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The Case Study of Santa Maria Paganica Church Damaged by 2009 L'Aquila Earthquake

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Abstract Santa Maria Paganica Church, built in the second half of XIII century, represents one of the most important church for L'Aquila history (being the second so-called "capoquarto" church). During the centuries, due also to the damages suffered by various earthquakes, important structural modifications, which are decisive for the interpretation of the seismic response, followed. In particular, as a consequence of L'Aquila earthquake (April 6, 2009), severe collapses interested the church, which in particular occurred in: the dome and dome cladding, the whole roof (with exception of apse), the upper part of the lateral wall on left side, the gable of façade. Several vulnerability factors facilitated the collapse of these portions, in particular: the constructive precariousness of nave's masonry walls; the asymmetric transversal stiffness on the two opposite sides of nave; the replacement of the original roof. In the paper, starting from the analysis of the constructive details and the subsequent transformations which interested this church, the interpretation of its seismic response will be discussed. Moreover some preliminar issues, associated to the different solutions for the church rebuilding and the strengthening interventions which should be adopted, will be examined.

Keywords: Seismic response, church vulnerability assessment, damage analysis

Introduction

Past and recent earthquakes have shown the high seismic vulnerability of monumental buildings. In particular, churches turned out to be very vulnerable if compared to palaces or other ancient structures: as matter of fact, often in case of low intensity earthquake churches were the only types of structures that systematically suffered some damage. As confirmation of this, it appears intersting noting as the total number of churches in L'Aquila significantly dropped during the centuries (and in particular after the earthquake which occurred in 1703): in fact, several churches heavily damaged or collapsed have not been rebuilt. Also the 2009 L'Aquila earthquake confirmed the high vulnerability of this type of buildings.

Among several churches which suffered heavy damage, the paper focuses the attention on the case of Santa Maria Paganica church. In particular this church appears particularly intersting due to the following main factors: its significance (being the second "capoquarto" of L'Aquila); the heavy damage occurred which poses several possibilities with regard to the rebuilding; the subsequent transformations, which it was subjected to during the centuries, which greatly affected its seismic response. In particular, in the paper, starting from the analysis of the constructive details and the subsequent transformations which interested this church, the interpretation of its seismic response will be discussed and some preliminar issues, associated to the different solutions of rebuilding and strengthening interventions which should be adopted, will be examined.

Brief Historical Notes

Santa Maria Paganica Church was built in the second half of XIII century (as testified by an inscription on the architrave of façade portal): then important structural modifications, which are decisive for the interpretation of the seismic response, followed.
Located in the most high point of the city, the church was built adjacently to an ancient bell tower which probabily was a prexesisting defensive structure (whose impressive basement reveals how originally its heigth was greater than the actual one).

Fig. 1 summarizes, even in schematic way, the most significant planimetric and volumetric transformations which occurred (the initial configuration is marked in red). Firstly (as marked in green), small aisles were added to the single original nave (not all the historians agree to this configuration, but it seems the most recognized). Then (as marked in yellow), in occasion of damages occurred after the earthquake that shocked L'Aquila in 1703, the church was extended (by enclosing the adjacent tower) and raised up (as testified by façade) reaching the actual configuration. During this phase, the aisles were closed and turned in chapels by means of transversal masonry walls aimed to work also as buttresses. At the same time, in addition to the apse and transept, a dome, positioned directly on the pendentives of connection to the triumphal arches below and connected to the external octagonal dome cladding through masonry buttress, was built. Lastly, in the sixties, the original wooden roof was replaced by a mixed masonry-reinforced concrete structure.

Moreover the actual configuration is charactherized by the presence of further additional small buildings which are attached on the rigth side.

