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Seismic Damage to Churches: Observations from the L'Aquila, Italy, Earthquake and Considerations on a Case-study

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Abstract The earthquake that hit the city of L'Aquila, in central Italy, on the 6th of April 2009 has severely damaged most of the heritage buildings of the area. Soon after the event, a first survey of damage to ancient churches and palaces has been carried out according to a predefined classification procedure. Subsequently, a more detailed damage analysis was started in order to facilitate decision on future interventions. For one of these churches, S. Biagio Amiterno, damage consisted in the collapse of the upper part of the façade, in the localized collapse of the main vault, and in an extended crack pattern in vaults, columns, and walls. This damage pattern is interpreted here as case study. In more general terms, the exam of specific case studies gives the possibility of shedding light on various issues related to the seismic behavior of the building typologies concerned.

Keywords: Heritage building, historic masonry, seismic behavior, seismic damage, case study

Introduction

On the 6th of April 2009 the city of 'Aquila, in the Appennine mountains of central Italy, was hit by a strong earthquake, of M_L = 5.8 and Mw = 6.3. The event arrived after a swarm that had started in December 2008 and has been followed by a long series of aftershocks. The main shock and some particularly strong aftershocks caused severe damage in the city and in the surrounding region, devastating its rich historical building stock and monuments.

In the immediate post-event period all the technical activity was concentrated on the emergency response, assessing the damage and deciding on practicability of public structures and dwellings. Damage to the cultural heritage, however, started soon to be examined and classified. A thorough operation of damage assessment has been carried out according to a damage classification procedure based on a fast visual examination (PCM-DPC 2006a, b). This procedure had been prepared as a result of studies and experience acquired in the seismic events that hit the cultural heritage in the last decades. This first screening was followed, where necessary, by provisional interventions, like temporary bracing, scaffolding, etc., aimed at stabilizing the buildings for aftershocks and permit safer access for further inspections and future rehabilitation work. A total of 973 churches were examined, out of which only 324 could be reopened without any provision or intervention (MiBAC 2009). All the others were affected by some degree of damage.

Soon after, a more detailed survey and damage analysis program on heritage buildings was started. This comprised for each case (a) a circumstantial description, usually associated to a graphic rendition, of the damage, with details of the collapsed areas and crack patterns, and (b) the interpretation of damage mechanisms that had occurred or were at some stage of development. This information was collected as documentation of the state of the buildings that could be used to support decision on future rehabilitation and strengthening interventions. A selection of churches and some historical palaces were assigned as case studies to different groups composed mainly of university researchers. Among these cases is the church of San Biagio Amiterno.

In more general terms, the exam of specific case studies gives the possibility of sorting out significant aspects of the seismic response associated to building typologies. The case studies of churches and palaces addressed particularly two questions: the first was the recognition of typical damage and collapse mechanisms, with the aim at confirming patterns derived from previous observations, possibly identifying new ones, and acquiring more detailed knowledge on the structural

conditions that generate them. A second objective concerned the effects of strengthening interventions. Many of these buildings had undergone some type of structural rehabilitation in the past, often with the intention to improve their seismic resistance. The study aimed at assessing the effectiveness of such interventions, recognizing possible adverse effects, and at devising efficient and conservation- compatible criteria for repairing and strengthening historical structures.

Seismic Damage and Mechanisms

Seismic damage to the masonry structures of historic heritage buildings has for long been recognized to concentrate in specific building elements, like facades, bell-towers, vaults, etc., according to recurring patterns. When damage evolves into a failure mechanism, collapse usually remains localized without expanding to the whole structure (Giuffré, 1995; Doglioni et al. 1994; Neumair et al. 2002; D'Ayala and Speranza, 2003). The most frequently observed types of mechanisms have been classified, formulating their collapse acceleration as a function of loads, geometry, and material properties. In the recently issued Italian building code, limit analysis of collapse mechanisms is proposed as a computational method applicable for evaluating the seismic capacity of existing masonry buildings. Guidelines for mitigating the seismic risk of the cultural heritage that rely on this approach have been issued (Cons. Sup. LL. PP. and MiBAC, 2006). Methods for assessing the seismic vulnerability as well as for damage classification of historic palaces and churches are based on recognizing the potential for mechanisms, and their initial or advanced state in the surveyed structure (Lagomarsino and Podestà, 2004a, b, c; Beolchini et al. 2005; Valluzzi et al. 2007; Binda et al. 2007). These methods were improved after the Umbria-Marche earthquake, 1997. A Committee of the Civil Protection Department, GLABEC, (members: L.Marchetti, L. Binda, C. Modena, S. Lagomarsino et al.) proposed the documents then used for the damage survey in the L'Aquila earthquake as mentioned above (PCM-DPC 2006a, b). In this framework, in the analysis of the current case study the mechanisms corresponding to the observed damage are discussed.

