

# Numerical characterization of the structural behaviour of the Basilica of Pilar in Zaragoza (Spain). Part 1: Global and local models

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## Abstract

The Basilica of Pilar, located in the city of Zaragoza, is one of the most famous Spanish temples. Several domes of this church contain frescoes painted by Francisco de Goya, which have suffered damages in the past decades due to various pathologies. The frescoes of the Regina Martirum dome are being restored at the present time. In this paper, we present a set of structural models of the entire temple and local models of the Regina Martirum dome by discussing and comparing the obtained results. The main objective of the research was to identify the current structural state of the church, its safety level and the relationship between the structural behaviour and the damages observed. The behaviour of the main material used in the construction, brick masonry, was simulated first with linear elastic isotropic models and later with several non-linear isotropic models including brittle behaviour in tension and plastic behaviour in compression. In addition, we consider the historical construction and the reinforcement works added to the structure in its history, with the purpose of testing the finite element models by reproducing the pathologies described from the beginning of the current Baroque construction. © 2007 Elsevier Ltd. All rights reserved.

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## 1. The building and its history

The Basilica of Pilar is one of the most important worship places in Spain. The actual temple is a large complex brick masonry construction with rectangular plan of about 100 m long and 70 m wide. Their construction process was difficult and took long time [1]. In the current site, a small Visigothic chapel was first built more than a thousand years ago; then later on, it became a Romanesque church with cloister that suffered after the Gothic enlargement.

Nevertheless, all the aforementioned constructions were small in size compared with the huge expansion taken place

in XVII century when the Baroque church project was set up by the Spanish architect Ventura Rodriguez. In addition a reorientation to the main axis of the temple took place and part of the new construction was erected on terrain taken to the adjacent river. Fig. 1a presents a sketch describing the position of each building along the history and some plans; Fig. 2 shows several views of the actual Basilica.

The temple is composed of three longitudinal naves (Fig. 1b). The central one contains the main dome of circular design and double shell, and two more domes of elliptical shape (Fig. 1d). The two lateral naves have eight more domes placed at a second level, the Regina Martirum dome belongs to this second level, located next to the central dome (Fig. 1c). Surrounding the principal naves there is a series of chapels and rooms with up to 11 additional domes at the third lower level. The domes at the third level are located between the 16 external buttresses and the four towers, of more than 90 m height, that mark the corners of the building and form the external perimeter. The