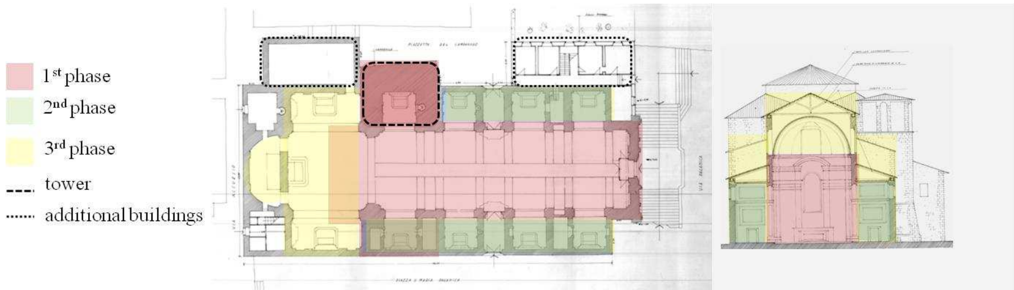

Figure 1: Schematic view (both on plan and section) of the subsequent transformations occurred

Constructive Details

Relevant constructive details were made in full view by severe damages which occurred. In the following, the attention is focused on those which seem the most significant for the interpretation of seismic response.

In particular, the longitudinal sections of lateral walls highlight a set of subsequent transformations which are distinctly ascribable to the different - above mentioned - historic phases. As shown in Fig. 2, it is possible remarking three portions which are characterized by different features. The lower portion of section (quoted as *a*) is composed by two panels not coupled (made on hewn stone masonry): presumably, the external panel corresponds to an enlargement of transversal section due to the baroque raising up of church. At level of the cornice (quoted as *b*), passing from lower to higher portion, a wooden element represents both overhang for this artistic asset and base for the upper panel, stressing the discontinuity between these two structural portions. Finally the upper part (quoted as *c*), ascribable to the baroque raising up of church, is composed by a hewn stone masonry panel: moreover a wooden element, lined up in the masonry wall (as testified also by bolts visible in façade), was introduced (see also Fig. 3). In case of both *a* and *c* portions, a further cover, made by brick (ascribable to the baroque transformation), is placed against the internal panel by slight toothing. Of course, it is evident as all these subsequent transformations, coupled to a poor quality of connections, stress the constructive precariousness of nave's masonry walls.

Also the façade clearly shows the signs of the raising up.

With reference to other structural elements, the dome, apse and transept vaults, built in the baroque phase, were made by brick masonry, whereas that of central nave was a wattle vault. In case of triumphal arch which support the dome, it is important noting a poor scarf in correspondence of tower side due presumably to the different masonry types. In particular in case of dome, it is worth noting the presence of wooden elements arranged at 45 degrees at the base of arches (see Fig. 3). Actually, the insertion of these elements, noticed also in case of transversal masonry walls and in buttresses, is typical of the constructive rule-of-art of L'Aquila (post-1703).

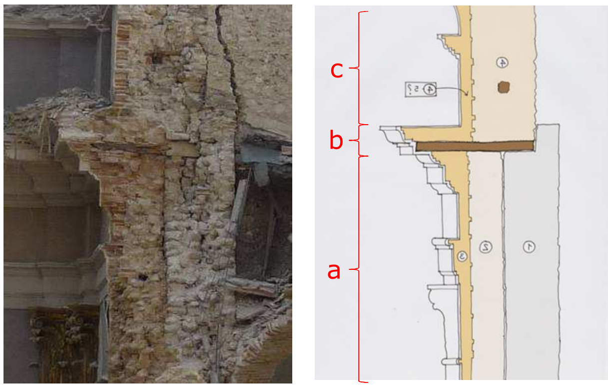

Figure 2: Masonry nave walls: constructive details of longitudinal section

Figure 3: Insertion of wooden elements in: buttresses, transversal walls and at the base of dome arches (from left to right)

The roof, as previously mentioned, was made by a mixed masonry-reinforced concrete structure: in particular it was composed by prefabricated trusses (like as the “Varese” type) and steel tie-rods with brick flats and heavy concrete slab. Some details are shown in Fig. 4.

Figure 4: View of reinforced concrete roof after the mainshock on 6th April 2009 and of some constructive detail

Damage and Vulnerability Survey

Due to L’Aquila earthquake (April 6, 2009), severe collapses interested Santa Maria Paganica Church (as shown in Fig. 5), which in particular occurred in: the dome and dome cladding, the whole roof (with exception of the apse), the upper part of the lateral wall on left side, the gable of façade.

Indeed, the actual damage state has been reached by two subsequent phases (see Fig. 6): in particular, after the main shock of 6 April, a roof portion lived on, then the subsequent shocks caused the disastrous worsening of actual damage pattern.

