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Renato Masiani, Department of Structural Engineering and Geotechnics, La Sapienza University of Rome, via Gramsci 53, Rome 00195, Italy

*Cesare Tocci, Department of Structural Engineering and Geotechnics, La Sapienza University of Rome, via Gramsci 53, Rome 00195, Italy; e-mail: cesare.tocci@uniroma1.it

SUMMARY

After the terrible eighteenth century earthquakes (L'Aquila, 1703; Lisbon, 1755; Reggio Calabria, 1783), specific anti-seismic precepts were introduced in the rules of the art of masonry construction. Scrupulously adhered to in the first years after the earthquake, those precepts gradually ceased to be used until they were almost completely forgotten, centuries later, by which time the earthquake had become a distant memory. The church of San Pietro di Coppito, one of the most important churches of L'Aquila, is emblematic of this singular process. Deeply transformed in accordance with new anti-seismic construction techniques after it was particularly badly damaged in the terrible 1703 earthquake, the church was subjected, in the 1970s, to drastic alterations by the Commissioner Mario Moretti, who demolished all the baroque additions and redesigned it in the "medieval Abruzzo" style, eliminating in the process the intelligent anti-seismic provisions introduced in the eighteenth century. In addition to documentary purposes, this work aims to underline the effectiveness of this early eighteenth century example of anti-seismic engineering in the belief that the constructive solutions it employed could still form a valid architectural and structural model in view of the massive restoration task which, unfortunately, still today, L'Aquila is waiting for.

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KEYWORDS

Art of building, early earthquake engineering, masonry structures, L'Aquila earthquake, seismic improvement, static restoration.

1. INTRODUCTION

Except for sporadic, and particular, moments in the history of *the art of building*, in which we may trace embryonic scientific features (Masiani and Tocci, 2012), even though in a context of real construction activity rather than explicit theoretical reflection, it is only in the eighteenth century that mechanics starts to be systematically and consciously used to assist in the architectural design. In the middle of the previous century, Galileo had clearly shown the way forward to address the problem of the bending beam and subject it to rigorous analysis, even if he failed in finding the exact solution. At the threshold of the new century and with reference to a different typology, de La Hire tackled a similar problem by examining equilibrium limit conditions in arches and suggesting the possibility to verify the correctness of the traditional design rules based on geometry. Moreover, experimental researches conducted at the beginning of the century, pursued the same goal (although in a different direction) which had by then irreversibly entered the cultural horizon of the time, and, in a nutshell, involved the dimensioning of structures on a scientific basis (Di Pasquale, 1997).

It is therefore not surprising that it was precisely in the Age of Enlightenment that the earthquake no longer came to be regarded as a punishment of God but a natural phenomenon to be understood and to act against. In this case, too, like for the mechanical formulation of structural problems, there were some isolated anticipations – such as the famous anti-seismic house devised by Pirro Ligorio in the aftermath of the Ferrara earthquake of 1570 (Guidoboni, 1997): however, it was only in the eighteenth century that an attempt was made to solve the problem of resistance to seismic actions on a rational basis, resulting in significant changes in building techniques.

After the devastating earthquakes that struck first L'Aquila in 1703, then Lisbon in 1755, and finally Calabria in 1783, the rules of the art of masonry construction acquired an explicit anti-seismic orientation thanks to the introduction of an additional series of provisions intended to give buildings the capacity to resist the horizontal actions induced by earthquakes. This change is supported, in different times and places (from the beginning to the end of the century, both in Italy and elsewhere), by a substantially similar mechanical idea that demonstrates how that primitive anti-seismic engineering had understood which parts of a building were most likely to be affected by seismic action and which design features were required to increase resistance to earthquakes.

This is a crucial turning point in the history of the art of building, which in technical-constructional terms reveals significant analogies with the contemporary process which, at the theorical level, sees mechanics being employed for the first time in the definition of the structural aspects of architecture and achieves a striking manifestation in the famous controversy, in the middle of the century, concerning the stability of the dome of St Peter’s (Capecchi and Tocci, 2011).

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In this context, the constructional events surrounding the church of San Pietro di Coppito in L'Aquila, damaged by the earthquake of 2009 and currently undergoing static restoration work, are emblematic: not only for the anti-seismic effectiveness of the reconfiguration and constructional solutions put in place after the earthquake of 1703 but also, vice versa, for the anti-seismic unawareness which characterizes the restoration of 1970, to which, as we shall see, we may largely attribute the damage from the last earthquake. This circumstance must be read not so much as a demonstration of the technical inexperience of those who implemented the interventions but rather as the result of a more dangerous process of removing the memory of the earthquake, with the consequent progressive downgrading of the original anti-seismic provisions which, sadly, happened not just in the area of L'Aquila but in many other places.

In this paper the major phases of the constructional and seismic history of the church of San Pietro di Coppito are presented. The opportunity for this research was supplied by the structural advice which one of the authors of this paper was asked for, in the aftermath of the earthquake, by the technicians of the *Soprintendenza per i Beni Architettonici e Paesaggistici per l'Abruzzo* (Government Department responsible for Abruzzo environment and historical buildings) who were given the task of defining the criteria for the restoration of the church. The main results of the research are summarized giving greater emphasis to the fact-finding phase (§ 3.1-3.3) while the technical choices of the suggested interventions are presented much more concisely (§ 3.4).

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2. ANTI-SEISMIC PROVISIONS IN L'AQUILA POST 1703

RECONSTRUCTION

The construction techniques that are needed to make buildings safer and more resistant also to earthquakes rest, according to Giuffrè, on a general elementary criterion: *«prevent the outward movement [of the walls] with steel or wooden tie rods; prevent inward movement with wooden or masonry buttresses»* (Giuffrè, 1993; trans. by the authors).

The awareness of the importance of this criterion, in areas of high seismic risk, is common to all the changes in construction techniques brought about by the great eighteenth-century earthquakes. Independently of the specific technical solutions adopted, the fundamental idea was always the same and can be systematically identified in the above criterion.

In the area of L'Aquila, this criterion is applied with a remarkable methodicalness and refinement: *radiciamenti* (see below), tie rods, buttress arches, props, as well as lightweight eaves and lightweight vaulted ceilings: all this reveals an awareness of the greater severity and frequency of earthquakes, which drives constructive culture to develop more effective solutions than those adopted in non-seismic contexts. This awareness is fully acquired after the 1703 earthquake, which led to a clearer understanding of the main weakness of masonry buildings - the lack of effective connections between the different elements - and the implementation of a series of measures to address this defect.

The first and most important of these measures is the systematic use of what are called *radiciamenti*, wooden logs inserted in masonry walls, which not only link the walls to each other but also improve their shear strength, functioning in the manner of a stretcher (Carocci and Tocci, 2010). The *radiciamenti* are almost always placed horizontally, within the vertical walls, to connect walls orthogonal to each other or to reinforce an isolated and excessively thin wall, like the false front of a façade (fig. 1); in some cases, though, logs were placed vertically, especially in corners, as if to form a frame (fig. 2, left). Wooden logs are also found in cloister vaults to prevent deformations of the abutments due to thrusts, which must have been a cause for concern once the danger from the horizontal actions of earthquake had been recognized (fig. 2, right).

The same intent of interlocking different parts together, in a way that was more effective than usually considered acceptable in normal circumstances, can be seen in another construction method commonly adopted in the area of L'Aquila, the so called *impalettatura* – i.e. the pegging of trusses and roof structures to the cornices of the walls – as well as in the linking of the ceiling beams to the bearing walls (fig. 3, left).

All the construction techniques mentioned aim to increase the capacity of the building to act as a whole to withstand external actions (which are not exclusively seismic), implicitly recognizing that the best way to make traditional masonry structures resistant to the devastating fury of an earthquake is to be found in the pseudo Gothic ideal of Leon Battista Alberti: «[...] *So we also should connect the Ribs [of buildings] together, and fasten them together well with Nerves and Ligatures; so that the Communication among the Ribs should be so continued, that if all the rest*

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of the Structure failed, the Frame of the Work should yet stand firm and strong with all its Parts and Members [...]» (Alberti, 1755; first English translation of the fifteenth century edition by J. Leoni). Nor does the focus on the structural layout, i.e. the correct organisation of masonry walls, stop here: again after the 1703 earthquake, not only is the utmost care taken to ensure block bonding between different orders of walls but, and above all, interventions are also carried out on inherently weak structural layouts for the explicit purpose of making them more resistant to earthquakes. It is no coincidence that many eighteenth century religious buildings, as well as baroque *riattamenti* (i.e renovations) of buildings damaged in the 1703 earthquake, are of the single nave type with side chapels: evidently because this scheme was believed to be intrinsically resistant to horizontal actions. We shall return to this aspect and discuss it in more detail with specific reference to the history of San Pietro di Coppito.

The anti-seismic effectiveness provided by the above construction techniques to the rule of the art of masonry is demonstrated by the extent and nature of the damage caused by the earthquake of 6 April 2009 (which revealed, so to speak, the tricks of the trade, which before then had not been fully understood).

If we exclude situations that show clear structural defects, due to the original design or deriving from later interventions - poor quality walls, unsatisfactory structural layouts, replacements of wooden floors by heavier r.c. floors, etc. (Carocci and Lagomarsino, 2009) -, and if we also exclude situations in which seismic actions may have been amplified by geological features of the sites or position of the buildings, we see that many buildings were almost untouched by damage while, in damaged buildings, only in-plane (second mode) mechanisms (which are not

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disastrous, because cracks appears in the walls but the building does not collapse) were systematically activated: a clear sign that *radiciamenti* and *impalettature* were effective in preventing out-of-plane (first mode) mechanisms which often damage, even quite badly, buildings devoid of the systematic connections that existed in L'Aquila (fig. 3, right).

