DAMAGE IN ANCIENT CHURCHES DURING THE 9TH OF JULY 1998 AZORES EARTHQUAKE

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SUMMARY

In the 9th of July of 1998, an earthquake of magnitude 6.2, on the Richter scale, occurred in the Azores Islands. The earthquake was registered in almost all the islands of the archipelago but with structural damage occurring mainly in the Faial and Pico islands. Massive damage occurred, with intensities larger than VIII in the Modified Mercalli scale. Some villages were almost completely destroyed.

This paper focuses on the earthquake performance of ancient churches of the Faial and Pico islands and aims at describing and interpreting the most significant types of damage sustained by this type of unreinforced stone masonry structures, with large exterior walls, inner arches and light wooden roofs.

The study presented on this paper is based on the in-situ damage observation on 30 churches. The damage modes and possible collapse mechanisms were identified to all the churches and the damage level of each one were quantified based on a set of indicators. The observed damage was correlated with the structural typology, with the quality of the construction and with past interventions suffered by the churches.

The observation of the different constructions allowed the clear identification of typical patterns of structural damage. These patterns and the observed damage levels are very dependent on the seismic action level, on the quality of the masonry used in the constructions and on the existence of structural interventions made in the sequence of previous seismic events.

INTRODUCTION

On the 9th of July of 1998, an earthquake of magnitude 6.2, on the Richter scale, occurred in the Azores Islands. The earthquake was registered in almost all the islands of the archipelago but with structural damage occurring mainly in the Faial and Pico islands.

Especially in some zones of the Faial Island, a massive destruction occurred, with registered intensities larger than VIII in the Modified Mercalli scale. In this island, 8 people were killed and a large percentage of the population lost their homes. Some villages were almost completely destroyed.

The larger structures that were hit by the quake were the churches, most of them ancient churches with masonry structures. Since the population is deeply religious there is a relatively high density of churches in the territory.

This paper focuses on the earthquake performance of ancient churches of the Faial and Pico islands and aims at describing and interpreting the most significant types of damage sustained by this type of structures.

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BRIEF DESCRIPTION OF THE EARTHQUAKE

The Azores islands are characterized by an important and constant seismological activity due to its location. The archipelago is located near the crossing of the middle Atlantic rift and the separation between the European and the African tectonic plates.

In the past, other important seismic crisis affected the islands that are object of this study. In Faial there was a major event in 1926, which caused large destruction on the city of Horta, and in 1957, during the eruption of the Capelinhos volcano, the island trembled for almost one year. An important earthquake affected the Pico Island in 1973.

The epicenter of the earthquake was located in the ocean, between the two most affected islands, Faial and Pico, about 5 km from the northeast corner of the Faial island, as shown in figure 1. In this figure are also presented the isoseismals, based on locally collected information.

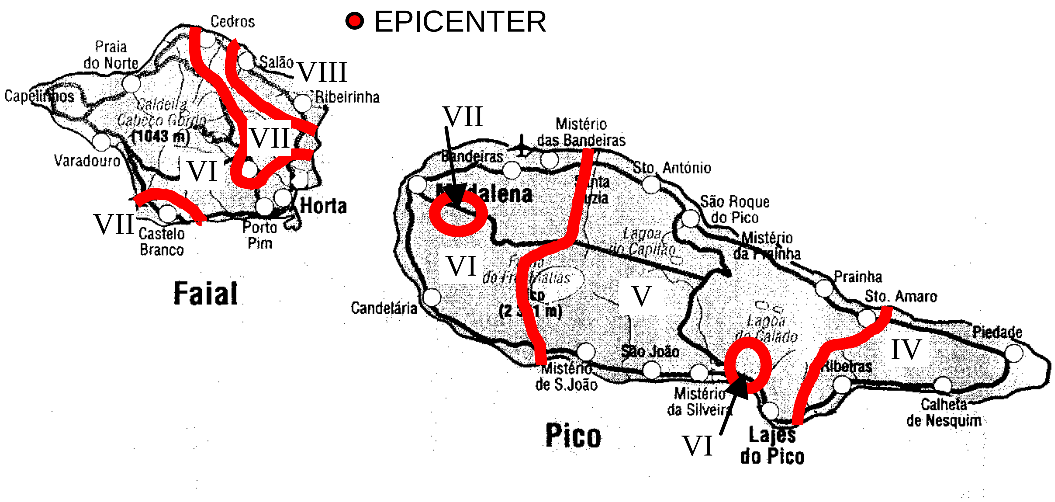

Figure 1 – Epicenter location and isoseismals of the 9th July of 1998 Azores earthquake (Oliveira, 1999; Nunes, 1998).

