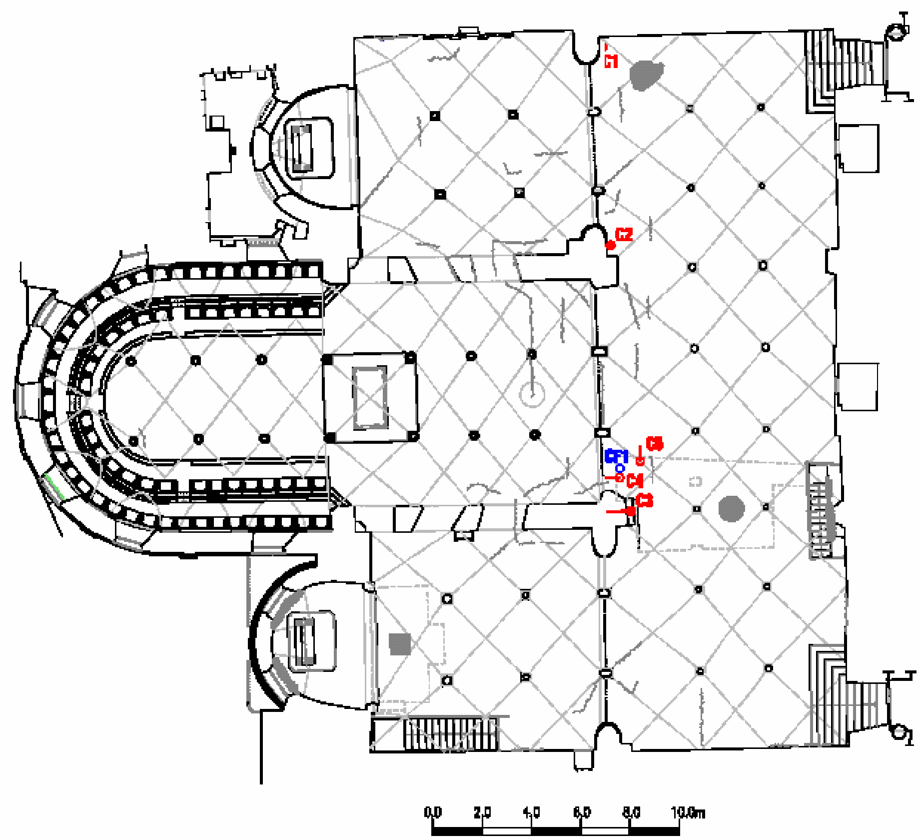


Figure 6:

Cn: core samples performed on vertical structures and inspections with video endoscope (red)

CFn: core samples performed on the foundation structures and inspections with video endoscope (blue)

n is the progressive number of the test

Results of the corings

core samples on the foundation structures

The structure tested is completely foundation-less; few centimetres below the floor of the crypt a clayey soil is found (see figure below)