It is interesting to note, as mentioned in the introduction, that a similar process as happened in L'Aquila after the 1703 earthquake took place also after the other two powerful eighteenth century earthquakes, involving the same mechanical principles. With reference to the Calabrian Messina earthquake of 1783, which is of major relevance to our reasoning, the so called *casa baraccata* (Vivenzio, 1783) – which did no more than rationalize construction techniques that had already developed spontaneously (Ruffolo, 1912; Barucci, 1990; Tobriner, 1987; Langenbach, 2007) and was assumed as the basis for the Bourbons legislation for reconstruction – is clearly based on the same mechanical awareness, which, albeit still in its infancy from the point of view of theory, we saw already well developed, in terms of results, in the *radiciamenti* and *impalettature* techniques used in the L'Aquila area. The aim is always the same – to make sure the different components act as a whole – and is achieved in one case by an ideal truss structure in which the functions of struts and ties are carried out respectively by the masonry walls and the wooden *radiciamenti*, while in the other by a completely wooded (truss?) structure in which it is not easy to pin point the role played by masonry.

Moreover, it is worth noticing that we have an "experimental" demonstration of the anti-seismic effectiveness of the *casa baraccata* – entirely similar to the one proposed above for the post 1703 L'Aquila technique – in the description of the damage caused by the earthquake of

December 28, 1908 (contained in the Report of the Commission responsible for drafting the housing regulations for municipalities affected by the earthquake) that seems almost to reflect the typical scenario caused by the earthquake of April 6, 2009 – with the almost complete prevalence of in-plane response mechanisms due to the effectiveness of the system of wooden and metal connections (Reycend 1909).

Nor does the analogy in the changes in construction techniques, determined by the two earthquakes at the beginning and end of the eighteenth century, stop here; because the prescriptive nature of those early anti-seismic techniques weaken with time, to be completely ignored once the memory of the traumatic events has gone. These techniques were never in fact completely abandoned, but they were no longer systematically applied as in the initial phase: they began to be used only sporadic and occasionally, and not applied with the previous technical rigour. This circumstance has, unfortunately, frequently been observed in several buildings of L'Aquila, for which we cannot but repeat word for word the judgment of the 1908 Commission: «*[…] it is truly regrettable that after only a few decades they [the Bourbons anti-seismic provisions] have descended into oblivion; had they been strictly observed and extended to other regions they would have saved our country the terrible number of deaths we have recently experienced, especially in 1894, 1905 and 1908, since it is known that houses constructed under these provisions resisted all subsequent earthquakes*» (Reycend 1909, p. 15; trans. by the authors).

The centuries old constructional history of the church of San Pietro di Coppito in L'Aquila, which we will examine in some detail in the next section, dramatically illustrates the

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considerations we have been so far discussing. From a paradigm of the new constructional techniques that had become firmly established after the great 1703 earthquake, in terms of both structural layout and building quality, the church was subjected, in the 1970's, to a heavy intervention which completely removed, in one fell swoop, the memory of that constructional culture which had drawn lessons from its experience of earthquakes to introduce, for the first time in the history of building techniques, explicit provisions to address the issue of seismic actions, until then extraneous to the rules of the art of masonry.

3. THE CHURCH AND ITS EVOLUTION

In the first decades of the fourteenth century the urban layout of L'Aquila, a *civitas nova* (new city) founded in the middle of the previous century, had basically already been established, in spite of the great changes caused, in the physiological evolutionary processes of its urban fabric, by the periodic occurrence of destructive earthquakes (Clementi and Piroddi, 1986). Soon after it was founded, the city was hit by earthquakes several times (the first in 1315, and there was an even stronger one in 1349), and it would continue to be hit frequently and with great violence (as in the case of the terrible 1461 earthquake and the catastrophic one of 1703).

Initially made up of "*locali*", urban portions which reflected the residents' place of origin, with a church and a square at the centre, the town began to expand and "*quarti*" (neighbourhoods) developed in the orthogonal layout of the Anjevin city (1266) - built around pre-existing Swabian settlement, and which was to form the basis for the development of the city's urban fabric, at least until the sixteenth century. The importance of the "*quarti*" for the evolution of the subsequent administrative and fiscal structures of the city meant that the so called "*capo di Quarto*" churches played a decisive role in urban development (Spagnesi, 1975).

San Pietro di Coppito is one of L'Aquila's "*capo di Quarto*" churches, and one of the first "*locale*" churches, being contemporary (Gavini, 1927) with the church of Santa Giusta di Bazzano (1257). Unfortunately we have no idea of its original layout, and the façade we see today is a modern reconstruction in mediaeval style dating back to the 1970's (see below, § 3.1.2); so we can only form hypotheses based on the historical iconography of the city.

3.1. The church before 1703 earthquake and its eighteenth-century reconstruction

Struck by powerful earthquakes in 1315 and 1349, and certainly badly damaged by the violent earthquake of 1461, during the fifteenth century the pre-existing church was completely rebuilt in the "medieval style" (Miarelli Mariani, 1979). This reconstruction seems to be confirmed by comparing the first realistic depiction of the city (the *Gonfalone*, painted by G. Paolo Cardone in 1579 from an original dating back to 1462) with G. Pico Fonticulano's town plan (in the version engraved by G. Lauro in 1600). In the *Gonfalone* (fig. 4, top), in which the city has a North-South orientation, the church of San Pietro has a square façade in front of what seems to be a single room building, as can be deduced from the shape of the roof, with a lower room on the right, which could be an aisle (the left side is hidden by another building). In Fonticulano's plan (fig. 4, centre) (as well as in Antonelli's 1622 plan), which is oriented east-west, the church seems to be divided into three aisles of different height, with the square façade which is also in

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front of the lower aisles and the left aisle having three windows and a doorway next to the back façade; a tower can also be seen.

However, in both cases, if we discount the above differences, San Pietro di Coppito seems to have been built in line with the church typology of the first century after the city was founded, in which, both for the three-aisle layout of the most important churches and in the one-nave design of smaller churches, the façade is totally independent from the rest of the building. Shaped like a large rectangular prism, it functions more as a scenic backdrop to urban space rather than a projection of interior space.

Among the most damaged churches in the violent 1703 earthquake, together with S. Bernardino, S. Silvestro, S. Agostino and the Cathedral (Gavini, 1915; Costantini, 1915), in the eighteenth century San Pietro di Coppito was transformed into a single nave building with side chapels. Historical iconography is extremely helpful in documenting the church's new phase of evolution, allowing us to give further details about Gavini's hypothesis (1927), which dates the above transformation to the next century. In Vandi's plan (Franchi, 1752), the first truly topographical plan of the city (fig. 4, bottom), we can clearly make out the new building as it resulted from the reconstruction following the 1703 earthquake with an intervention similar to what can be seen also, for example, in the church of Santa Maria Paganica: a transformation of the original three aisle plan into a single nave design with side chapels. Vandi's plan also shows an asymmetry in the layout, which would make us suppose, if compared to depictions made prior to 1703, that the left aisle was definitively removed and the three aisles now become incorporated into the area originally taken up by nave.

Vandi's plan therefore gives us 1752 as a *terminus ad quem*, allowing us to suppose that the new baroque church built on the ruins of the destroyed medieval church had by then been completed – except for the façade and the dome which will be realised in nineteenth century – which is consistent with the fact that post 1703 reconstructions for almost all religious buildings were carried out during the Austrian viceroyalty (1707-1734) which, not by chance, being the heir of the Holy Roman Empire, had close ties with the Holy See (Varagnoli, 2000).

The church typology of one nave with side chapels is based on the neo-sixteenth century Jesuit model, which, given also the massive presence of the Roman school in the Abruzzo region after the 1703 and 1706 earthquakes, is prevalent in many eighteenth century religious buildings and in many of the baroque "renovations" made to buildings damaged by the earthquakes (Benedetti, 1975), and not only in L'Aquila.

Given the predominance of the one nave model also in the construction of new religious buildings, even before the eighteenth century earthquakes, it would perhaps be excessive to see an anti-seismic intention behind this typology.

However, although introduced apart from structural reasons, this typology could have been seen as an inherently anti-seismic model in the aftermath of the violent earthquakes of the beginning of the eighteenth century. The evidence of earthquake damage scenarios may have shown the extreme transverse weakness of three aisle (or one nave) buildings and the anti-seismic effectiveness of transverse (shear) walls – which could be introduced by simply transforming the side aisles into chapels or by building new chapels.

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During the nineteenth century, starting in 1862, the church underwent further transformations (Signorini 1868) with the construction of the dome and the completion of the façade (fig. 5) on which, other interventions are also documented, up to the beginning of the twentieth century (Moretti, 1973).

3.2. Moretti's "restoration"

Between 1969 and 1972 the church underwent major transformations at the hands of Mario Moretti (Moretti, 1973), who demolished the eighteenth-century church and redesigned it in the *Abruzzo medieval style* (figs. 6, 7).

This intervention, together with the more famous one on the Basilica of Collemaggio, aroused strong controversy at the time, which was echoed in the press (Zevi, 1973; Pace, 1971) and culminated in a vote – which was ignored – of the second and third section of the *Consiglio Superiore delle Antichità e Belle Arti* (Antiquities and Fine Arts Council) of 6 October 1971 (Miarelli Mariani, 1979) which called for the immediate suspension of all the restoration work in progress throughout the region of Abruzzo and the adoption of measures against the Commissioner. However, Moretti's views were anything but isolated among the authorities of those times, though perhaps not always expressed with the same rudimentary clarity, and reflected moreover a predilection for medieval rather than baroque forms, also among the most knowledgeable sectors of public opinion – the writer Silone, said that the baroque additions to the Basilica of Collemaggio were dreadful (Silone, 1968).

Leaving these controversies aside, what we wish to emphasize here are the structural consequences of the interventions on San Pietro di Coppito, concerning which we have the considered judgment of Gianfranco Spagnesi, who states that Moretti's restoration «*failed to understand the eighteenth-century city*» (Spagnesi and Properzi, 1972), in such a way accurately defining not only the architectural characteristics of Moretti's intervention but also their structural implications.

The intrinsically anti-seismic layout of the eighteenth-century church was, in fact, irreversibly destroyed by Moretti's restoration, which transformed the baroque church into a (hypothetically) medieval structure by: (i) removing the transverse walls of the chapels, (ii) opening the three arches in the right side wall of the nave; (iii) removing the longitudinal walls of the transept and the choir, and the transverse wall of the transept aligned with the two pillars (and taking apart the dome); (iv) restructuring the polygonal apses, perhaps by rebuilding the wall separating the central apse from the one on the left (fig. 8).

