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The Behaviour of S. Agostino Church during 6th April 2009 Earthquake in L'Aquila: Vulnerability and Damage Assessment

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Abstract The church of S.Agostino in L'Aquila was built at the beginning of XVIII century, replacing an older church collapsed during the strong earthquake of 1703. The building has a central layout. During April 6th earthquake, it suffered many damage. The lantern collapsed. Severe cracks concerned the hall-drum-dome elliptical system, the apse and the bell tower. Moreover, the façade was subjected to an overturning mechanism. The elliptical layout of the building induced a mainly longitudinal seismic response. In the paper, a extensive description of the damage is provided. Moreover, the seismic behavior of the church is discussed on the basis of observation of damage and vulnerability features of the structure. A correlation between damage, vulnerability and seismic actions is finally proposed.

Keywords: Seismic response, damage assessment, elliptical dome, L'Aquila

Introduction

The church of S. Agostino in L'Aquila has suffered severe damage during 6th April earthquake in L'Aquila. In particular, many cracks occurred on the large elliptical dome (whose main axis is approximately 20 m long). Presently, the safety of the building is guarantee by provisional works carried out by firemen.

Aim of this paper is to provide an interpretation of suffered damage on the basis of the assessment of the vulnerability of the structure and the type of damage suffered. The authors are aware that further analyses, based on mechanical models, are required.

It should be considered that, by now, the data concerning the monuments in L'Aquila are quite poor, due to the difficulties in retrieving the drawings and the information collected in the archives. For this reason, the drawings of the church (plans and sections) reported here have been drawn by the authors on the basis of: few graphical documents provided by the local Superintendence of Architectural Assets, direct observation of the building, information provided by firemen. Moreover, it is worth noting that no test has been carried out on the constituent materials.

Description of the Structure

The church was built after 1708, after the earthquake of 1703 destroyed the original basilica dating back to XIII century. The building was designed by Giovanbattista Contini (1641-1723), an architect of Bernini's school. The building works were carried out from 1710 to 1725, approximately.

The main body of the church is made of three architectonical elements, aligned along the principal longitudinal axis (Fig. 1): the atrium (a); the elliptical hall (b), with three couples of chapels (c); the presbytery, closed by a circular apse (d). On one side, a L shaped bell-tower stands out (e). Moreover, around the church, close to the presbytery and the apse, is the sacristy (f) and a set of other small buildings.

The central hall is covered by a big elliptical dome (g), which lays on a squat drum. The dome is closed by a octagonal dome cladding and is surmounted by a lantern (h). Eight buttresses stand in correspondence of eight internal strips (i). A rigid infill is likely upon the dome, up to the upper level of the buttresses (Fig. 2). The small chapels around the hall are covered by ribbed vaults, while the bigger ones are covered by barrel vaults.

From information provided by firemen, a timber roof covers the dome, according to the scheme shown in Fig. 2. The roof does not push on the walls of the dome cladding. In fact, in correspondence of the eight internal strips and the buttresses, eight vertical walls supporting the timber structure stand out. These walls play the fundamental role of connecting the dome to its cladding, acting as bracing.

The façade is articulated in two parts: a lower façade (corresponding to one of the walls of the atrium) and an upper rear façade (obtained on one of the sides of the dome cladding).