STRUCTURAL CHARACTERISTICS OF THE OBSERVED CHURCHES

The recognition mission team analysed a total of 30 churches (Azevedo et al., 1998). The majority is ancient masonry churches. Only 3 of the total visited churches were reinforced concrete built. These late 3 examples were located in areas severely affected by previous earthquakes, and resulted from substitutions of churches severely damaged in the 1957 crisis.

The typical configuration of the observed masonry churches is a main body with a central nave and two laterals, smaller than the first, and the apse in the extension of the central nave. The main structure of the main body is composed by a system of arches in the transverse and longitudinal directions. The ceilings are made of light timber roofs with, in some cases, an internal plaster covering. In the facade most of the churches present a fronton in the top. There are also examples of smaller churches, with just one nave.

With just one exception, all the churches presented at least one tower. In the old masonry churches, the towers were connected to the main body. A different solution appears in two of the reinforced concrete churches where the towers are separated elements. In the masonry churches several possible combinations are present: one central tower in the facade, two lateral towers or one lateral tower. All the towers have bell cells.

Most of the churches have adjacent buildings, attached to the posterior part of the main body.

With little exceptions the masonry churches presented external walls composed by irregular blocks.

The structure of the observed reinforced concrete churches is composed by a series of one bay frames in the transverse direction, supporting the cover of just one interior nave.

In figures 2 and 3, the location of the analysed churches is presented. In tables 1 and 2 the description of the churches in terms of their structural material is listed.

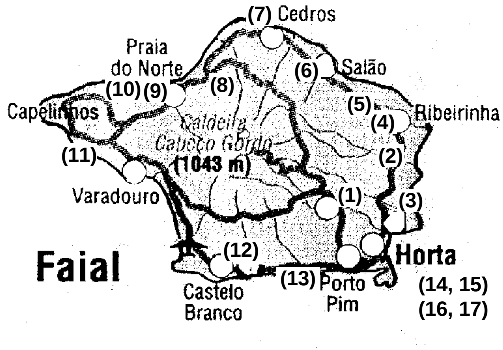

Figure 2 – Localisation of the Faial island churches.

Table 1 – Faial island churches (description).

Nº	Church	Material
1	Flamengos	Masonry
2	Pedro Miguel	Masonry
3	Praia de Almoxarife	Masonry
4	Ribeirinha	Masonry
5	Espalhafatos	Reinf. Concrete
6	Salão	Masonry
7	Cedros	Masonry
8	Ribeira Funda	Masonry
9	Praia do Norte	Reinf. Concrete

Nº	Church	Material
10	Norte Pequeno	Reinf. Concrete
11	Capelo	Masonry
12	Castelo Branco	Masonry
13	Feteira	Masonry
14	Ermida do Pilar	Masonry
15	Angústias	Masonry
16	Conceição (Horta)	Masonry
17	Matriz (Horta)	Masonry

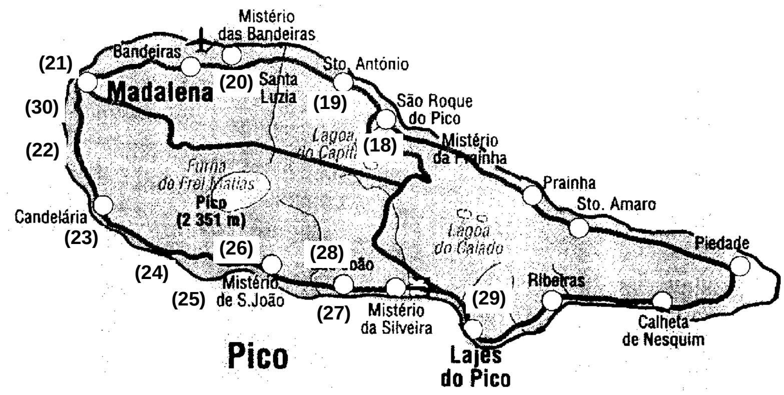

Figure 3 – Localisation of the Pico island churches.

