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Analysis of the failure mechanisms of the basilica of Santa Maria di Collemaggio during 2009 L'Aquila earthquake

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ABSTRACT

In the paper are presented and compared different analytical and numerical models to explain the failure of the transept columns, which led to the collapse of the central dome of the 13th century basilica of Santa Maria di Collemaggio during the 2009 L'Aquila earthquake. The three models have been used to analyse respectively the horizontal performance of the church (*Beam model*), the vertical performance of the transept (*Vertical model*) and the residual capacity of the façade (*Soil–Brick model*). Results show that the collapse of the transept columns due to axial load is unlikely, while the collapse due to the global torsional behaviour of the church is more probable as already indicated by the authors elsewhere. Furthermore, numerical results have also shown that the frontal façade, without the temporary scaffolding system, would have not been able to withstand seismic events such as the 2009 L'Aquila earthquake.

1. Introduction

The April 6th, 2009 L'Aquila earthquake in Italy has shown the seismic vulnerability of historical monumental buildings and churches in the town of L'Aquila. Among those, the basilica of Santa Maria di Collemaggio has attracted more interest, because it was the only church in L'Aquila that was recently seismically retrofitted after 1997 earthquake in Central Italy. Due to the 2009 earthquake, the transept collapsed, while the façade was not damaged. Probably this happened because of the presence of a temporary scaffold system. Thus further analyses are needed to estimate its residual capacity.

Debate about the structural behaviour of the basilica under the seismic action is controversial and still open as shown in [1,2]. In the paper of Cimellaro et al. [3] it has been presented and showed the importance of the global effects of stiffening, strengthening and damping produced by the retrofit interventions [1–4]. The authors believe that the capacity was exceeded at the piers side, leading to their collapse [4]. Instead, according to others, the reason of collapse is the crush of the pillars due to axial load. Details about this discussion can be found in Cimellaro et al. [1,2]. Therefore this paper, in order to further clarify the discussion, is analysing the failure mechanisms and the seismic performance of the basilica of Santa Maria di Collemaggio. Three analytical models have been developed to estimate the residual seismic capacity of the façade and to analyse the collapse mechanism of the transept. These models study the vertical behaviour of the transept, the horizontal behaviour of the basilica in the North–South axis, and the residual capacity of the façade, using different types of analysis:

(i) *Response spectrum analysis.*
(ii) *Pushover analysis.*
(iii) *Time history analysis.*

2. Description of the basilica of Santa Maria di Collemaggio

The basilica (Fig. 1) is the largest 13th century medieval church in the Abruzzo region. It is located in Piazza Collemaggio in the South-West side of the town of L'Aquila. Construction began in 1287 by the Order of the Celestines. Inside the church, Peter of

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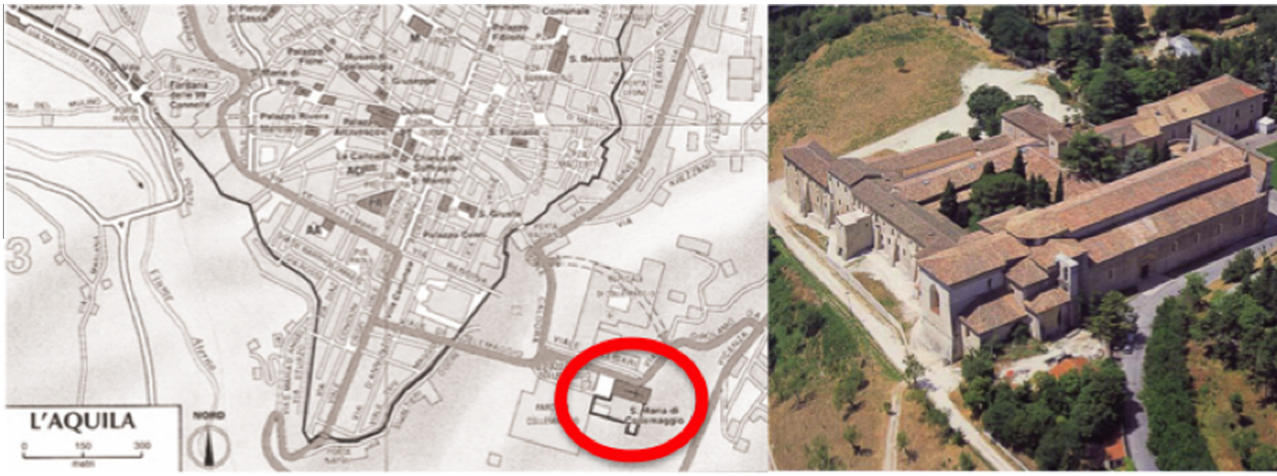

Fig. 1. Location (left) and aerial view (right) before 2009 earthquake of the basilica.