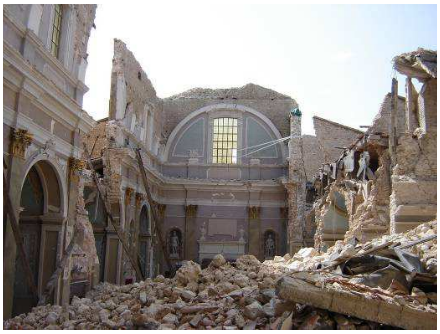

Figure 5: Damage internal overview of Santa Maria Paganica Church

Figure 6: View of Santa Maria Paganica Church (from left to right): historic view before the earthquake; damage state after the main shock; damage state reached after subsequent shocks

A detailed analysis of damage has been carried out following the survey form adopted by the Department of Civil Protection (D.P.C.M. 23/02/2006) to assess seismic damage in churches. In particular, the methodology is based on the identification of macroelements, which consist of architectonic elements whose seismic behavior may be assumed as almost independent from the rest of the structure (e.g. façade, apse, dome, etc.), and of their relating possible collapse mechanisms (in all 28). Thus, on the basis of the actual macroelements which are present in the church examined, a damage index id (which varies from 0 to 1) is defined as a normalized mean (weighted on the weight k assigned to each mechanism as a function of the relevance of the macroelement within the building's context) of the damage grades (dk, graduated on 5 levels) assigned for each mechanism. Moreover, in addition to damage analysis, the vulnerability assessment has been carried out according to the procedure proposed in the Italian Guidelines for evaluation and mitigation of seismic risk to cultural heritage (Directive of the Prime Minister, 12/10/2007). In particular, this procedure leads to the evaluation of a vulnerability index iv (which varies from 0 to 1), which, similarly to id, represents a normalized weighted mean taking into account the effectiveness of anti-seismic measures (vkp) and vulnerability factors (vki), both graduated on 3 levels, assigned for each macroelement.

Table 1 summarizes the damage levels and scores which have been attributed for each macroelement actually present (in all 21). In particular vkp and vki factors have been assigned on the basis of analysis of constructive details above described. As shown in Table 1, with reference to the main mechanisms which have been activated, in addition to the macroelements fully collapsed (which a damage level of 5 corresponds to), those associated to the nave's transversal response and façade overturning appear particularly relevant. In case of overturning façade, damage aggravated after the subsequent earthquake shocks: in fact in a first phase, due to the partial restrain offered by wooden tie-rods, an activation corresponding to level of 3 occurred; then, the raising up portion played a crucial role in the collapse of top part (see also Fig, 6) which occurred in subsequent phases. Moreover, Figure 6 shows the damage pattern occurred in buttresses associated to the transversal nave response.

Table 1: Summary of damage and vulnerability scores assigned

Macroelements and associated failure mechanisms	*Weight mechanism ρ_k [0.5 or 1]*	*Damage level d_k [from 0 to 5]*	*Anti-seismic measures score v_{ki} [from 0 to 3]*	*Vulnerability factors score v_{kp} [from 0 to 3]*
Overturning of façade	1	4	1	2
Damage at the top of façade	1	**5**	3	0
In-plane shear damage of façade	1	3	2	2
Nave's transversal response	1	4	2	2
In-plane shear damage of side walls	1	1	1	2
Overturning of transept's walls	1	3	2	2
In-plane shear damage of transept's walls	1	2	1	2
Vaults of transept	1	**5**	0	1
Triumphal arches	1	**5**	2	2
Dome, drum and tiburio	1	**5**	1	2
Overturning of apse	1	2	2	1
In-plane shear damage of presbitery or apse	1	3	1	2
Vaults of presbitery or apse	0,5	2	0	0
Roof damage: side walls	1	**5**	2	1
Roof damage: transept	1	**5**	1	1
Roof damage: apse, presbitery	0,5	1	1	1
Overturning of chapels	1	0	0	1
Vaults of chapels	1	**5**	0	0
Interaction with adjacent buildings (plan/ altimetric irregularities)	1	2	2	1
Bell tower	1	1	1	2
Belfly	1	2	0	2
Resultant Damage Index i_d		$i_d = \frac{1}{5}\frac{\sum_{k=1}^{n}\rho_k d_k}{\sum_{k=1}^{n}\rho_k} = 0.64$		
Resultant Vulnerability Index i_v		$i_v = \frac{1}{6}\frac{\sum_{k=1}^{n} v_{ki} - v_{kp}}{\sum_{k=1}^{n}\rho_k} + \frac{1}{2} = 0.47$		