Apart from modifying the layout of the church, individual elements were also drastically changed, first and foremost the main façade, which was returned to its medieval square shape reducing its height (by demolishing the upper part of the nineteenth century façade), adding new parts (in order to obtain the squared outline) and thickening the wall (in order to realize a continuous vertical plane). If the two façades are compared side by side (before and after the 1969 restoration) we see that the discontinuities in the stone facing of the present façade correspond to the first order of pilasters in the nineteenth century façade (fig. 9). This can be clearly seen in the right corner pilaster, where there is a vertical dark patch in the upper part.

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Therefore, during Moretti's restoration, the area between the pilasters was levelled, using thin slabs (see below, § 3.2), and the mouldings of the cornice and the bases of the trapezoidal pilasters of the second order were cut to flatten them at the level of the surface of the pilasters.

As a result, Moretti's interventions have undoubtedly determined an increase of the vulnerability of the church, with regard to both its general layout and the constructive quality of its elements.

The nave is at present deprived of any transverse supporting structures because of the removal of the internal walls of the chapels - since the right aisle does not seem to have been designed to act as a support for the nave - and is weakened longitudinally by the presence, on the right wall, of the three arches that link the nave and aisle.

As for the transept, the indecipherable architectural solution implemented by Moretti - the roof and underlying structures are incongruent – corresponds to the precariousness of the whole structural system. In fact, while longitudinally the transept can count on the support offered by the massive contiguous structures of the polygonal apses and the side walls of the nave (provided, of course, they are linked at the roof level to give stability to the high piers), transversally the alignment of two piers seems to be decidedly weak, failing, moreover, to connect the side walls of the transept.

It was this new, weaker structure that was hit by the earthquake of 6 April 2009.

4. The survey of masonry works' quality

The on field survey and the constructional interpretation of the building which were carried out few months after the earthquake were conditioned, on the one hand by the possibility of analysing just the elements of the nave (so that repair work on the most seriously damaged parts could get started as soon as possible; we were not concerned with the analysis of the bell tower), and on the other by the absence of an accurate geometric and architectural survey.

However, the results of the work performed on the church (direct survey and investigation on masonry works), together with the results of the historical research detailed in the previous paragraph, clearly document the reasoning outlined in the introduction to this paper and allow us to give a coherent explanation of the nature and extent of the damage that occurred during the earthquake of 6 April 2009.

Here we shall limit ourselves, for obvious reasons of space, to the theme of masonry quality, which was assessed by direct observation (after removing plaster from the walls, drilling small holes in the masonry or removing single stones) and by instrumental analysis (Russo, 2011) (including in situ micro-seismic and vibration tests, flat-jack tests, laboratory analysis on mortar samples and monitoring of cracks).

The judgment on masonry quality, which is indispensable for a study of any historical building, is even more crucial in this case. In fact, the extent and seriousness of the damage sustained by buildings affected by the 2009 earthquake led many scholars to be highly critical of the masonry

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techniques used in L'Aquila, interpreting particular, and relatively unknown, constructional techniques as defects, thus penalizing (perhaps unjustly) entire constructional contexts.

In the case of the church of San Pietro di Coppito, what clearly emerges and may be used to make a general assessment on constructional survey, is the fair to good quality of the masonry in the walls and pillars of the nave, except in the parts where extensive alterations were made and which can introduce more or less marked discontinuities or a lack of homogeneity (these alterations are the result of the complex building history of the church and the great number of constructional phases, often to repair damage caused by traumatic events: from medieval repairs to the 15^{th} century renovation, from the baroque reconstruction to the "restoration" in the last century).

This can be seen first and foremost in the nave walls, both the façade and side walls whose masonry quality deserves to be looked at in detail (fig. 9, top). The walls are built using relatively small stones (up to 20 to 25 cm) in relation to the thickness of the walls themselves and, for this reason, they do not seem to be in line with the classical interpretative parameters of the rules of the art of masonry, as set out in late nineteenth century treatises (Curioni, 1875; Breymann, 1878), since it was evidently impossible to respect the fundamental requirement that imposes the use of large stones (headers) in the masonry to ensure transverse compactness of the walls (fig. 9, lower left). However, it would be wrong to say that this system simply does not respect the rules of masonry. It is more correct to say that the system respects a rule somewhat different from the classical one (and, undoubtedly, more complex and difficult because it makes use of poorer quality material) but whose mechanical intent is the same – and can be always summarized in the wish of ensuring the transverse compactness and the horizontal layering of the walls (Carocci and Tocci, 2012).

This rule, observed in the church and frequently recognized in other buildings of L'Aquila and of the minor historical centres in the surroundings, involves keeping to a rigorous arrangement of stones throughout the thickness of the wall (fig. 9, lower right), using stones of the same size for the two outer facings and for the inner core (thus not the type of masonry known as "*a sacco*"), and compensating for the lack of transverse block bonding, such as that provided by headers, with a distributed connection provided by stones of uniform size: these are arranged in regular courses – overlapping the stones of superimposed courses and toothing them out in the same course (where they are laid, alternately, with their main dimension parallel or orthogonal to the wall plane, i.e. as headers and stretchers) - and the gaps between them are filled with smaller stones and bricks wedged in.

The best demonstration of the effectiveness of L'Aquila rule of masonry, as it appears to be applied in San Pietro di Coppito, is the absence of any noticeable damage to the masonry walls (both the façade and the side walls) which, during the last earthquake, underwent considerable out of plane oscillations whilst maintaining their monolithic quality.

It is difficult to suggest relative dating of the different masonry types in the church, since we do not know how much of the church that was rebuilt in the 15th century was incorporated into the baroque church and how much of the latter was spared by Moretti's restoration. We may note, however, that there are signs of eighteenth or nineteenth century alterations made using thin

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bricks and lime mortar, firmly clamped to the rough stone masonry in which they are inserted, which shows that we are in the presence of a constructional culture analogous to the original.

Compared to these masonry works, which we can describe as being of average to good quality, even after the subsequent (eighteenth or nineteenth century) modifications in brick, the alterations made by Moretti can be distinguished by a certain crudeness – such as can easily be seen in the left side wall – or a complete indifference to the dangers of seismic action – as in the interventions for the reconstruction of the façade (fig. 10).

With regard to the latter, our statement is proved by different constructive solutions. The great window in the nineteenth century façade, below the present rose window, has been closed up without the new masonry being clamped in any way to the adjacent structure. Again, the square outline of the facade has been realized by simply adding new parts to the curved nineteenth century facade, in this case too without any form of toothing out – and it would have been fairly natural to add, as in the nearby church of San Silvestro (or in imitation of the construction techniques used in L'Aquila), effective in-plane bonds by inserting the traditional wooden *radiciamenti*. Finally, consider the solution to the problem of giving a stone facing to the façade: first by thickening it above the line that can be seen today at the top of the trapezoidal pilasters (where the nineteenth century façade tapered) without, for the umpteenth time, any block bonding to the original wall, and then by roughly laying big stone slabs on a thick layer of cement mortar. This type of connection is acceptable only in the area included between the stone pilasters of the nineteenth century façade (effectively bonded to the masonry behind them), due to the constraint they create for the stone cladding, reducing the possibility of a buckling collapse

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of the cladding itself; but it involves an extremely precarious situation in the upper zone (not by chance, the cladding still adheres perfectly on the lower part of the façade, despite the strong oscillations to which it was subjected, while the whole upper portion has mostly come away, especially near to the collapsed areas).

What we said about the masonry works of the nave walls can be repeated for the two pillars of the right wall (fig. 11, top). These both consist of an external face with a pseudo-isodomum arrangement of ashlar stone, and an inner core of rubble embedded in lime mortar, but exhibit, nonetheless, significant constructional differences, fully compatible with the different damage induced by the last earthquake.

The pillar closest to the façade has a stone facing of constant thickness on all four sides (20 - 25 cm), with well-placed ashlars and thin vertical joints; the inner core (for which no samples were taken but sonic tests (Russo, 2011) were performed) shows an adequate compactness, although being (obviously) less rigid than the faces and with an asymmetric distribution of damage (consistent with the greater damage detected towards the nave).

The second pillar, instead, which had already suffered serious prior damage, has been extensively and extremely badly reworked. The facing overlooking the aisle on the right consists almost entirely of thin slabs, no more than 10 cm thick, which can be clearly ascribed, also from the surface work, to the restoration done in the last century by Moretti: we may suppose that before this, the pillar was joined to a wall that was then removed, and so facing needed to be added to the part that was originally not in view. The other visible faces of the pillar, especially that overlooking the nave, show clear signs of previous seismic damage: the filling between the

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stones has come away quite noticeably and old gaps, some of them quite wide, have reappeared in the ashlars and in the vertical joints, brought to light by the movements induced by the tremors of latest earthquake. The inner core of the pillar is also in a poor state of preservation probably due to the considerable oscillations it had been subjected to, not only during the last earthquake, which produced the evident loss of cohesion and consistency in the core.

Finally, one last constructional aspect to note concerns the clear and generalised lack of block bonding between the building walls (fig. 11, bottom). The side walls of the nave simply lean against the façade wall and the triumphal arch wall and the movements induced by the tremors of the last earthquake have further displaced them to such an extent that in some places they have come away.

Similarly, we see that Moretti's r.c. tie-beams – which, placed on the cymatia of the nave side walls, naturally led to further alterations in the masonry structure to even out the upper surface - are connected neither to the façade wall nor the triumphal arch wall, falling just short of both of them. Neither are the roof trusses connected to the r.c. tie-beams, being simply supported by wooden or stone elements that rest on the extrados of the tie-beams themselves.

In this case, too, we cannot help noticing the enormous difference in technique with the eighteenth century builders. After removing the plaster from the left wall there emerged the remaining portions of the *radiciamenti* that linked the partition walls of the chapels of the baroque church to the outer side wall, an unmistakable sign of constructional foresight which stemmed from a clear understanding of the danger of horizontal seismic action and an awareness of the need for more solid construction techniques to address them.