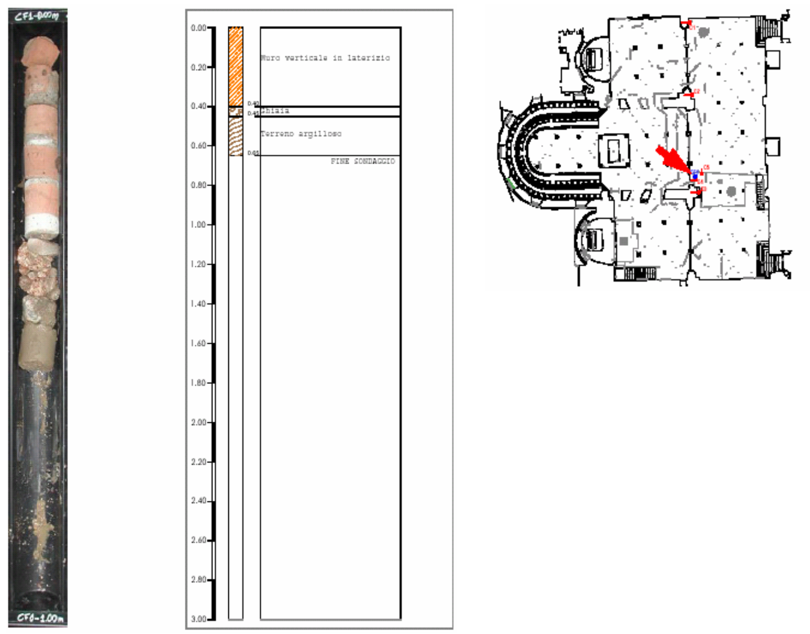


Figure 7: Core sample CF1

core samples on vertical structures

The core samples C1,C2 and C3, carried out respectively on one of the perimeter pillars of the crypt and on the two central pillars, encountered brick masonry presenting in general poor mechanical characteristics.

In particular, inside the masonry of the pillars, some pieces of disarranged bricks and several cavities due to the scarce cohesion of the mortar, which has been often washed away by the water used for the perforation, were found.

The core samples C4 and C5 performed on the room underlying the crypt, shown brick masonry walls positioned against the confining ground, with a thickness of 0,20 m.