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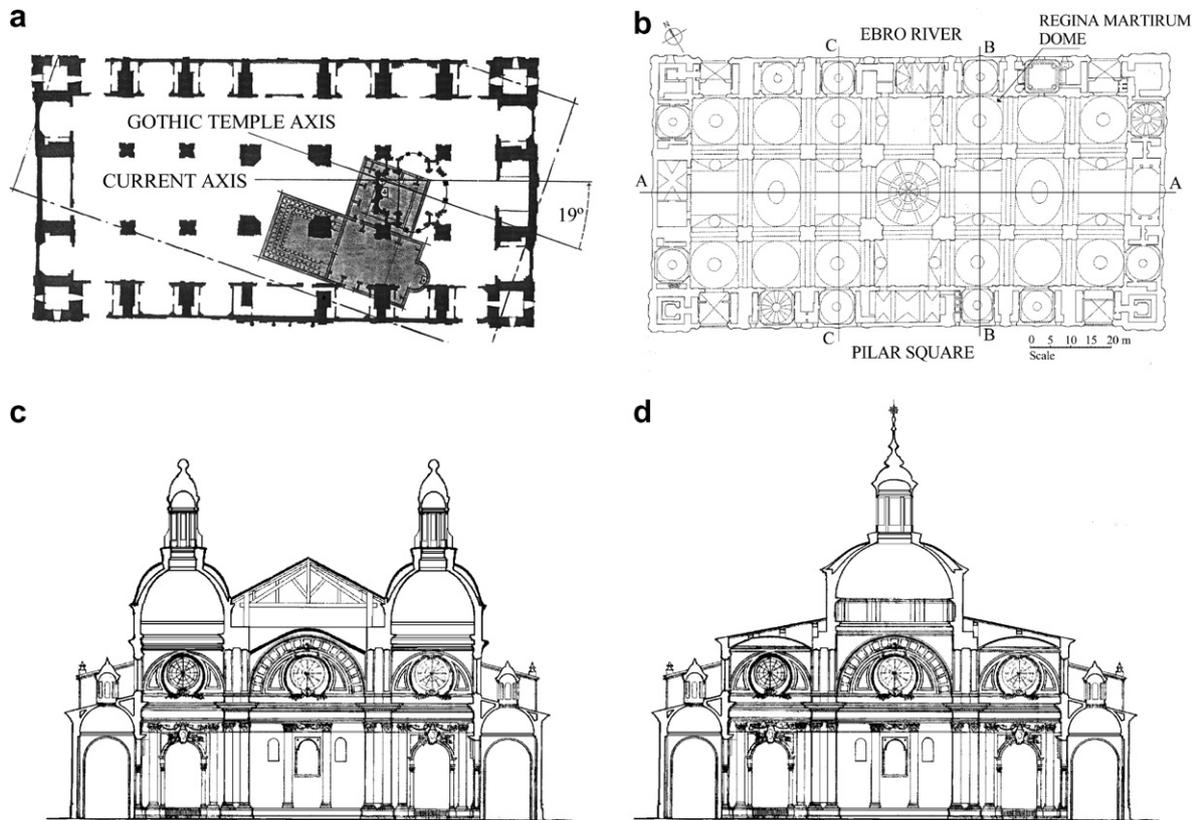


Fig. 1. Plans: (a) evolution of the worship site; (b) inferior top view; (c) front section BB for the Regina Martirum dome; (d) front section CC for the elliptical dome.

central dome was erected by the middle of XIX century, and the first two towers of Pilar square façade were finalized at the end of the XIX century while the towers of Ebro river façade were erected in 1940.

## 2. Structural pathologies and past repairing works

The first references to verify problems about fissures in arches, tambours and vaults, especially in elliptical domes, appeared in 1796, and also in 1804 some reports come into view concerning structural problems in several arches and vaults. In 1907 after the completion of the southern towers symptoms of general ruin emerged, and then in 1927 cracks of significant size were visible in arches, pillars were out of their vertical orientation and important relative displacements were observed in the Regina Martirum dome. In fact a discontinuity of about 4 cm, located in the connexion between the dome and its tambour, and throughout a third of a meridian could be observed in the Regina Martirum dome at the present time (Fig. 5b). Therefore, an ambitious programme of repairing works was approved under the direction of the architect Teodoro Ríos in 1927. The rehabilitation task continued until the beginning of the Spanish civil war started in 1936 and after the war, it was resumed again to be completed in 1940 (Fig. 3). The most important features of the restoration (Fig. 4) can be summarized as follows.

- An extensive injection of cement grouting in the soil.
- Foundation improvement with reinforced concrete beams linking steel lining at pillars foundation.
- Temporary support and steel reinforcement of central arches and pillars.
- External reinforcement of several tambours by reinforced concrete.
- Installation of inclined supports in tambours under the central and the elliptical domes, connecting them with external buttresses.

A few years ago other structural pathologies, in a smaller scale of previously mentioned, were observed. They were significant because they could affect frescoes of one of the most brilliant Spanish painters, Francisco de Goya. These pathologies are:

- Presence of humidity, small fissures and loss of material in frescoes of Regina Martirum dome (Fig. 5) and other domes.
- Cracks in several arches near the Santiago apostle chapel.
- Deterioration of masonry towers, especially in the towers of square façade.

To determine if the damage of frescoes was due to structural pathologies, and if this was the case, to outline the

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