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The lack of connections between the different parts is, moreover, made worse by the very characteristics of the present layout. Vibration tests (Russo, 2011) identified modal deformations and interactions between the structural macro-elements (nave, transept, bell-tower), confirming the very low level of coupling, an evident consequence of the structural configuration of the building, and the absence of effective connections between the component parts.

5. THE DAMAGE CAUSED BY THE EARTHQUAKE OF APRIL 6, 2009

Something that is always promptly seen after every earthquake, provided it is non-destructive of course, is that old masonry buildings are not all affected in the same way; poorly constructed buildings or those that have been badly modified are severely damaged, some collapsing, while those that are well-built rarely suffer irreparable damage. This observation is fully confirmed in the church of San Pietro di Coppito: alterations made to the structure of the church by Moretti's heavy handed structural interventions - which eliminated all forms of transverse buttressing of the nave and weakened longitudinal buttressing - were brought to the fore by the earthquake of April 6, 2009.

The survey of the damage to the church - together with the observation of cracks in the buildings overlooking the square - shows there were considerable seismic actions in both planimetric directions, though stronger longitudinally.

The longitudinal actions caused the damage to the bell tower and the upper part of the façade. The façade has come away from the two side walls of the church, with cracks along the previous crack lines which get bigger as they approach the top, where, in the remaining portion of the roof, the purlins of the rafters have partly (some completely) come out of their housings in the façade. The greater weakness of the right wall of the church, due to the three arches that drastically reduce the shear resistance area (limited, in fact, only to the solid part behind the façade), is consistent with the stronger longitudinal oscillations affecting the right side of the church and the consequent collapse of the upper part, not effectively held in place, of the façade (the part that collapsed was the one added by Moretti in order to create the squared shape) (fig. 12).

The masonry wall behind the façade, on the right, was badly damaged, as also the two pillars in which some ashlars were crushed by concentrations of load due to the oscillations. Moreover, the removal of the plaster from the masonry highlighted the extensive alterations made to the structure even before Moretti's interventions, and the consequent constructional weakness – in addition to geometric insufficiency – of the right wall (fig. 13, top).

The left wall, too, was more badly damaged near the façade, where the greater concentration of shear stresses was accompanied by a particular weakness of the wall in terms of both geometry (the wall is less thick because of a niche) and constructive quality (due to the presence of prior damage and consequent alterations to the masonry work) (fig. 13, bottom).

The cracks in the two pillars by the orthogonal faces of the nave, and the loosened stones in the second arch, show that there was also transverse movement (fig. 14). This is confirmed by cracks

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in the façade which are not attributable to the rotational movement responsible for the collapse but rather to forces acting in the plane of the façade itself.

Transverse movement also triggered the damage to the triumphal arch of the transept and its left pier. The arch was affected by the classic mechanism known in the literature as bending mechanism, in which cracks appear at the top of the intrados and at the bottom of the extrados, while the pier on the left has clearly visible shear cracks on the external surface and less clear ones on the inside, due to the extensive alterations it underwent, highlighted by the effects of the last earthquake.

Moreover, the dislodgment of the key stones and the cracks in the stones next to both abutments, nave side, reveal the out of plane rotation of the arch and confirm the strong longitudinal seismic movement (fig. 15).

The vertical cracks in one of two piers of the transept are due to the rotation of the piers and the consequent concentration of load at the base.

The cracks were monitored. A topographic survey carried out in the period from 08/2010 to 03/2011 gives façade displacement figures that are negligible, between -2 mm and +1.6 mm, while continuous static monitoring for the period 13/05/2011 – 12/07/2011 shows amplitude variations in the cracks probably due only to temperature variations.

6. The restoration currently underway

At the conclusion of this work, we wish to mention some design issues concerning the project for the general restoration of the church and the repair of the most damaged parts as defined by the *Soprintendenza*, also on the basis of the research that we performed for the structural advise one of us was asked for. The interventions that we suggested are currently underway.

Because of the church's major structural problems, as they emerged after the earthquake of 6 April 2009 and highlighted by the analysis detailed in the previous sections, the restoration of the architectural organism involved not only repairing the worst damage (in order to prevent things getting worse and to make the church safe in the event of a new earthquake), but also implementing an overall seismic improvement strategy so as to address the precariousness – in the church layout and in constructive quality of the elements – which played a decisive role in the type and extent of damage.

From this point of view, and with reference to the nave, which the improvement project was limited to, the major problem is poor containment in both planimetric directions which is a consequence of Moretti's improper interventions and, on the contrary, had been one of the most serious concerns of the baroque builders, as it clearly arises from the historical research. An effective seismic improvement strategy would thus require, recalling the anti-seismic configuration of the eighteenth century church, the systematic introduction of connections to hold together the different structural elements, so that they act as a whole, with the introduction

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of additional buttresses where defects in the layout are such that they cannot be realistically remedied by the simple use of tie-rods (fig. 16).

The building walls will be connected to the façade and the triumphal arch by a reinforced masonry tie-beam on top, which in turn will be anchored to new trusses, and the roof structure will be braced by a double series of crossed wooden planks so that each slope of the roof can behave as a diaphragm connecting the supporting walls. More tie-rods will be inserted into the longitudinal walls at an intermediate height and, for the right wall, these elements will be connected to the masonry tie-beam at the top of the right aisle walls and to the rafters of the aisle roof, which will also have a double wooden plank bracing system. The left wall will be buttressed by three external masonry spurs, clamped to the wall using metal tie-rods, and connected at the top to the above mentioned intermediate longitudinal tie-rods.

These structural interventions, aimed at improving the seismic behaviour of the church, will be completed by the repair (or reinforcement) of the most damaged parts (fig. 17): the façade (for which the collapsed upper right part will be reconstructed, inserting a double row of in-plane tie-rods at the height of the lower edge of the collapsed part and inside the top masonry tie-beam, the thickening of the upper part of the nineteenth century façade (by Moretti) will be bonded to the old wall, the adherence of the stone facing will be improved by replacing some of the thin slabs with stone blocks bonded to the rear masonry wall), the pillars of the nave (whose broken or thin ashlars will be replaced by new ashlars firmly toothed out to the inner core, together with the repair of the core itself), the nave walls (where the parts that had been more deeply altered will be repaired).

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This series of interventions will produce an overall structural improvement of the nave which, beyond any structural analyses (anyway briefly discussed in the next section), is logically proved as soon as the damage occurred during the 2009 earthquake is compared, according to the results of historical analysis and constructional survey, with the weaknesses introduced by Moretti on the anti-seismic organism conceived after the 1703 earthquake. Thanks to the systematic connection of the different elements, the right aisle will compensate for the asymmetry in the longitudinal resistance of the two side walls and, together with the new spurs, will guarantee greater transverse resistance than we have today. As a consequence, the stiffened nave will be able to behave, together with apses, as a solid support for the transept, in both longitudinal and transverse directions, provided of course that a systematic connection is introduced for the elements of the transept too, so that the containment can be transferred to the masonry alignment defined by the two octagonal pillars. In this sense, the proposed improvement strengthen the weakest part of the church (i.e. the nave) but also provide a solid basis for subsequent interventions in the transept area.

In line with current Italian legislation (Min. Infr.&Trasp., 2008; Cons. Sup. LLPP, 2009), structural analysis has been carried out according to a verification methodology in which the analysis of the structure as a whole is rejected (as unrealistic) and the attention is devoted to single elements, or assemblies of elements, modelled as systems of rigid bodies whose mechanical behaviour is governed by the kinematic theorem of limit analysis.

It is well-known that mechanism analyses are pretty much elementary from the point of view of calculation but rather tricky when it comes to identifying the kinematic mechanisms to be tested

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and, especially, as regards the preliminary justification of the procedure which, assuming a monolithic behaviour of the portions involved in the mechanism, requires a reasoned judgment of the mechanical quality of the masonry.

In the case in question, the choice of a mechanism-based modelling strategy is supported by the constructional analysis detailed above (see above, § 3.2), and proved incontrovertibly by the monolithic behaviour exhibited during the last earthquake by both the façade – it was not by chance that one of the two corners added in the 1970s restoration collapsed – and the side walls – the outside face of the left wall, straightened and made vertical by adding cladding (while the inner face is clearly off plumb), shows both greater historical transverse weakness and the capacity of the wall to withstand significant out of plane movements without significant loose in monolithism. This does not mean that the masonry structure of the above walls does not need interventions to improve their compactness (see above, § 3.4.1) but that, even in the present state, they are able to sustain the onset and evolution of rigid body kinematic mechanisms.

Although a detailed discussion of the different mechanisms analysed is beyond the purpose of this paper (some of them are illustrated, as an example, in figure 18), a particular aspect deserves nonetheless to be underlined. The project state is described, for both the façade and the nave side walls (the structural portions that have been considered in the analyses), by a succession of mechanisms which involve increasing resistant contributions – as provided for in an increasingly effective improvement strategy – and allow modelling the individual effectiveness of each intervention with the aim to take into account the possibility that some of them proves to be ineffectual, depriving the building of a stability factor that should therefore be excluded from the

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calculations. Such a supposition derives from the fact that the kinematic mechanisms assumed for the evaluation of seismic improvement are based on hypotheses about the structural behaviour of the reinforced building, which, even if reasonable, are, however, still characterized by margins of uncertainty that are far from negligible, since they presuppose uncertain (and difficult to assess) structural interaction mechanisms.

With reference to the façade, for example, the effectiveness of intermediate tie-rods relies on the capacity of the nave side walls to absorb shear actions transferred to them: which requires, for the right side wall, the development of a rather complex truss-type resistance mechanism in the aisle roof (and external wall).

This kind of reasoning – that could be summarized in the simple statement that it is not wise to rely on what you cannot know – is at the basis of the heavier intervention proposed for the church and consisting in providing the left side wall of the nave, i.e. the weakest structural element in the transverse direction, with independent seismic reinforcements (masonry spurs), the effectiveness of which is not subordinate to the other interventions planned in the project and therefore ensures an improvement of the seismic behaviour that identifies a lower level for the resistance to horizontal actions of the restored building.