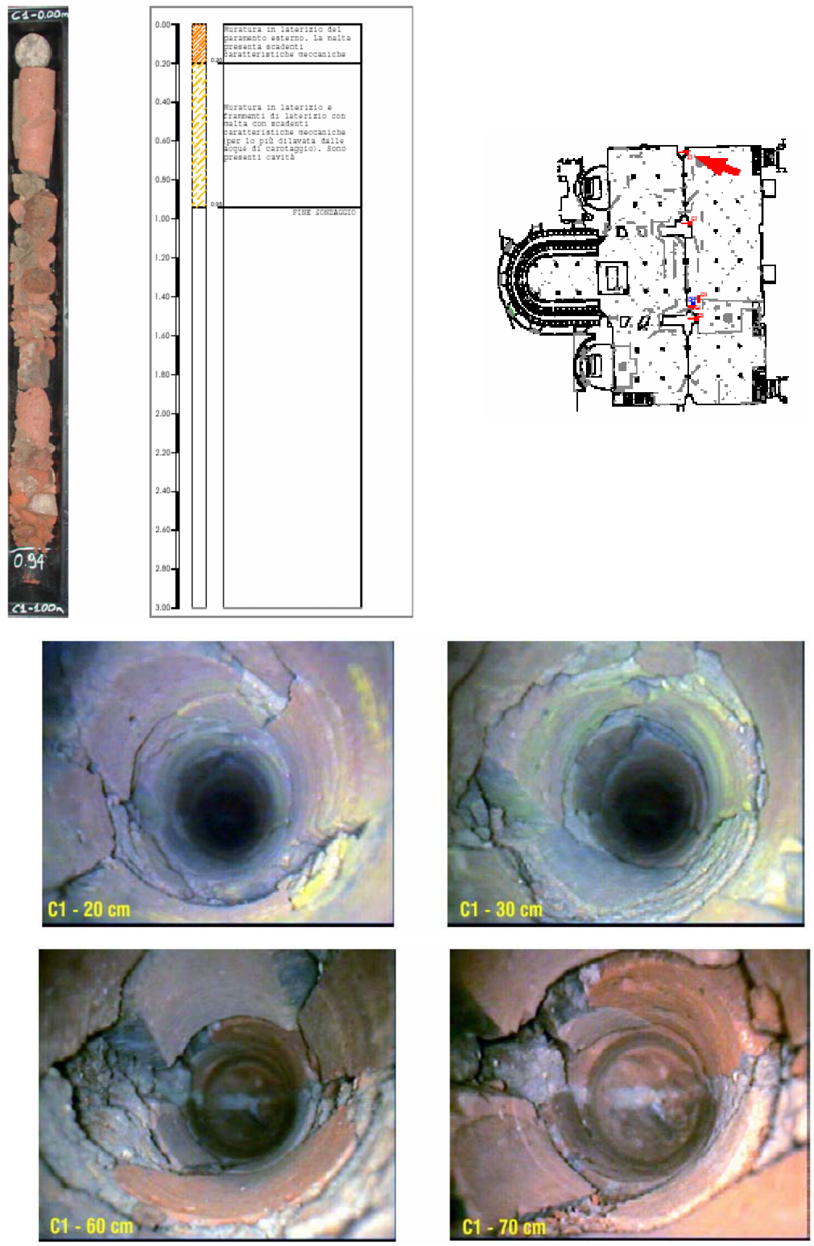


Figure 8: Core sample C1

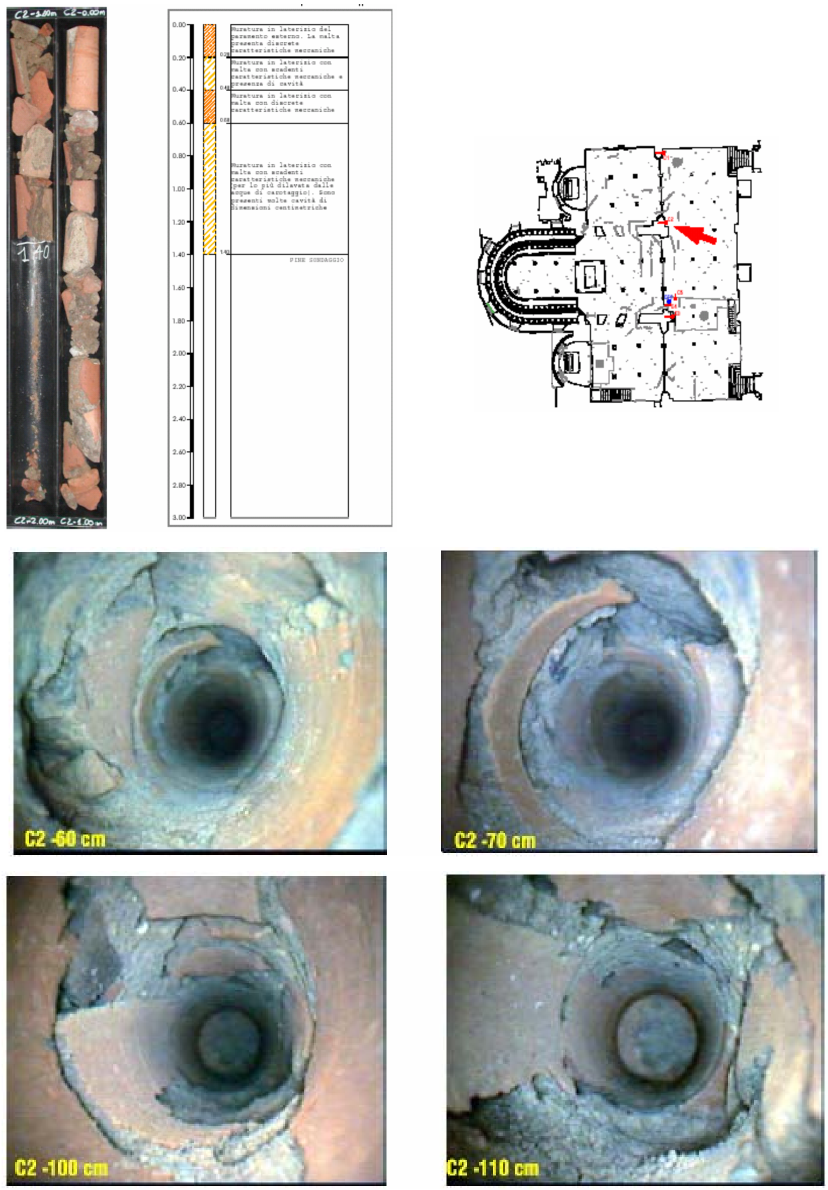


Figure 9: Core sample C2

4.3. The structural monitoring system

The monitoring system positioned on the structures of the S. Maria Assunta Cathedral of Reggio Emilia is composed by:

- 10 long base cable extensometers, to detect the relative displacements of the vertical structures;
- 13 electric extensometers, to measure eventual variations in the openings on the main fissures;
- 2 multi base extensometers, equipped with 3 measurement bases each, to evaluate the settlements of the foundations of the crypt's pillars with respect to points of the underlying soil, at the depths of 5, 10 and 15 m;
- 2 measurement panels, equipped with switch and thermometer, to perform the read-outs and to control the temperature.