Table 2 – Pico island churches (description).

Nº	Church	Material
18	S. Roque	Masonry
19	S. Luzia	Masonry
20	Bandeiras	Masonry
21	S. Madalena	Masonry
22	S. António Monte	Reinf. Concrete
23	Candelária	Masonry
24	S. Mateus	Masonry

Nº	Church	Material
25	S Caetano	Reinf. Concrete
26	S. Margarida	Masonry
27	S. Bartolomeu	Masonry
28	S. João	Masonry
29	Lajes	Masonry
30	Criação Velha	Masonry

DAMAGE OBSERVATION

The immediate objective of the recognition mission was to evaluate the extension of damage and the possibility of making a normal use of the churches.

Following a previously defined set of rules, the team performed a rigorous inspection of all the churches, with a complete register of all the observed damage. Special attention was given in the analysis of potential collapse mechanisms, like movements of the walls, extensive crack opening, relative movements of different parts of the structure, failure of the columns, and others examples. Previous interventions on structural rehabilitation or reinforcement were identified and registered.

Following the local inspection and based on the analysis of the collected information, the team decided about the possibility of making normal use of the churches. For this purpose the churches were classified in one of the four levels presented in Table 3.

Table 3 – Adopted levels of damage characterization.

Level	Description
A	No damage – Immediate use
B	Low damage – Immediate use
C	High damage – Use after repairing
D	Severely damaged – Impossible to use

ANALYSIS OF POTENTIAL COLLAPSE MECHANISMS

With all the data collected in the post-earthquake visit to the Faial and Pico islands, a study was developed in order to identify and understand the possible mechanisms of collapse of ancient masonry churches.

For the identification of the collapse mechanisms the methodology presented by Lagomarsino (Lagomarsino, 1998) was followed. This methodology was developed after the Umbria earthquake of 1998, and was applied in the analysis of the behaviour of the churches in that region.

According to this methodology, the interpretation of the churches seismic behaviour is made through the comparison of the observed damage with a certain number of characteristic damage patterns. In figure 4 is presented the chart proposed by Lagomarsino (Lagomarsino, 1998), with 16 different collapse mechanisms.

In the analysis of the Faial and Pico data were identified some further potential collapse mechanisms that did not fit the ones presented in figure 4. Those were the mechanisms involving longitudinal or transversal movement of the interior arches in the churches with more than one nave, or out of plane movements of the external walls. Other type of damage was the fall of decorative elements mainly in the facade. Although this late example of damage could not be considered as a collapse mechanism, it was found to be important enough to be referred since it can cause severe damage to other structural elements such as ceilings and even injuries to people. In table 4 the description of the complementary potential mechanisms of collapse are described.

Table 4 – Further characteristic damage patterns (in addition to those defined by Lagomarsino, 1998).

Mechanism	Description
17	Movement of the transversal arches
18	Out of plane movements of the walls
19	Movement of the longitudinal arches
20	Fall of facade decorative elements