7. Conclusions

After the catastrophic earthquake of 1703, the constructional culture in L'Aquila improved the traditional rules of the art of masonry with a series of precepts that showed an awareness of the need to introduce anti-seismic measures into the ancient art of building. If we were to sum up the

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sense of these precepts we should do so on two levels: firstly, it is clear the attempt to interconnect the various structural parts of a building in ways that are more effective than those provided for in tradition – wooden logs inserted in the masonry, acting like ligaments to strengthen isolated walls and turning them into a sort of firm box; wooden stakes placed through the supports of the trusses lower chords and anchored to the outside of the walls, closing the lid of this box –; secondly, the layout of masonry walls is recognised as the first and most important requirement of any anti-seismic building which should have an adequate number of shear walls in both main planimetric directions.

Strictly adhered to in the first years after the earthquake, these precepts gradually fell into disuse, their initial use and purpose being forgotten, until they were completely abandoned when, centuries after the catastrophe, the earthquake had become a distant memory.

We chose in this paper to exemplify this singular process – which is not limited to Abruzzo – with the constructional history of the church of San Pietro di Coppito: a paradigm of the new anti-seismic construction techniques that were introduced after the 1703 earthquake and emblematic of the process of memory removal two centuries later, in the nineteen seventies.

The aim of the work, in view of the massive restoration task awaiting the Abruzzo region (and which, three years after the earthquake, has, unfortunately, yet to be systematically implemented), is to suggest a possible course of action which, by recognising the effectiveness of masonry techniques adopted in the wake of the 1703 earthquake and their intrinsic coherence with the art of masonry, may draw inspiration from them to identify constructional measures that can reconcile the imperatives of safety and conservation.

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Moreover, the constructional history of San Pietro di Coppito highlights the more general issue of the methodology to be used for the analysis of the static and seismic behaviour of historic masonry buildings. The study carried out confirms once more the crucial role played by a multidisciplinary approach which, by closely correlating historical and architectural research with direct observation and constructional and structural survey, leads to an understanding of the resistance mechanisms and vulnerability factors that can make the mechanical analysis of buildings more comprehensive and objective, and moreover establishes a firm foundation for the definition of an informed and consistent strategy for restoration and seismic improvement.

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REFERENCES

Alberti, L.B. 1755. *The Architecture of Leon Battista Alberti in Ten Books* (first English translation of the fifteenth century edition by J. Leoni). Printed by Edward Owen. London.

Barbisan, U. 1997. *Il terremoto e le tecniche costruttive a Reggio Calabria e Messina nel 1908*. In Costruire in Laterizio, 56: 116-121.

Barucci, C. 1990. *La casa antisismica: prototipi e brevetti*. Roma: Gangemi.

ACCEPTED MANUSCRIPT

Benedetti, S. 1975. *L'architettura dell'epoca barocca in Abruzzo*. In Atti del XIX Congresso di Storia dell'Architettura. 275-312. L'Aquila.

Bertaux, E. 1904. *L'art dans l'Italie méridionale.* Parigi.

Breyman, G.A. 1926. *Costruzioni in pietra e strutture murali*. Milano.

Capecchi, D. and Tocci, C. 2011. *Le perizie sulla cupola vaticana di Le Seur, Jacquier e Boscovich*. In «Palladio», January-June 2011: 43-58.

Carocci, C.F. and Lagomarsino, S. 2009. *Gli edifici in muratura nei centri storici dell'Aquilano*. In Progettazione Sismica, 3:117-134.

Carocci, C.F. and Tocci, C. 2009. *Sicurezza e conservazione degli edifici storici monumentali. La chiesa di San Nicolò l'Arena a Catania*. Roma: Gangemi.

Carocci, C.F. and Tocci, C. (eds). 2010. *Antonino Giuffrè. Leggendo il libro delle antiche architetture. Aspetti statici del restauro, saggi 1985-1997.* Roma: Gangemi.

Carocci, C.F. and Tocci, C. 2012. *L'Aquila Region masonry works*. In VIII International Conference on Structural Analysis of Historical Constructions. Wroclaw, Poland.

Cons. Sup. LLPP 2009. *Circolare del Consiglio Superiore dei Lavori Pubblici n. 617 del 02/02/2009 recante Istruzioni per applicazione delle Norme Tecniche per le Costruzioni*.

Clementi, A. and Piroddi, E. 1986. *L'Aquila*. Bari: Laterza.

Costantini, B.1915. *I terremoti d'Abruzzo*. In Rivista Abruzzese, XXX (1915), 8: 281-295.

Curioni, G. 1870. *L'arte di fabbricare*. Torino.

ACCEPTED MANUSCRIPT

Di Pasquale, S. 1997. *La cupola, le fratture, le polemiche*. In *L'architettura della Basilica di S. Pietro. Storia e costruzione*, Atti del Convegno Nazionale di Studi, Roma 7-10 November 1995, edited by G. Spagnesi. Roma.

Franchi, C. 1752. *Difesa per la fedelissima città dell'Aquila contro le pretensioni de'Castelli, Terre e Villaggi che componeano l'antico Contado aquilano intorno al peso della buonatenenza*. Napoli.

Gavini, I.C. 1915. *I terremoti d'Abruzzo*. In R.A.S.L.A., XXX (1915): 235-250.

Gavini, I.C. 1927. *Storia dell'architettura in Abruzzo*, 2 vols.. Milan-Rome.

Giuffrè, A. (ed). 1993. *Sicurezza e conservazione dei centri storici in zona sismica. Il caso Ortigia*. Bari: Laterza.

Guidoboni, E. 1997. *An early project for an antiseismic house in Italy: Pirro Ligorio's manuscript treatise of 1570-74*. In European Earthquake Engineering, 4: 1-18.

Langenbach, R. 2007. *From "Opus Craticium" to the "Chicago Frame": Earthquake-Resistant Traditional Construction*. In International Journal of Architectural Heritage, 1 (2007): 29-59.

Masiani, R. and Tocci, C. 2012. *Ancient and modern restorations on the Column of Marcus Aurelius in Rome*. In International Journal of Architectural Heritage, 6 (2012): 1-20.

Miarelli Mariani, G. 1979. *Monumenti nel tempo. Per una storia del restauro in Abruzzo e nel Molise*. Roma.

ACCEPTED MANUSCRIPT

Min. Infr.&Trasp. 2008. *Decreto del Ministero delle Infrastrutture e dei Trasporti del 14/01/2008, Norme Tecniche per le Costruzioni*.Moretti, M. 1973[1]. *Restauri d'Abruzzo (1966-1972)*. Roma.

Moretti, M. 1973[2]. *Architettura medioevale in Abruzzo (dal VI al XVI secolo)*. Roma.

Pace, V. 1971. *Ancora sulla tutela del patrimonio artistico. Restauri ai monumenti d'Abruzzo*. In Paragone, XXIII (1971), 261:71-82.

Reycend, A. 1909. *Relazione della Commissione incaricata di studiare e proporre norme edilizie obbligatorie per i comuni colpiti dal terremoto del 28 dicembre 1908 e da altri anteriori*. In Giornale del Genio Civile, Roma.

Rivera, C. 1905. *Le piante ed i prospetti della città dell'Aquila*, in Bollettino della Deputazione Abruzzese di Storia Patria, XVII, II, pp. 104 sgg.

Ruffolo, F. 1912. *Stabilità sismica dei fabbricati*. Napoli.

Russo, S. (ed) 2011. *Monitoraggio delle chiese di S. M. Paganica e S. Pietro di Coppito all'Aquila*, Report X (final report). Convenzione tra l'Università IUAV e la Direzione Regionale ai Beni Culturali dell'Abruzzo.

Signorini, A. 1868. *Diocesi di Aquila, descritta e illustrata*. I. L'Aquila.

Silone, I. 1968. *Le avventure di un povero cristiano*. Milano.

Spagnesi, G. and Properzi, P.L. 1972. *L'Aquila. Problemi di forma e storia della città*. Bari.

Spagnesi, G. 1975. *L'architettura barocca all'Aquila*. In Atti del XIX Congresso di Storia dell'Architettura. L'Aquila, Settembre 1975: 495-518.

ACCEPTED MANUSCRIPT

Spagnesi, G.. 2009. *Il centro storico dell'Aquila. Memoria e progetto*. Rome.

Stockel, G. 1981. *La città dell'Aquila. Il centro storico tra il 1860 e il 1960*. L'Aquila.

Tobriner, S. 1997. *La casa baraccata: un sistema antisismico nella Calabria del XVIII secolo*. In Costruire in Laterizio, 56: 110-115.

Varagnoli, C. 2000. *Dal viceregno al regno. Abruzzo e Molise*. in Curcio, G. and Kieven, E. (eds) Storia dell'architettura italiana. Il Settecento, 294-301. Milano: Electa.

Vivenzio, G. 1783. *Istoria e teoria de' tremuoti in generale, ed in particolare di quelli della Calabria e di Messina del 1783*. Napoli.

Zevi, B. 1973. *L'ilare soprintendente ai monumenti. Assassinio chiamato restauro*. In Cronache di architettura (VIII)825-952: 349-351. Bari: Laterza.

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Fig. 1. L'Aquila: wooden log (*radiciamento*) in a shear wall (on the left). L'Aquila: the effectiveness of wooden logs inserted in the façade of the church of S. Silvestro preventing its global overturning (on the right).

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Fig. 2. L'Aquila: vertical wooden log, probably part of a more complex wooden frame (on the left). L'Aquila: wooden tie-rods in a cloister vault in Palazzo Ardinghelli (on the right).

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Fig. 3. Paganica (AQ): the tie-beams of the roof trusses of the nave are systematically anchored (pegged) to the outside part of side walls with wooden pegs (on the left). Poggio Picenze (AQ): the systematic use of metal tie-rods and wooden logs, and the wedge shape of the outside walls, prevented the out-of-plane collapse of the facing walls (and determined their in-plane cracking (on the right).