A Case Study: the Church of San Biagio Amiterno

The church of San Biagio Amiterno, recently rededicated to San Giuseppe Artigiano, Fig. 1, is located in the most ancient part of L'Aquila and dates from the first half of the 13th century. The church suffered severe damage during the earthquakes of 1315 and 1703 and was partially rebuilt after each. For historical reasons, its use was discontinued from the second half of the 18th century. The building was destined to activities of commercial type that fostered its degradation. At the beginning and again at the end of the 20th century it underwent major restoration. Recently it had been reconsecrated as church and at the time of the earthquake it was used as university chapel.

The church, a stone masonry structure, is part of a complex of interconnected buildings delimiting, on one side, a mildly sloping street. It has the original rectangular plan of a basilica, with three naves, separated by arches and pillars. The church plan is at an angle with the street direction. In order to accommodate the resulting gap the external façade, along the street line, and the interior of the church are connected by a short trapezoidal entrance hall.

The covering system is quite complex. The central nave is covered by a thin barrel vault made of timber arches, reeds, and mortar according to an ancient construction technique found frequently in the area. Light steel cables have been securing the vault to the timber roof structure above it since the last restoration in 2004, in substitution of formerly used stiff timber planks. The vault had been frescoed in the early 20th century. The roof structure above the vault consists of a series of parallel timber trusses and is covered with brick tiles. During a restoration performed in the 1980's, a massive and stiff concrete and brick slab was laid above the trusses to form the pent planes, according to a technique of the time intended to foster collaboration of roof and bearing walls. The lateral naves are divided by a series of transversal arches into square areas forming chapels, each covered by a spherical dome. The domes are presumably built with very thin bricks, following an old local technique. The low-rise vault over the short transept is elliptical.

Consequences of the Earthquake

During the first survey, damage to the church was classified as “very serious”, rating 4 in a scale of 5, where the maximum grade would correspond to extended or global collapse. Although in San Biagio some elements had collapsed, fortunately most of the widespread cracking had not evolved into a complete mechanism, as discussed in the following section. The building was initially declared not accessible. Provisional interventions amounted to removing or fixing some tottering parts and closing the large opening caused by the collapse of part of the façade, in order to prevent environmental damage. Afterwards, controlled access to the interior was permitted only for technical purposes and study.

Figure 1: The church prospect before the earthquake from a street post (left) and the church plan (right)

The Observed Damage The main damage occurred after the main shock and consisted in the out-of-plane collapse of the upper part of the façade and of the corresponding infill in the church interior, Fig. 2. Debris have cumulated outside and inside. Failure occurred according to a well known mechanism, also represented in the figure.

Figure 2: The façade top (left) and corresponding collapse mechanism (right)

In the church interior, local collapse occurred at different spots of the barrel vault over the main nave, bringing into evidence its cane structure, as may be seen in Fig. 3. This damage was likely due to debris falling from the roof area and breaking through.

Again in the interior, widely extended cracking had occurred. All the visible crack systems have been examined and rendered. In particular, cracking occurred

- in the lateral walls of the central nave, above the arches, where cracks developed systematically from the arch key area to the windows above with a moderate slant with respect to the vertical direction. An example is shown in Fig. 4, left;

- in the lateral naves, where all the spherical vaults over the chapels cracked along a parallel just above the base; additionally, the arches between chapels were cracked at the key, in a system connecting with the vault cracks. In Fig. 4, right, an example of the vault-arch crack system is shown;
- in the exterior walls of the lateral naves, where widespread cracks appeared, these cracks seem, however, narrower and more shallow;
- at the base of the pillars, with generally thin vertical cracks. Damage was mainly found in the layer of stiff decorative plastering, which at places detached into bubbles and broke off in others. No systematic inspection of the inner structure was possible.

Figure 3: The damaged interior

Figure 4: Cracks above the arches of the main nave (left) and in the vaults of the lateral ones (right)

Interpreting the Damage Patterns

Collapse of the tympanum in church façades recurred frequently in the L'Aquila earthquake as well as in foregoing earthquakes in Italy. It is usually ascribed to the roof ridge beam pounding into the façade wall or, at times, to a similar effect from the concrete beams added at the top of the lateral walls in order to strengthen the masonry. In this sense, strengthening interventions that produce excessive weight and stiffening of the top structures have proven to produce mostly detrimental effects.

In the current case, however, the main triggering cause of collapse seems to be the insufficient restraining of the collapsed part. By examining the collapsed area of the façade and the lateral walls, while no significant longitudinal displacement of the heavy concrete roof was noticed, the borders of the collapsed area revealed a particularly weak restraint situation. The façade top could be roughly considered an elongated plate, where the lower border, corresponding to the upper side of the large façade window, was basically free. At the top, the plate was very likely weakly connected to the new concrete roof. The roof border could be inspected by close after the collapse and showed no significant remains of interconnection. At the lower border just above the window, the presence of a timber tie-beam linking the lateral walls and visible in Fig. 2 constituted an additional discontinuity within the masonry. On the left side looking at the façade, a discontinuity in the masonry was present before the seismic event and is recognizable in pictures as well as in older drawings, like that in Fig. 1.