Figure 10: cable extensimeter EF1

Figure 11: cable extensimeter EF3 and electric extensimeter EL9

Positioning of the measuring devices

In the following scheme, at the level of the crypt, the positioning and the number of the measuring devices are shown:

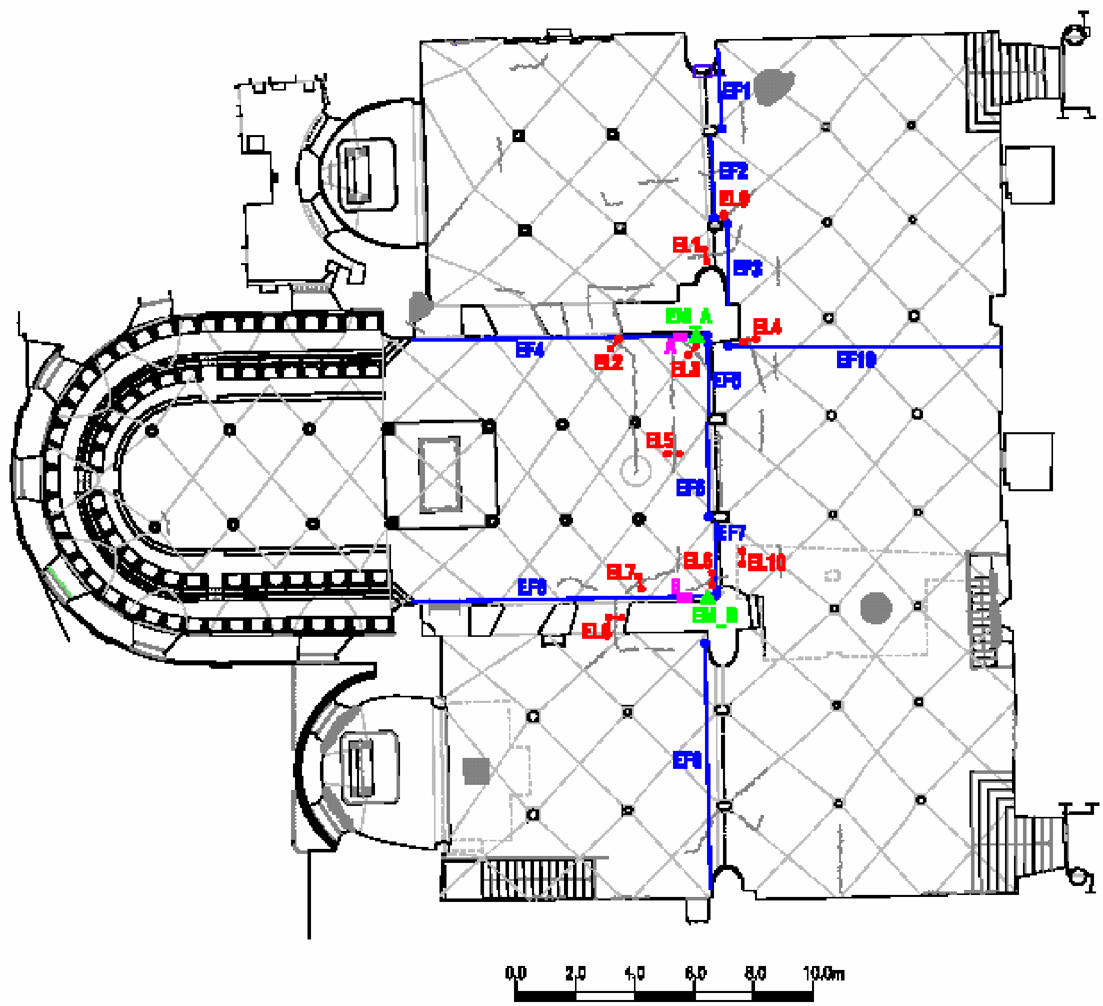


Figure 12:

EFn: long base cable extensometers (blue)

ELn: electric extensometers (red)

n is the progressive number of the position

The multi base extensometers are shown with the acronym **EM_A, EM_B** (green)

A,B: measurement panels (fuchsia)

The periodic read-out of the devices is carried out with a removable electronic unit.