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Fig. 4. Top: Gonfalone by G. Paolo Cardone (Clementi and Piroddi, 1986). Centre: Plan of L'Aquila by G. Pico Fonticulano in the version engraved by Giacomo Lauro in 1600, similar to Bleau's later engraving published by Mortier in 1680 (the original dates to 1575) (Rivera, 1905). Bottom: Vandi's plan (Franchi, 1752).

Fig. 5. Top: the façade and a view of the right side of the church of S. Pietro di Coppito before the 1969 restoration (Miarelli Mariani, 1979). The partition walls between the side chapels and the nave rise above the right side wall, effectively counterbalancing the higher walls of the nave. The two walls that delimit the transept rise to the same height as the wall of the nave, supporting the dome.

Bottom: plan and section of the church, before the 1969 restoration, as reconstructed by Gianfranco Spagnesi (Spagnesi and Properzi, 1972).

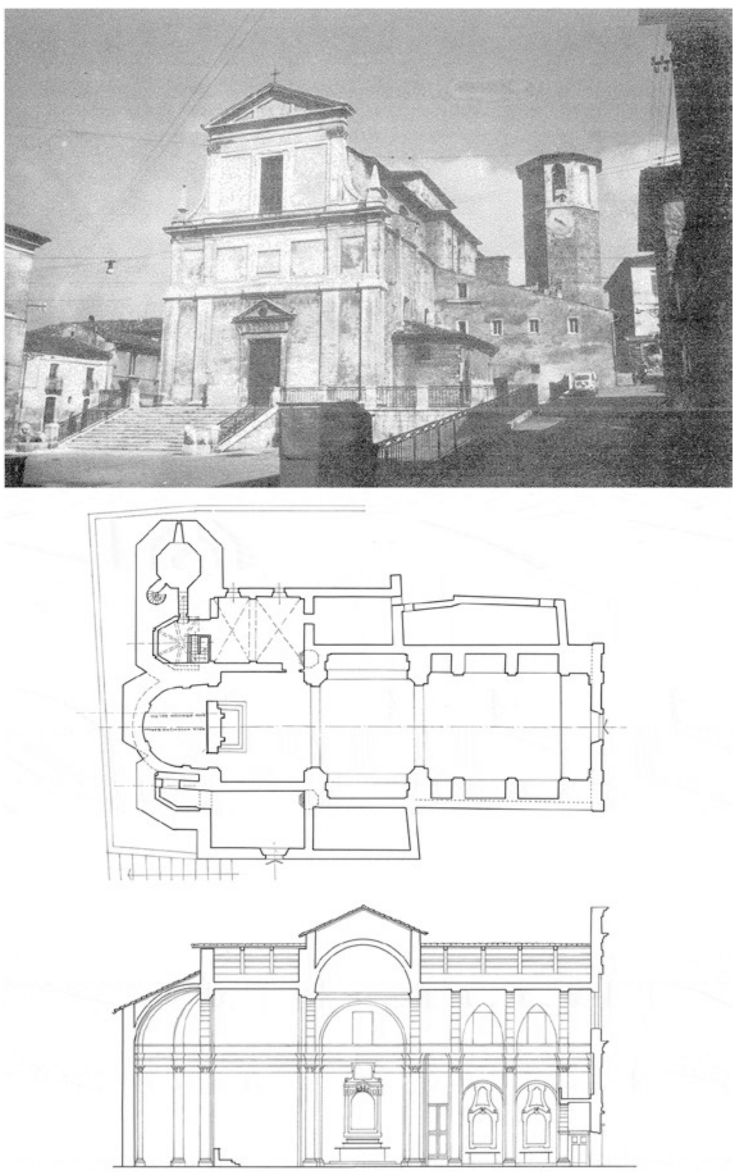

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Fig. 6. Top: nineteenth century façade, before and after the 1969 restoration (in the stone facing of the present façade the pilasters of the first and second order of the nineteenth century façade can be easily identified).

Bottom: polygonal apses before and after the 1969 restoration.

Fig. 7. Top: the façade and a view of the right side of the church of S. Pietro di Coppito before the 2009 earthquake.

Bottom: plan and section of the present church, in a drawing dating back to the 1969 restoration.

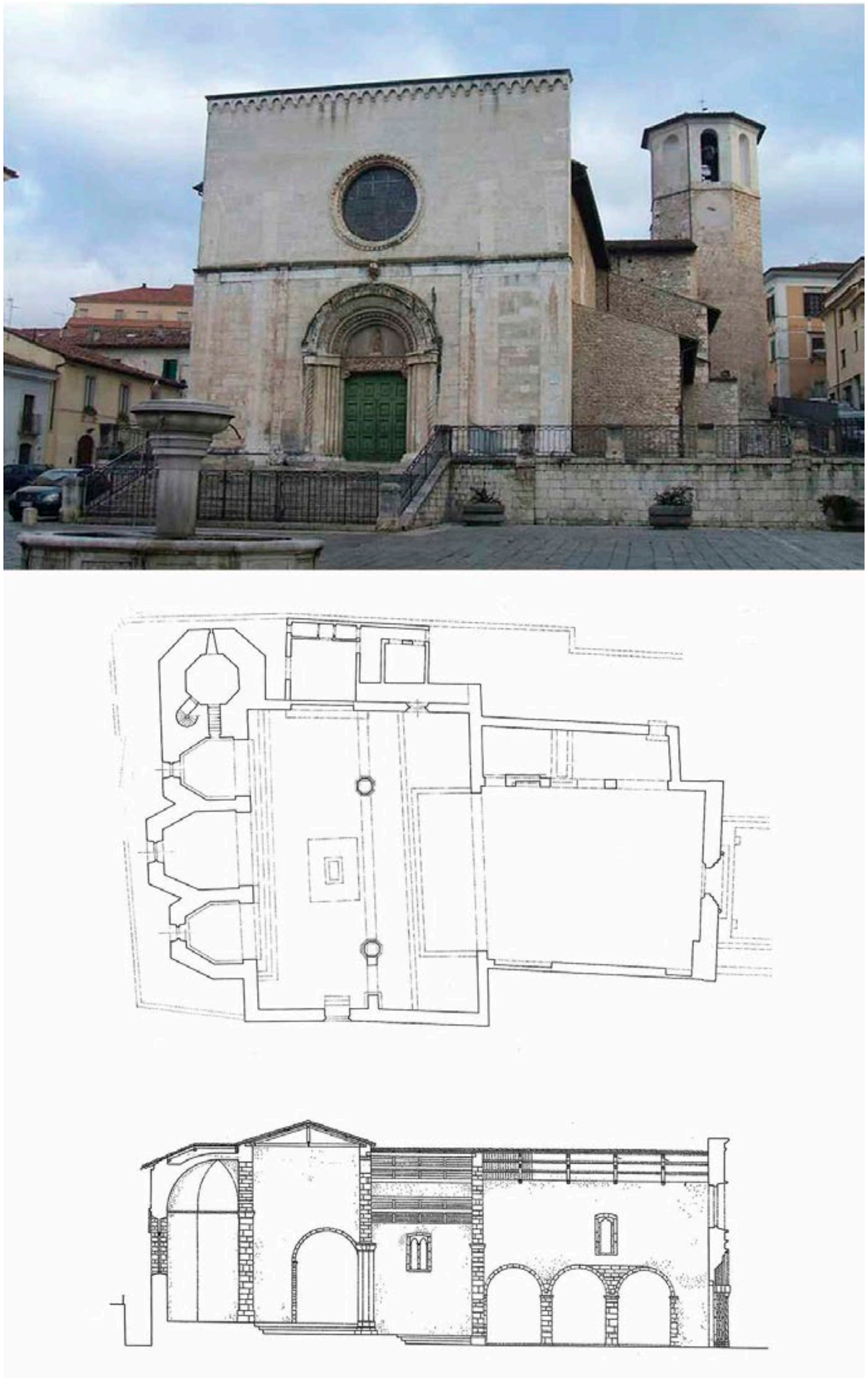

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Fig. 8. The present plan of the church superimposed on the nineteenth century plan as reconstructed by Gianfranco Spagnesi.

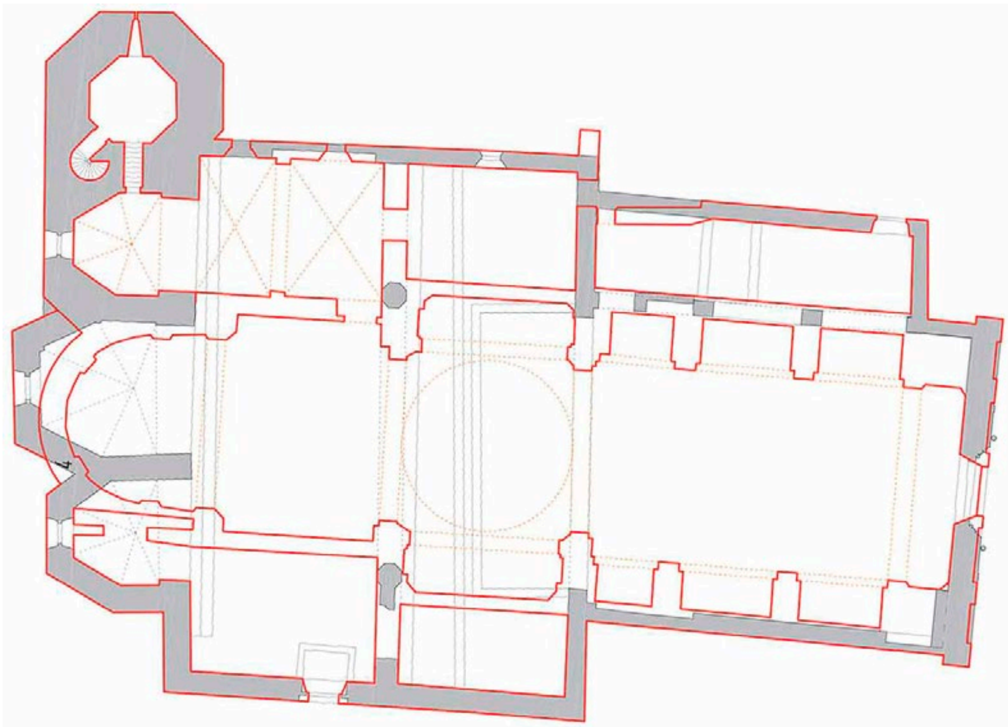

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Fig. 9. Top: direct survey of masonry works in the façade wall (on the left) and the left nave wall (on the right), by removing single stones from the outer facings.

