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Field observations and failure analysis of the Basilica S. Maria di Collemaggio after the 2009 L'Aquila earthquake

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ABSTRACT

On Monday, the 6th of April, 2009, a devastating earthquake struck L'Aquila causing the partial collapse of the Basilica S. Maria di Collemaggio, an important symbol of the city. The mechanism of the transept structure's failure, which left the external boundary walls almost undamaged, probably due to the sudden collapse of the large multi-lobed pillars at the end of the nave, is discussed in the paper by different points of view. A brief historical review of the monument restorations is followed by the analysis of the damage scenario recorded during the post-earthquake inspections. Finite element models of the Basilica, updated on the basis of available dynamic tests, have been used to perform a seismic assessment by response spectrum analysis according to the current Italian code, showing a high vulnerability, in the transversal direction larger than in the longitudinal one. The AQK earthquake accelerograms, recorded close to the site, have evidenced a prevailing component almost aligned with the longitudinal Basilica axis; the intensity is comparable with the one provided by the code, with exception in the vertical one greater than expected. Static nonlinear analyses have furnished the crack propagation in the masonry walls due to the increase of longitudinal horizontal loads. The presented failure description obtained by structural modeling is coherent with the direction of the registered polarized seismic action and it is compatible with the observed damage and with most of the debris positions coming from the collapse of the transept structures.

1. Introduction

Monumental churches have an inestimable value for our world cultural heritage. For this reason, continuous efforts are devoted to understanding their structural behavior. Nonetheless, monumental churches quite often undergo structural failures due to both static conditions and dynamic forces, sometimes with catastrophic consequences; and lengthy reconstruction efforts often leave the seismic vulnerability issues unsolved [1].

Because of this, great efforts are being made to comprehend the structural behavior of historical and monumental churches, mainly in Europe, with attention both to understanding cases of structural damage resulting from specific static conditions [2,3] and to evaluating vulnerability to earthquake-induced activity, if located in an active seismic area [4,5]. Due to the inherent complexity of tackling the physical problems, whether this means reconstructing the reasons for structural damage appearing under usual conditions (caused by permanent loads, boundary displacements slowly evolving in time and seasonal thermal changes) or predicting dynamical behavior under rare circumstances, such as those caused by

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earthquakes, the structural analysis of monumental churches is often accompanied by the extensive use of modern non-destructive testing techniques which permit the acquisition of valuable information at both the local (material) and the global (structural) levels.

Notwithstanding the common framework used by researchers in this specific field, the unique features of each church require the adoption of specially-tailored and well-balanced approaches in all the aspects and activities of the analysis. This includes historical investigations devoted to understanding the specifics of how the structure has evolved over the course of past interventions (such as are often performed on ancient monuments), the geometrical and material characterization, the information received by global dynamic testing (if performed), and the structural analysis and modeling.

Each activity hides a series of specific, experience-based skills, which must be guided by continuous engineering expertise if the final global results are to be valid. Valuable objectives can be reached in the case of complex and large monumental buildings if each ingredient of the overall study is deeply developed, well balanced and interconnected with the others [6]. In many cases, the investigations conclude with the determination of a strengthening intervention. Inherent uncertainties in the efficacy prediction are more difficult to determine in the case of seismic behavior enhancements, than in the case in which corrections are proposed for gravity loads or settlements, where the benefits of the interventions may be immediately realized [3,7].

Unfortunately, structural interventions on monuments are always accompanied by long debates regarding their desirability. This is especially so with rigorously conservative restorations that aim to avoid historically incorrect interpretations, even with regard to the monument structural behavior [8]. Besides that, the intervention costs are often prohibitive and generally require the unpacking of the whole restoration into successive phases, taking a long time. The process of preserving historical monuments today still remains a challenging issue [9–12]. The occurrences of failures are particularly important to study, in order to bring the critical points in the overall process into focus, and to clarify how to enhance optimal and sustainable paths of investigation and intervention [1,13,14].

In this respect, the Basilica of Collemaggio, a wonderful example of Romanesque architecture in Abruzzo, built at the end of the 13th century on a hill at the entrance to the city of L'Aquila, represents an important and representative case of study. Indeed, after the severe earthquake that struck the city of L'Aquila on April 6, 2009, causing the collapse of structural members sustaining the dome and the entire roof of the transept, the monument, with its undoubted historical, artistic and symbolic value, is currently in precarious conditions.

The present work discusses the observed damage caused by the seismic action and it describes the results of an historical survey, in situ testing and numerical modeling performed in order to correctly interpret the failures that occurred. The structural configuration of the church prior to the recent significant seismic event was the product of numerous structural modifications, most of which occurred subsequent to strong earthquakes that have taken place over the centuries.

In recent years, a series of interventions have been performed on the Basilica, in particular to improve its transversal behavior against seismic actions. Included among these interventions, injections were made to enhance the mechanical behavior of the masonry of the nave walls, and light steel bracings were inserted under the nave roof with the aim of increasing the effectiveness of the transversal members supporting the roof. Before the 2009 earthquake, the effects of the retrofitting on the Basilica's structural dynamics were already the object of specific studies conducted either by in situ testing or by numerical modeling [15–17].

The present study collects most of the information available on the structural behavior of the church in order to present a possible scenario of its seismic behavior. Several finite element models have been developed for this purpose, many of which take advantage of information acquired during different dynamic test campaigns. Seismic actions are described either through the Italian code or using the registered main shock recorded at the station, AQK, located close to the Basilica.

The effects of the modeling of different elements, such as the light steel bracings inserted at the level of the roof, the somewhat squat tower constructed at the right corner of the facade, and the slender bell tower inserted at the level of the transept are discussed.

Spectrum linear analysis and nonlinear static analysis have been performed to determine the range of possible values for the seismic response of the masonry structures, considering all the limiting hypotheses typical of this kind of analysis. The results obtained have been used, in combination with the authors' engineering expertise, to explain the observed partial collapse of the Basilica that occurred during the main shock of the April 6, 2009 L'Aquila earthquake.

2. The Basilica of Collemaggio and the damage scenario

The Basilica of Collemaggio is placed on top of a hill in the city of L'Aquila, just outside the ancient walls (Fig. 1a). The monastery, with a cloister and several annexes, is found facing the south side of the church. The Basilica's facade, made of pink and clear stones arranged to form crosses, is beautifully adorned with three rosettes and three Romanesque–Gothic portals (Fig. 1b).

The hall of the Basilica has a nave and two side aisles. The nave measures 61×11.3 m. The two side aisles measure 61×8 m (to the right of the nave) and 61×7.8 m (to the left). The maximum height of the nave is 18.3 m; each of the aisles is 12.5 m. The octagonal columns separating the three naves are seven on each side. The columns have an approximate relative distance of 7.5 m, a height of 5.25 m, and are about 1.0 m in diameter. They hold a total of 16 ogival arches. The double