In the following scheme, at the level of the church floor, the positioning and the number of the measuring devices are shown:

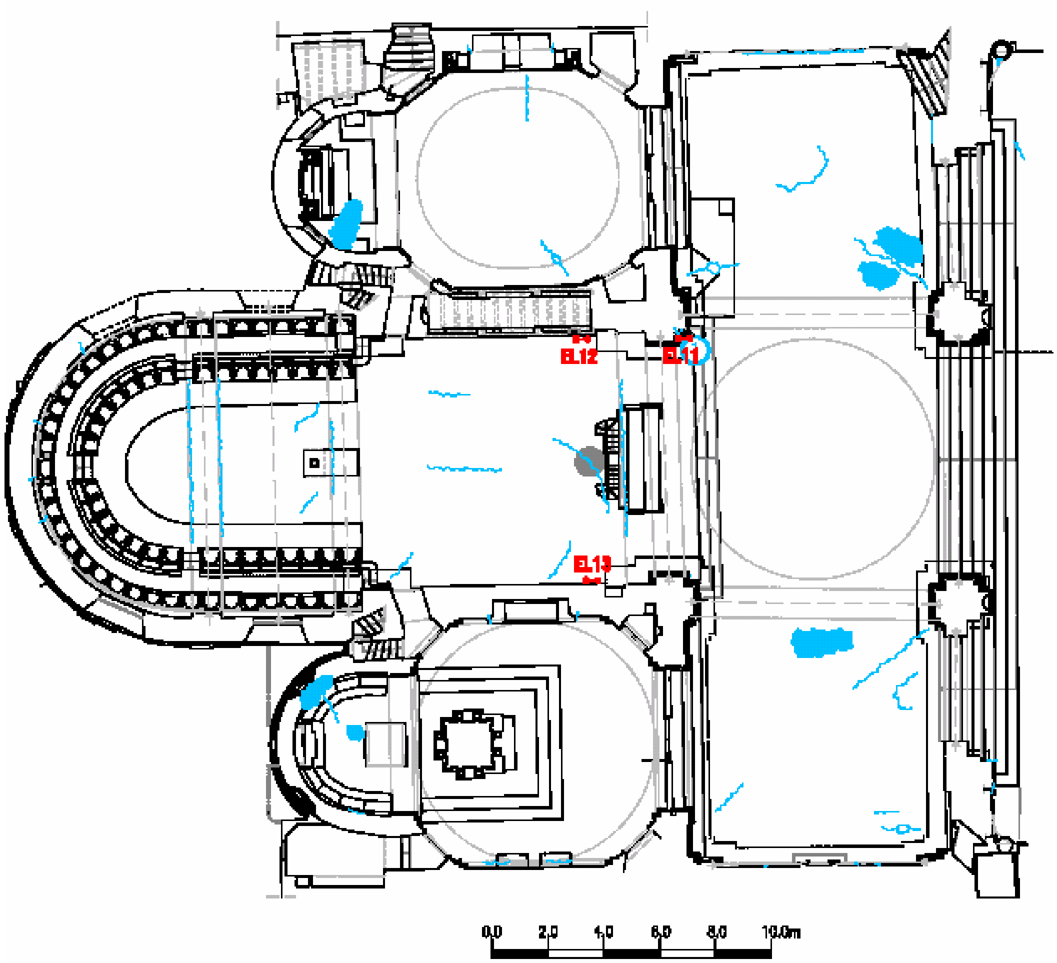


Figure 13:

ELn: electric extensometers (red)

n is the progressive number of the position

Description of the measuring devices used

The cable extensometers allow to check the variations, in terms of relative displacements, between two opposite vertical structures, at regular time intervals. The device is composed by an invar steel cable, kept in tension by a calibrated spring and by a potentiometric transducer, electrically insulated, ranging between 0,0 and 50,8 mm.