Figure 6: Details on the damage pattern associated to façade overturning (left, before and after the main shock) and to the transversal nave's response (right)

On the basis of the damage and vulnerability indexes which have been obtained (id =0.64 and iv=0.47, respectively), the correlation law with the Intensity I proposed in Lagomarsino and Podestà (2004) has been applied (I =3 arctanh(2id -1) -3.4375 iv+8.9125). In particular a value of I equal to 8.16 has been obtained which well agrees to the intensity estimated (in the 8-9 range) for the area which Santa Maria Paganica Church is located in. This result (which of course requires further confirmations on further cases) suggests how the use of these methodologies could provide useful information also for preventive mitigation policy and not only in case of emergency.

Of course the interpretation of the heavy damage pattern occurred in Santa Maria Paganica church is quite complex: in fact, several vulnerability factors concurred to affect its seismic response. The most significant ones may be recognized in: a) the constructive precariousness of nave's masonry walls (stressed by the subsequent transformations occurred); b) due to the presence of the tower and further additional small attached buildings, the different transversal stiffness on two opposite nave's sides; c) the replacement of the original roof .

With reference to issue b), in addition to the asymmetric restrain (which seems explain also the heavier damage occurred on left side) offered to the transversal nave's response, it is worth noting the difference between actions oriented towards outside or inside. In fact whereas outwards it was possible count on the effectiveness of buttresses, inwards only the wooden tie aligned on buttresses and the r.c. struts of roof (which replaced the original wooden trusses) could offer a poor restrain to the out-of-plane response of nave's walls. This supposal is confirmed by the collapse occurred towards the inside and by the orientation of some cracks occurred in buttresses.

Finally, with reference to issue c), in addition to the increasing of seismic loads due to the weight of the masonry-reinforced concrete roof, it is justifiable that the significant vertical component recorded in L'Aquila earthquake induced a relevant increasing of the force acting on tie-rods promoting their sudden collapse. Moreover, also the effectiveness of connection between r.c. tie-rods and masonry walls poses some crucial issues.

Reconstruction Notes and Final Remarks

Heavy damage occurred in Santa Maria Paganica Church make crucial and problematic the issues related to its reconstruction: which portions should be actually preserved? What materials should be adopted for the reconstruction? Even with the necessary strengthening interventions, which is the safety level that is it possible guarantee preserving its original configuration? Although it is impossible to identify an univocal answer, on the basis of the main vulnerability factors which have been previously analyzed , some possible strategies may be advanced.

With reference to the weaknesses highlighted on the transversal nave's response, after having verified the actual effectiveness of buttresses (verifying the need of increasing their section and improving the connection with the nave's walls), the seismic response towards actions oriented inward has to be improved. Regarding this, firstly it seems important improving the flexural stiffness of masonry portions between two adjacent buttresses; as an example, possible strategies should be the insertion of light tie-rods or steel flats posed on two side of masonry panels connected by bars. This latter solution seems particularly attractive since it allows to both overcome difficult issues related to the anchorage to masonry and reduce the effective height of wall. Secondly, in order to improve the inwards out-of-plane walls response, the structural system founded only on buttresses effectiveness seems inadequate: thus in addition to the improvement of the connection between buttresses and nave's wall (as an example by replacing wooden ties by steel elements), the introduction of further structural elements seems necessary. In particular, a possible solution is that of inserting internal transversal arches in correspondence of buttresses.

With reference to the roof reconstruction, particular attention has to be paid both in order to avoid a strong seismic loads increasing and to improve the connection with the masonry walls.

Finally, further issues concern both the strengthening of masonry wall on rigth side and the reconstruction of that on left side. As stressed in constructive details analysis, particular attention should be paid to the precauriouness due to a poor connection between panels.

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