The border restraints resulting from this entire picture were very louse and probably incapable of resisting strong out-of-plane forces. In fact, collapse followed these borders, including the discontinuity on the left, as may be seen by comparing Fig. 1 and 2. The masonry tooth seen in the figure was subsequently removed, to avoid danger of further collapse.

Considering the entire building, both the collapse of the tympanum and the general crack patterns that developed in the interior appear associated to an important motion in the longitudinal direction, normal to the façade and along the nave. A global longitudinal mechanism concerning 3-nave churches and involving the same structural elements as in S. Biagio, i.e. lateral vaults, nave walls, and pillar bases, had been observed in other seismic events and was reported as a possible reference case in the damage evaluation form, although for a different vault shape (PCM-DPC 2006,a). The effects of motion in the transversal direction were less visible, probably also as a consequence of some degree of continuity offered by the location of the structure within a block. Yet, some effects were evident, witnessing the occurrence of a significant component of motion also in this direction. An example is found at the first arch between main and left naves: the through-crack that developed from the key upward shows clear sign of lateral sliding.

The façade mechanism pointed out here has been further confirmed by performing its limit analysis. The procedure, implemented by Modena et al. (2004), requires defining all the contributions in terms of forces that derive from weights, possible thrusts, ties, and from inertia. In spite of uncertainties, results are usually meaningful especially in comparing different possible mechanisms for the same macroelement. In this case the mechanism that actually developed had a low collapse coefficient that fully justified the outcome in relation to the level of the L'Aquila earthquake.

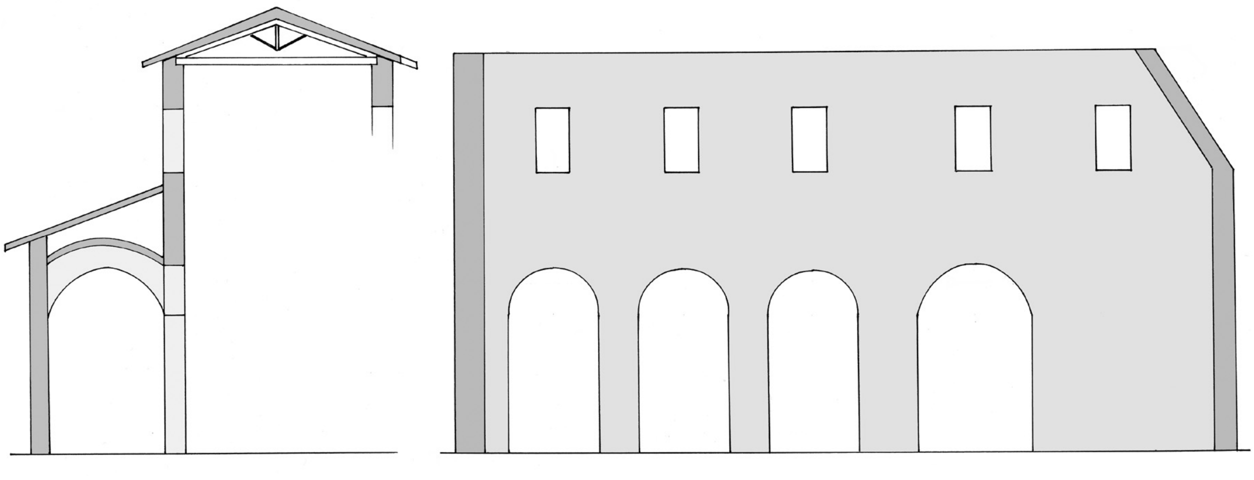

Figure 5: Transversal and longitudinal sections

In order to identify possible repair and strengthening strategies for the church as a whole, attention need to be focused on the two main longitudinal walls that border the central nave. These walls are the main resisting system of the entire complex, providing support to arches and vaults and to the roof structure. The longitudinal view of these walls is reported in Fig. 5 together with a transversal section showing the openings, i.e. the large windows, in the upper part and the arches in the lower.

As mentioned above, the church seems to have suffered the effects of motion in the longitudinal direction, which has been approximately the direction of propagation. Initial considerations and first computations, however, suggest that the structure is more vulnerable in the transversal direction. Considering the unrestrained upper part of these walls, above the lateral naves, that extends for approximately 6 m, a simple overturning equilibrium would result in a low collapse acceleration of the order of 0.15 g. The simple analysis of the structural masses has shown also that the weight increase due to the roof concrete slab is limited, compared to the weight of masonry walls underneath.

From this general picture, the need for a detailed analysis based on an accurate description of all the structural components, effects, and contributions is highlighted.

Conclusions

The damage occurred to the church of San Biagio Amiterno during the L'Aquila 2009 seismic event has been described and analyzed as a case study, interpreting the seismic behavior and discussing aspects of the analysis procedure. Reference to recognized collapse mechanisms simplifies the description of damage and makes it particularly effective. Different conditions, however, may trigger a particular mechanism. The evaluation of limit equilibrium associated to the mechanism may permit, as in the current case, to verify the interpretation of causes. Global strengthening interventions will have to be based on analytical models capable of representing all the significant structural contributions.

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