The device is connected by a multipolar cable to the electric panel, being this last periodically connected to the manual read-out unit.

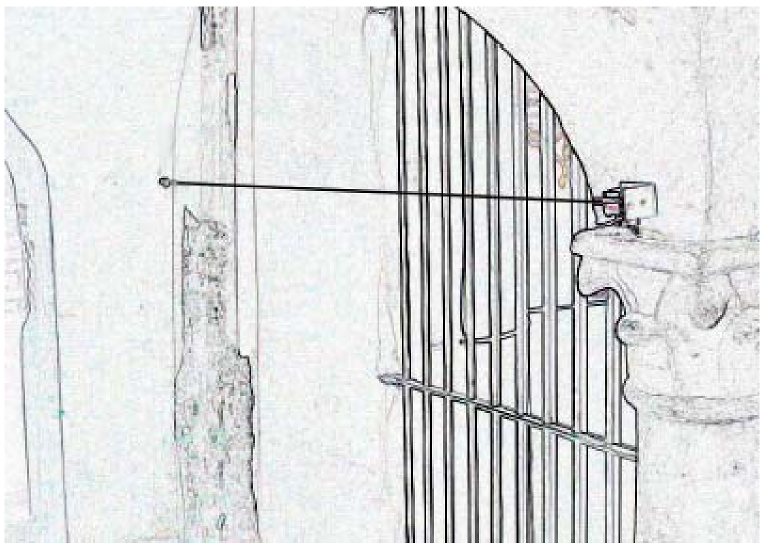


Figure 14: cable extensimeter

the fixed electric extensometers, allow to detect an eventual variation of the opening of the main fissures. These devices are fixed to two stainless steel pins, positioned at the sides of the opening and fixed to the wall with epoxy resin. The coupling of the measuring device to the rigid pins is realized by ball and socket joints, that allow the movement of the instrument on three orthogonal axis avoiding any flexural stresses on the transducer.

A linear potentiometric electric displacement transducer, electrically insulated and waterproof, ranging between 0,0 and 12,5 mm, is inserted in the device.

The device is connected by a multipolar cable to the electric panel, being this last periodically connected to the manual read-out unit.

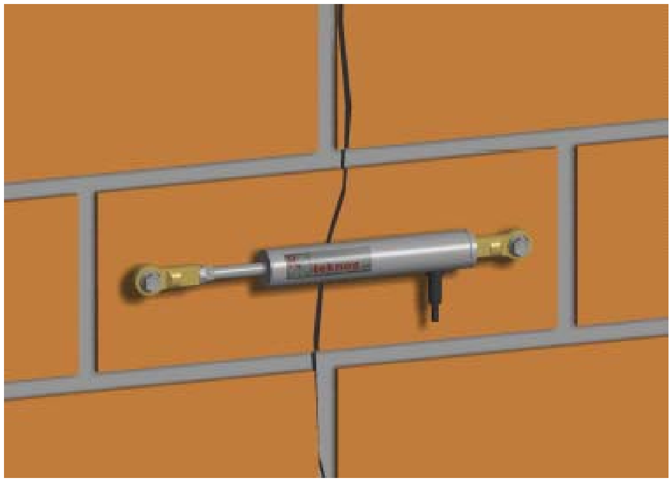


Figure 15: electric extensimeter

the multi base extensometers allow the measurement of the relative displacements (settlements) between points of the soil aligned on the same vertical at different depths. The measurement bases consist in fibreglass poles (diameter 6 mm) which are anchored at their lower extremities to the ground by a galvanized steel bar fixed to the ground itself by injections, while at the upper end are fixed to the displacement transducers connected to the foundation structure.