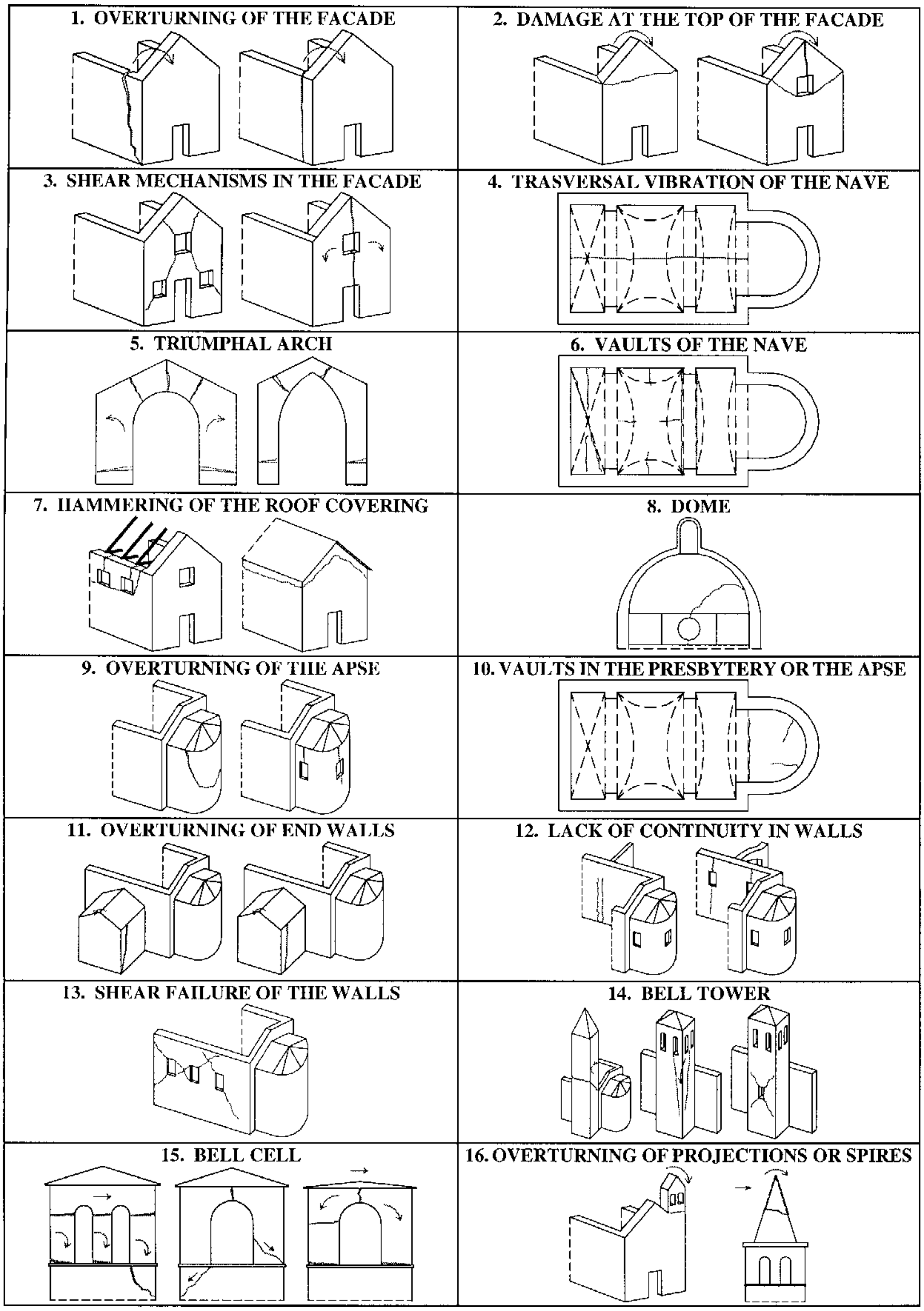

Figure 4 - Potential collapse mechanisms (from Lagomarsino, 1998).

The identification of the collapse pattern in each church was made with a classification of the amount of damage associated to each mechanism type. In the definition of the damage severity the following simplified scale was adopted:

1 - Observed mechanism but with light damage

2 - Fully developed mechanism but repairable tom some extent

3 - Severe damage, near collapse or collapse

The result of the identification of the collapse mechanisms with the classification of the severity of each mechanism is presented in table 5. The classification presented in the last column of the table is related to the evaluation of the possible use of the church according to the definition presented in table 3.

Table 5 – Characteristic damage patterns identified according to its severity.