Bottom: Comparison between the stone arrangement prescribed in classic nineteenth century treatises (on the left) and the stone arrangement surveyed in the church (on the right).

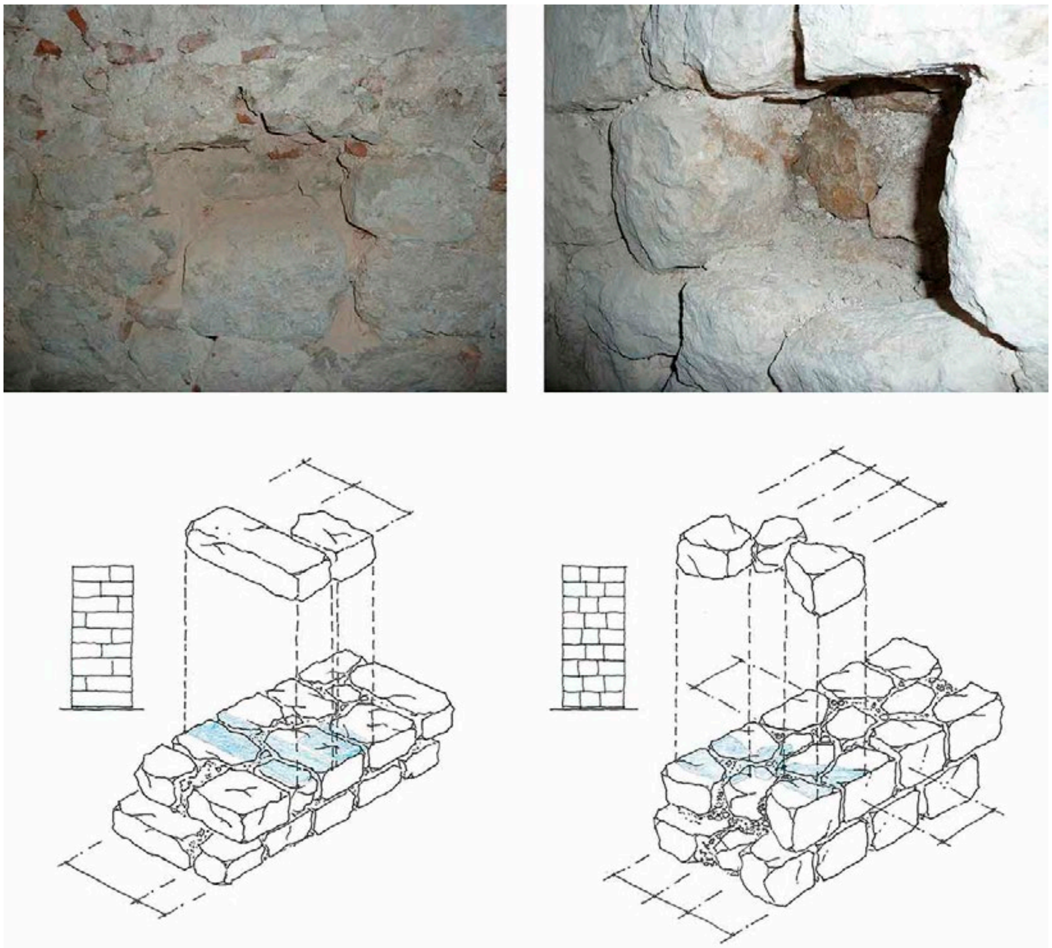

Fig. 10. Top: (on the left) the surviving false front of the façade (we can clearly see where the new masonry added by Moretti, rough stones laid on cement mortar, joins – without toothing out – to the original masonry, wedged with bricks and lime mortar, like the masonry visible on the façade wall inside the church); (on the right) the thickening of the nineteenth century façade obtained by Moretti by simply placing a new wall side by side with the existing one.

Bottom: direct survey of the stone facing in the façade by removing single stones from the cladding; on the right we can recognize the block bonding of the pilaster's ashlars in the rear masonry wall and the thick layer of cement mortar where big stone slabs are laid.

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Fig. 11. Top: (on the left) the filled-in joints of the first pillar (from the façade), face overlooking the aisle are still intact; (on the right) the poor quality of the inner core of the second pillar, face overlooking the aisle can be seen under Moretti's thin slab cladding.

Bottom: (on the left) the r.c. tie-beam is not anchored to the façade; (on the right) the tie-beam of the first roof truss behind the façade simply rests on a wooden sleeper placed on the extrados of the r.c. tie-beam (the supportig shelf is in fact hanging from the tie-beam).

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Fig. 12. Damage due to the earthquake of 6 April 2009. The right corner of the façade has collapsed, as also the top of the bell tower, which, falling, also badly damaged the roof of the transept. The collapse shows that the stone cladding consists of thin stone slabs stuck onto the wall; moreover, the first row of stone cladding, which remained in place, does not seem to extend beyond the part (trapezoidal pilasters) where Moretti reused the stones elements of the previous façade for his restoration (top and lower left). Inside the church, the cracks follow the lines of the Baroque façade (lower right).

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Fig. 13. Top: in-plane shear cracks in the right nave wall, in both the masonry structure behind the façade and the two pillars. The cracks are bigger than those in the left nave wall because of a smaller overall stiffness (due to the presence of the pillars); this in turn is responsible for the more pronounced movements seen in the right part of the facade and the consequent collapse of the top portion of the latter.

Bottom: in-plane shear cracks in the left nave wall. It should be noted, moreover, that the inner side of this wall is not perfectly vertical and was corrected by adding a substantially perpendicular external facing. This is an evident sign of prior damage repaired by external cladding.

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Fig. 14. Top: the first pillar on the right of the nave. Cracks can be seen both in the face overlooking the aisle (on the right) and in the orthogonal face (on the left) and reveal both longitudinal and transverse movements (in line with the damage found on the facade and the triumphal arch of the transept). On a corner (towards the aisle and towards the transept), the stones were crushed by the longitudinal and transverse oscillations of the pillar.

Bottom: the second pillar on the right of the nave. Cracks can be seen in the surfaces that face (on the right) and are orthogonal (on the left) to the nave, revealing both longitudinal and transverse movements. Previous cracks, some of them big, have been plastered. The damage in this pillar is much more serious than in the other since it had already suffered previous damage.

Fig. 15. The triumphal arch between the nave and the transept has cracks consistent with a classic flexural mechanism, at the top of the intrados and at the bottom of the extrados (top and lower left); the diagonal cracks in the left pier of the arch are consistent with an in-plane action. The dislodgment of the key stones (lower right) and the cracks in the stones next to both abutments, nave side, reveal the out of plane rotation of the arch and confirm the strong longitudinal seismic movement.

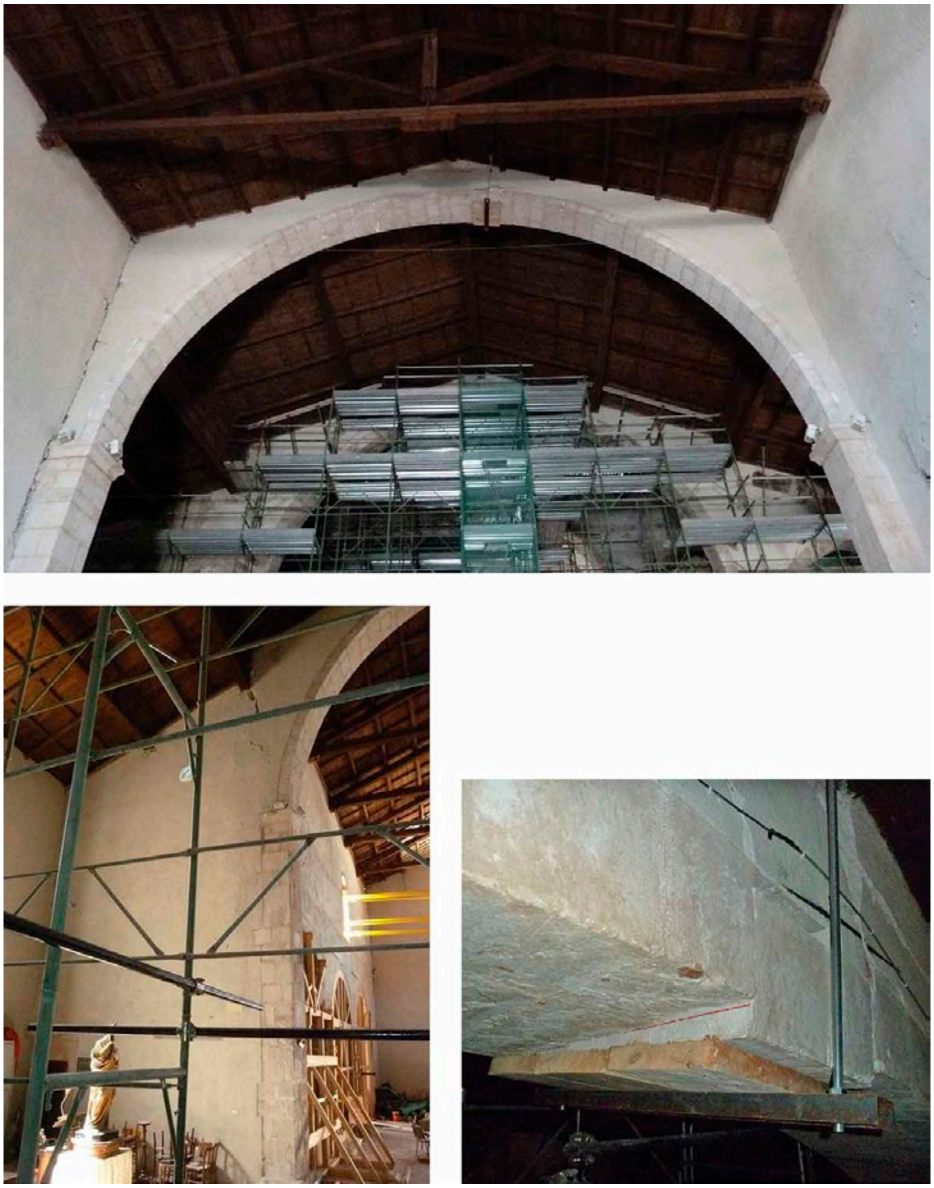

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Fig. 16. Overall view of the connections designed for the nave.