The fibreglass poles are covered by a Rilsan nylon flexible pipe. The device is connected by a multipolar cable to the electric panel. The displacement is measured by the value D = L x C, where D is the displacement in mm, L is the read-out in mV and C is the instrument constant.

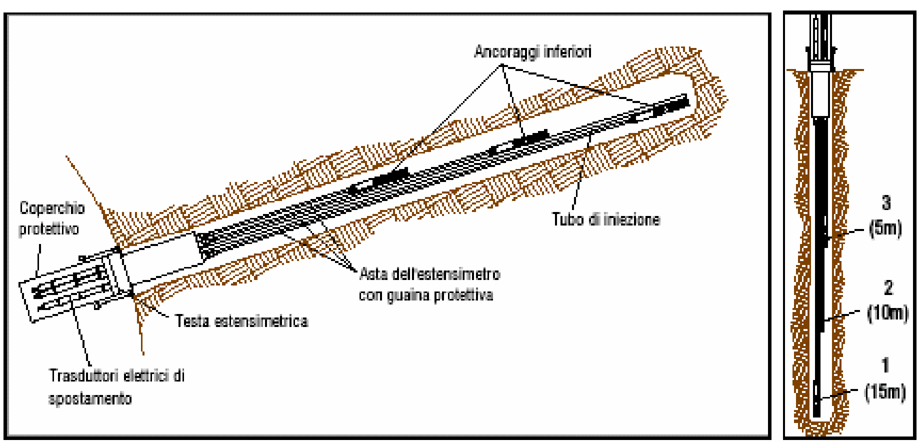


Figure 16: multi base extensimeter

The digital read-out unit is composed by an electronic portable system with rechargeable batteries. The connection to the panel, to which arrive from the measuring devices the multipolar cables, is carried out by a 6 poles jack. The measure is shown on a 4 digit display.

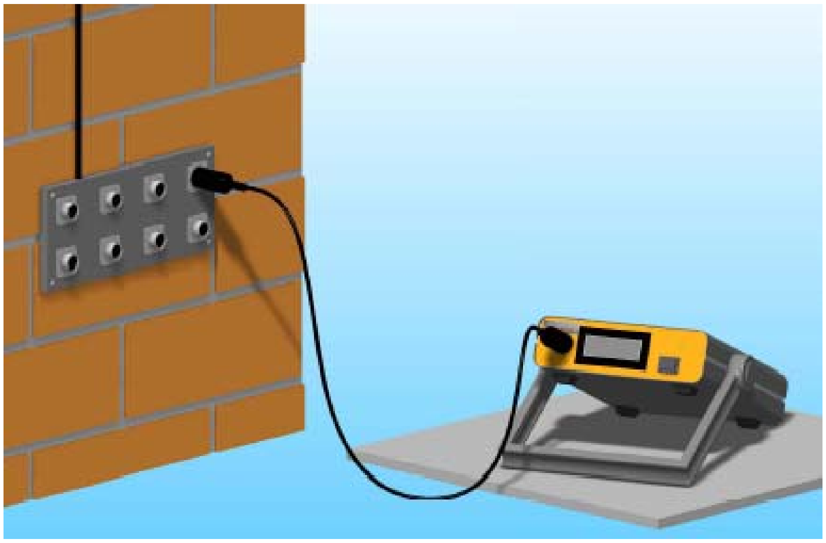


Figure 17: digital read-out unit

Figure 18: cable extensimeter EF9 and electric extensimeter EL8

Figure 19: electric extensimeter EL10 and read-out of the displacements with the electronic switchboard

Figure 20: measurement panels A and B and view of the top of the multi-base extensometers

5. SEISMIC DATA

5.1. Introduction

The seismicity of the Reggio Emilia area is well documented. Low magnitude earthquakes are typical of the region and generally localize all along the pre-appennines hills strip.

During the past centuries the earthquakes that struck the Reggio Emilia area never exceeded the VIII Mercalli Cancani Sieberg seismic intensity, manifesting lower values respect other Italian regions.