Nº	Church	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	U
1	Flamengos		2	1				2				3			1						3	C
2	Pedro Miguel									3	3	3		2	2			2				D
3	Praia de Almoxarife		2								1	2				2					1	B
4	Ribeirinha										3							3	3			D
6	Salão																					D(1)
7	Cedros														2	2						C
8	Ribeira Funda			2							2			2		2						C
11	Capelo																					A
12	Castelo Branco		2				2	2						1		2	3					B
13	Feteira		2	1				1		1				1	1	2		2				C
14	Ermida do Pilar										1			1								B
15	Angústias		2	2								1			1	1					3	B
16	Conceição (Horta)													1						2		B
17	Matriz (Horta)						1															A
18	S. Roque (Pico)										1			1								A
19	S. Luzia (Pico)													1	1							A
20	Bandeiras (Pico)		2								2			1	2	2					1	C
21	S. Madalena (Pico)			1														2				C
22	S. Ant. Monte (Pico)		2								1			1								B
23	Candelária (Pico)		1	1			1							1								A
24	S. Mateus (Pico)	1												1				1				B(2)
25	S Caetano (Pico)											1		1								B
26	S. Margarida (Pico)																					A
27	S. Bartolomeu (Pico)										1			1						1		B
28	S. João (Pico)	2		1				1							2	2					1	B(3)
29	Lajes (Pico)																					A
30	Criação Velha (Pico)																					A

(1) – Total collapse; (2) – Important plaster fall; (3) – Problems in the tower.

Observing Table 5, it can be said that there is a good correlation between the classification regarding the decision about the possible use, which was done immediately after the visit, and the damage interpretation which was carried out later.

The most observed damage pattern, although not very severe, corresponds to the shear failure of the walls. The most severe ones correspond to overturning of the end walls and failure of vaults in the presbytery. Other frequently observed damage patterns are damage in the frontons, shear in the façade and damage in the bell towers and cells.

In figure 5 to 10 some examples of the identified potential collapse mechanisms are presented. In figure 5 one can see the severely Ribeirinha (no. 4) church with a clear view of the collapse of the lateral nave due to an out plane movement of the exterior wall (18). In this figure severe damage is also visible in the exterior walls of an adjacent building.

The Pedro Miguel church (no. 2) was one of the most damaged and was in a pre-collapse stage. As it can be seen in figure 6, there is evidence of extended shear failure of the walls (13). This church presented also large displacements on the interior columns and shear failure of the tower walls (14).

In figure 7 one can see an example of hammering of the roof covering (7) that occurred in the Flamengos church (no. 1).

Other problem that was registered in a large number of churches was the damage in the arches due to movements in the transverse direction in relation to the main body of the church. In figure 8 is presented one of the most damage churches, the Ribeirinha church (no. 4), where this type of collapse mechanism (10) was present with total collapse of the arch between the nave and the apse.

In figure 9 an example of failure of the fronton in the top of the facade (2) is presented. This was another of the most commons examples of damage registered in the observed churches, in this case the Feteira church (no. 13). This decorative element in most of the situations is not connected to the rest of the structure except on its base. That means that it acts like a cantilever for movements in the perpendicular direction of its plane. The vulnerability of this type of facade for movements in the pointed direction is evident.

In figure 10 one can see the damage occurred in the Castelo Branco church (no. 12) spire (16). This type of damage could be observed in some other churches although not so severe.

Figure 5 – Ribeirinha church.

Figure 6 – Pedro Miguel church.

Figure 7 – Flamengos church.

Figure 8 – Ribeirinha church.

Figura 9 – Feteira church. **Figura 10 - Castelo Branco church.**

CONCLUSIONS

The damage patterns observed in the churches hit by the 9 of July 1998 Faial earthquake are in accordance with the damage patterns observed during other earthquakes. The classification of damage patterns proposed by other authors was successfully used with minor adaptations.

This classification, together with a case by case evaluation of the damage severity are important tools for an immediate assessment of the extension of damage to this type of structures, for the necessary evaluation of the possibility to use them and finally to support the necessary rehabilitation interventions.

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REFERENCES

Azevedo, J.; Bento, R; Guerreiro, L.; Lopes, M. and Proença, J. [1998] “IST mission to Faial and Pico after the 9 of July, 1998 Azores earthquake – Inspection of schools and churches (in portuguese)”, ICIST report, Lisboa.

Lagomarsino, S. [1998] “A new methodology for the post-earthquake investigation of ancient churches”, XI European Conference on Earthquake Engineering, Paris.

Nunes, J; França, Z.; Oliveira, C. and Ortiz, R. [1998] “Seismic intensities distribution on the Pico island for the 9 of July, 1998 earthquake: morphological, geological and tectonical conditions (in portuguese)”, APMG First Symposium on Meteorology and Geophysics, Lagos, Portugal (in press).

Oliveira, C. [1999], personal communication..