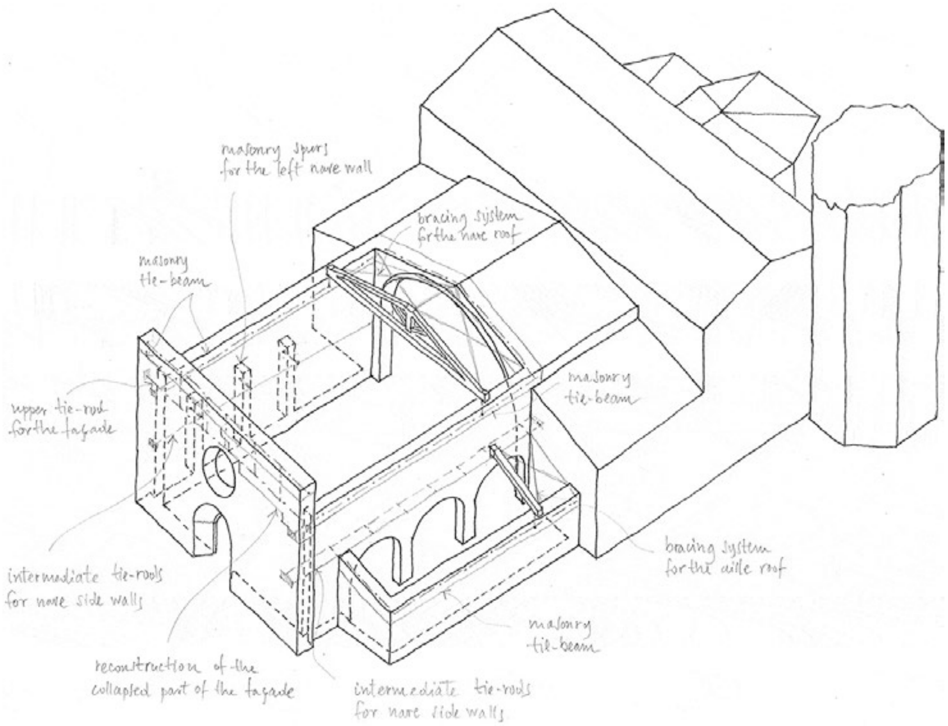

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Fig. 17. Detailed survey of the façade and intervention criteria.

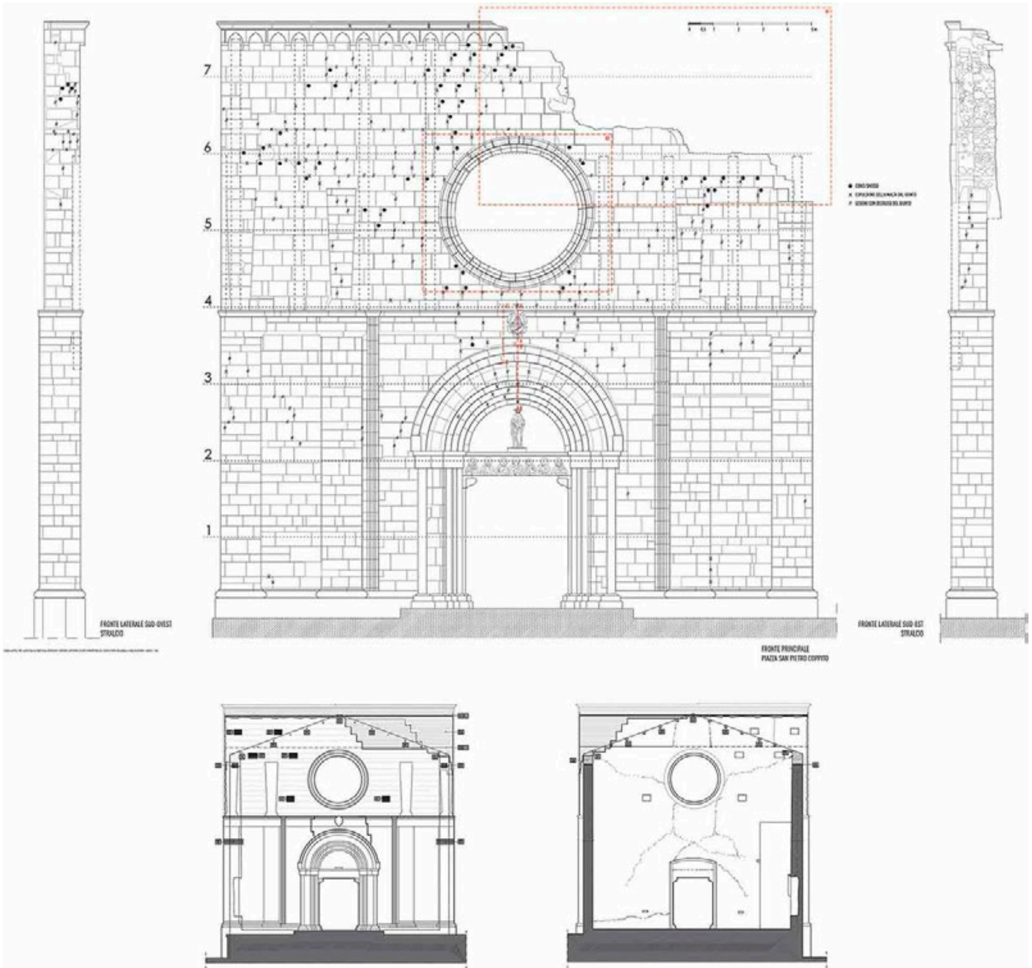
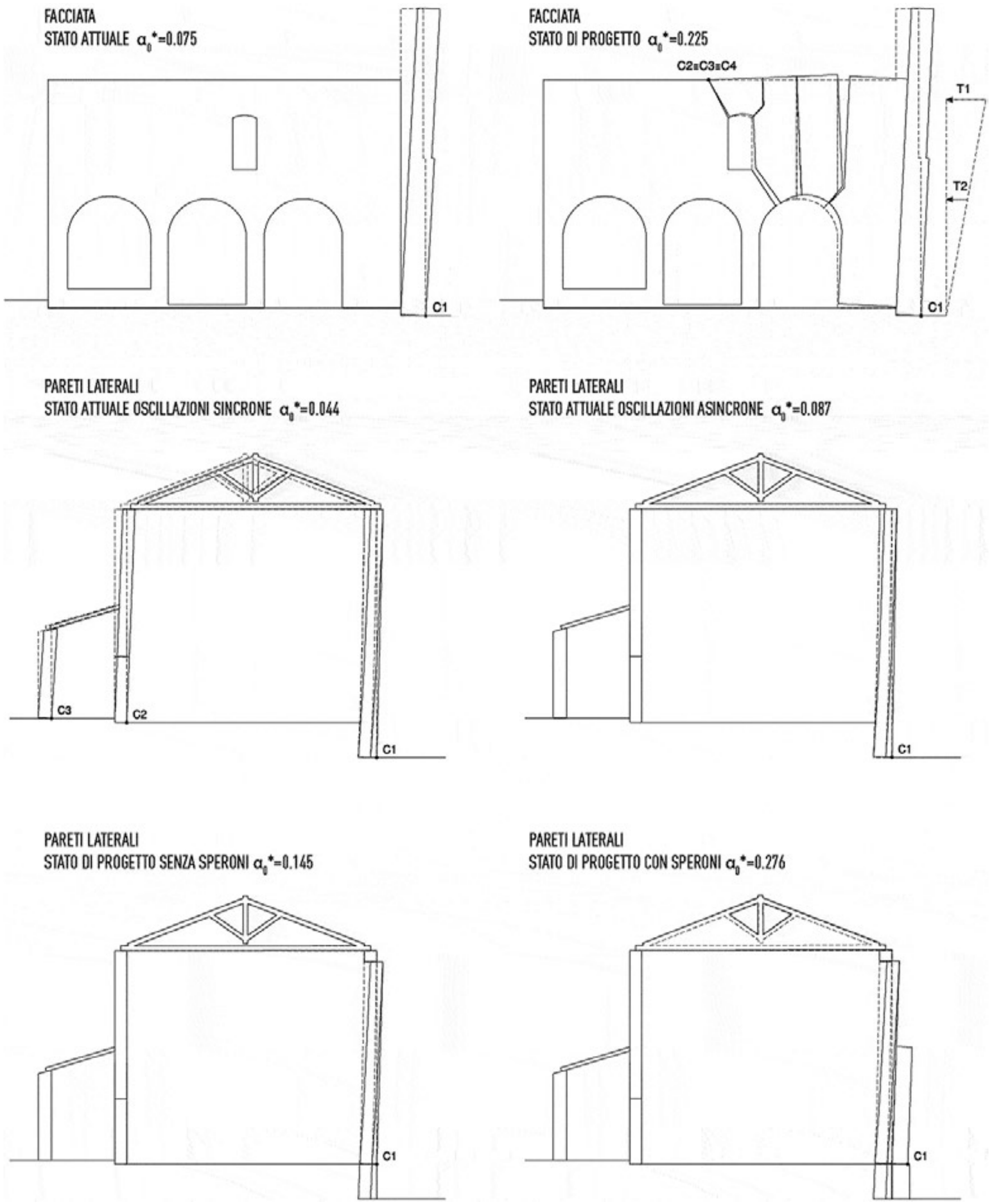


Fig. 18. Collapse mechanisms for the façade (top) and the nave walls (bottom), at present and in the project.



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