The main seismic events happened in 1465 (VI/VII Mercalli Cancani Sieberg seismic intensity), in 1547 (VII MCS), in 1832 (VII/VIII MCS) in 1996 (VII MCS), besides low magnitude events of the XX century.

The last remarkable seismic sequences in the area happened in 1996 (characterized by a main shock on the 15th of October, followed by a sequence of minor tremors during the whole month of October) and in 2000.

5.2. Earthquakes (1000 – 1899)

Earthquakes which struck the Reggio Emilia area until 1900 were (Reggio Emilia latitude is 44,71 North, longitude is 10,63 East):

- 31st of January, 1345: VII MCS, latitude 44.72N, longitude 10.67E;
- 15th of April, 1465: VIII MCS, latitude 44.83N, longitude 10.50E;
- 1485: VI MCS, latitude 44.67N, longitude 10.67E;
- 4th of October, 1522, 23:00h: VII MCS, latitude 44.67N, longitude 10.67E;
- 1524: VII MCS, latitude 44.67N, longitude 10.67E;
- 10th of February, 1547, 13:20h: VII MCS, latitude 44.70N, longitude 10.63E. Several chimney tops, roofs and cornices fell down, damages in the Cathedral and St Agostino towers and in the St Prospero church and arcade;
- 24th of August, 1548: VI MCS, latitude 44.70N, longitude 10.67E;
- 27th of December, 1549, 11:00h: VI MCS, latitude 44.70N, longitude 10.67E;
- 24th of May, 1591: VII MCS, latitude 44.70N, longitude 10.67E;
- 6th of January, 1608, 13:00h: VI MCS latitude 44.67N, longitude 10.67E;
- 11th of September, 1831, 18:15: VII-VIII MCS latitude 44.75N, longitude 10.55E; following tremors for the remaining period of the year. Several chimney tops, tiles and debris fell down,

cracks opened in the walls; damages were detected in the town hall and in the st Domenico and St Mauro barracks;

- 13th of March, 1832, 7:45h: a main shock VII / VIII MCS (latitude 44.83N, longitude 10.50E) and several successive, caused the fall of 6.000 chimneys, the opening of cracks in walls and vaults of many buildings and damages in towers. Particularly affected were the lower class and the Jewish ghetto houses.
- 26th of February, 1885, 20:46h: VII MCS latitude 44.70N, longitude 10.63E;

5.3. Earthquakes (1900 - today)

Earthquakes which struck the Reggio Emilia from 1900 up to today were:

- 13th of January, 1900, 3:30h: III MCS, latitude 44.67N, longitude 10.62E;
- 25th of February, 1904, 22:59h: III MCS, latitude 44.70N, longitude 10.67E;
- 10th of August, 1915, 23:10h: VI MCS, latitude 44.73N, longitude 10.46E;
- 6th of May, 1918, 8:05h: V MCS, latitude 44.67N, longitude 10.60E;
- 6th of May, 1950, 3:43h: IV MCS, latitude 44.92N, longitude 10.55E;
- 12th of June 1959, 10:00h: III MCS, latitude 44.80N, longitude 10.60E;
- 3rd of April, 1966, 13:00h: V - VI MCS, latitude 44.80N, longitude 10.90E;
- 9th of November, 1983, 16:29h: VII MCS, latitude 44.70N, longitude 10.34E. It caused small cracks and plaster detachment, chimney and cornices, rotation of statues, pouring off of liquids from vessels, falling of objects from shelves, moving of pieces of furniture;
- 24th of April, 1987, 20:00h: VII MCS, latitude 44.81N, longitude 10.72E, a main shock with following tremors;
- 15th of March, 1988, 12:03h: VI MCS, latitude 44.78N, longitude 10.68E;
- 15th of October 1996, 9:56h: VII MCS, latitude 44.78N, longitude 10.61E, a main shock with following tremors. Damages were limited, some chimney pots, tiles, cornices fell down.
- 18th of June, 2000, 9:42h: VI – VII MCS.