Morrone was crowned Pope Celestine V in 1294 and later buried there. The basilica is an example of both Abruzzese Romanesque and Gothic architecture. The façade is made of white and pink limestone geometrically and chromatically arranged to form bi-chromatic texture crosses. There are three entrances with three rosettes above and there is an octagonal tower attached to the right side of the façade.

Fig. 2 shows the section of the Romanesque church (prior to the 2009 earthquake) that is made of three naves: the central spans 11.3 m and is 18.3 m tall, while the lateral naves span about 8 m with a height of 12.5 m.

The roof of the naves is made of wood trusses and in the central and lateral naves there is a steel bracing system, which was installed in 1999. The columns that divide the naves are 5.25 m tall with a distance of 7.5 m apart and an octagonal shape with a diameter of about 1 m. The nave – before the 2009 earthquake – was separated from the transept by two large columns, with a floral shape and an equivalent diameter of 1.7 m that supported the two barrel vaults, the dome and a part of the internal walls. Behind the transept there are three apses that are made of masonry. The thicknesses of the external walls vary between 0.95 and 1.05 m, while the internal walls are about 0.9 m.

2.1. History of the structural damages and restorations of the basilica

Usually, heritage masonry constructions like historical churches are characterized by a wide variability of wall texture, degree and quality of connections, heterogeneity and uncertainty typical of the constituent materials.

Therefore, each structure is a singular case and archival information is required. The present state of the church is the consequence of articulated developments of building phases, with reconstructions and renovations. These began right after the construction of the Celestinian church (1287–1294) and concluded with the retrofit of the Jubilee (2000). Over the centuries, the church was affected by numerous changes due to earthquake damage or stylistic renovations, which are summarized in Table 1. Further details about the historical interventions can be found in [4]. After the 1915 earthquake, the upper left side of the facade was rebuilt with an accurate replica of the original ashlar coursework (Fig. 3). Between 1918 and 1921 concrete beams were introduced in the walls to strengthen the walls of the monumental façade with spurs and tie rods. Later in 1960, the transept was rebuilt with light RC and the masonry walls were strengthened introducing RC beams. In 1970, the Romanesque structure was restored, removing the wooden baroque ceilings and raising the aisles' walls of about 3 m and adding ring beams at the top of the walls. In 2000, an energy dissipation bracing system with steel hysteretic dampers (one near the façade and one near the transept) were installed at the roof level, beneath the wooden trusses of the central nave and the two aisles, while the walls' nave were injected with cement mortar [5].

Before 2009 earthquake, several diagnostic tests have already been performed on the church [5], with the purpose to show the improvement of its mechanical behaviour and its seismic resistance after 2000 seismic retrofit. Moreover, identification tests were performed at the basilica by the research team from the University of L'Aquila [5] to verify the elastic behaviour of the church before and after the intervention. The structure has not exhibited any torsional mode. The first two frequencies before retrofit were 1.25 and 1.7 Hz. After retrofit, all frequencies were shifted to higher values. In particular, the first two frequencies of the retrofitted structure were 1.45 and 2.12 Hz.

2.2. Description of the structural damages during 2009 L'Aquila earthquake

The naves of the basilica of Santa Maria di Collemaggio are oriented in the East–West direction. Hence, this is the strong axis of the basilica, while the North–South axis is the weak axis. The

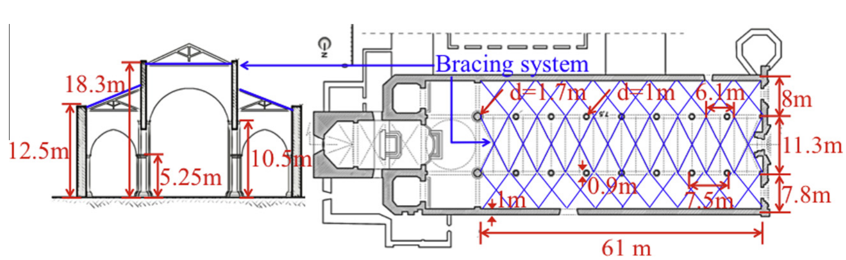

Fig. 2. Section and plan view of the basilica of Santa Maria di Collemaggio.