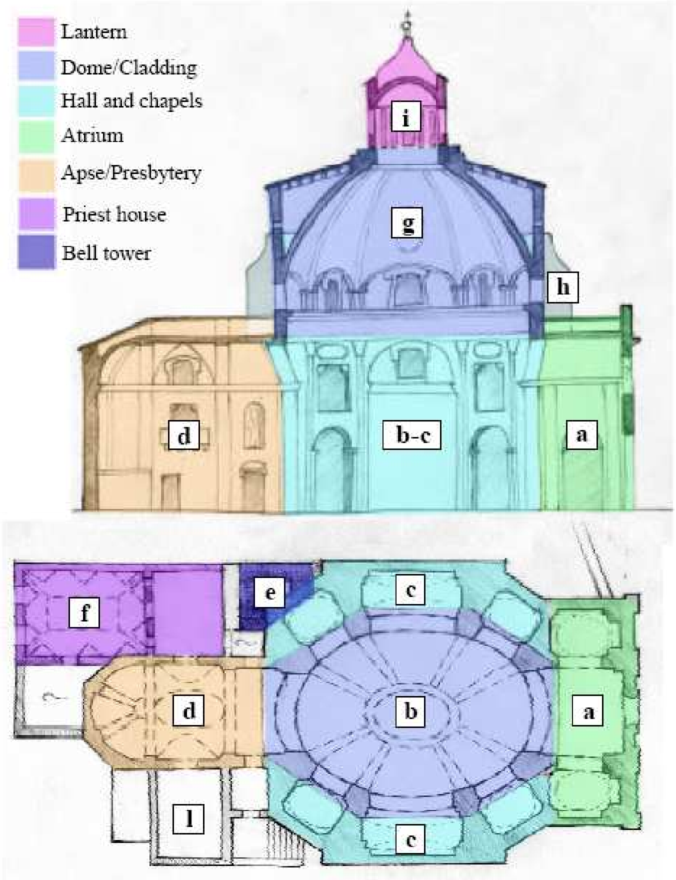

Figure 1: Scheme of the church

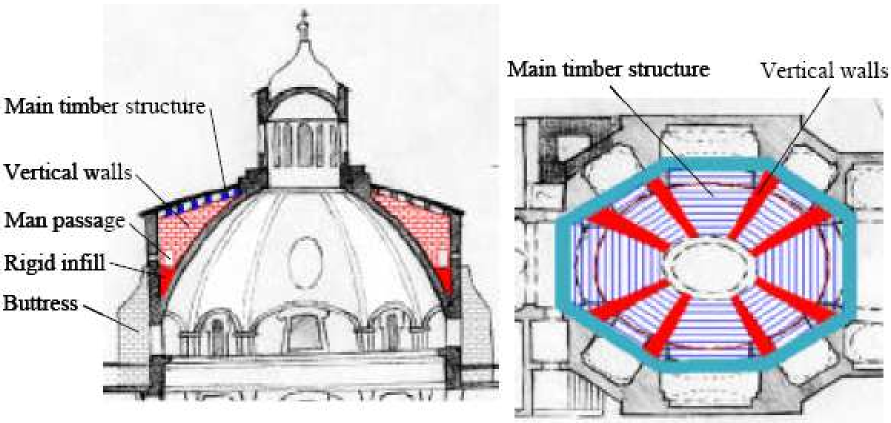

Figure 2: Scheme of the roof

The structure is made of masonry. By a visual analysis, it has been assessed that all arched or vaulted elements and lintels are made of brick masonry of good quality (Fig. 3, left), while vertical structures are made of rubble stone-brick masonry of medium quality (Fig. 3, right). The connections between vertical walls are made of good quality stone masonry.

Figure 3: Material of the dome (left) and vertical walls (right)

In some case, typical wood ties are visible above lintels. Iron ties are not visible within the building; however, iron bolts visible on the external walls state their presence. Fig. 4 shows a scheme of the iron ties defined on the basis of visible bolts. The asymmetric distribution of ties may be observed: the ties are concentrated on the free side of the building, toward S. Agostino street. On the opposite side, adjacent buildings (ex-monastery of S. Agostino) contrast the movements of the church.

The main body of the church, constituted by the elliptical hall and dome-drum system, has bracings of different stiffness in the longitudinal and transversal direction. In fact, in the transversal direction, very stiff buttresses, together with adjacent buildings and ties, are present. In the longitudinal direction, only the walls of the apse and two walls in the atrium (both quite slender) act as bracing.

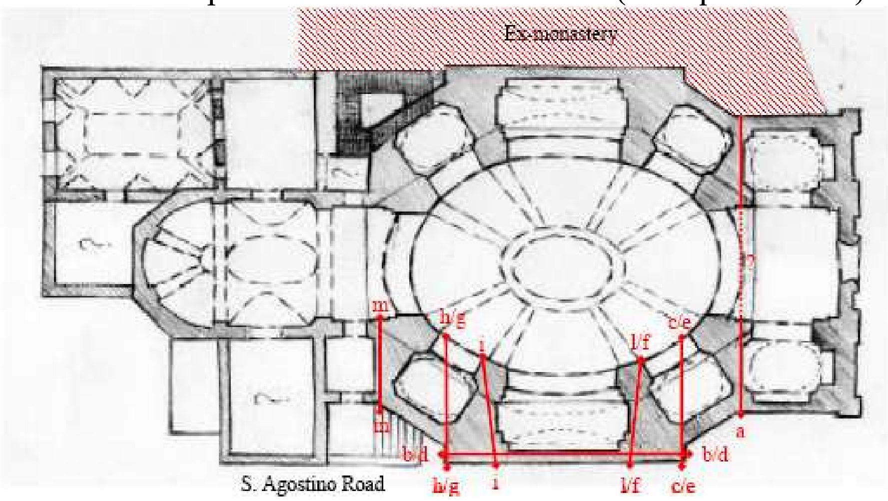

Figure 4:Scheme of assessed iron ties

It is worth noting that the church has not suffered many modifications during time. The only meaningful change concerns the lantern, which was completely reconstructed in early '80 with a steel structure connected to the dome through a reinforced concrete elliptical tie.

Damage Caused by the Earthquake

Fig. 5 shows the damage pattern of the church after 6thAprile earthquake. Main damage of the building occurred in the dome-drum system. The lantern totally collapsed. The dome and the drum has severe diagonal cracks on all sides, with particular concentration on the openings (Fig. 6a). Some of the lintels of drum openings collapsed (Fig. 6b). Moreover, a crack on a parallel of the dome developed on the side of the apse (Fig. 6c). Cracks are also present at the base of the drum, in the big arches separating the hall from the lateral chapels. Shear cracks on the lateral walls and the vault of the apse are visible. Finally, cracks denouncing a partial rotation of the façade are visible on the external walls.

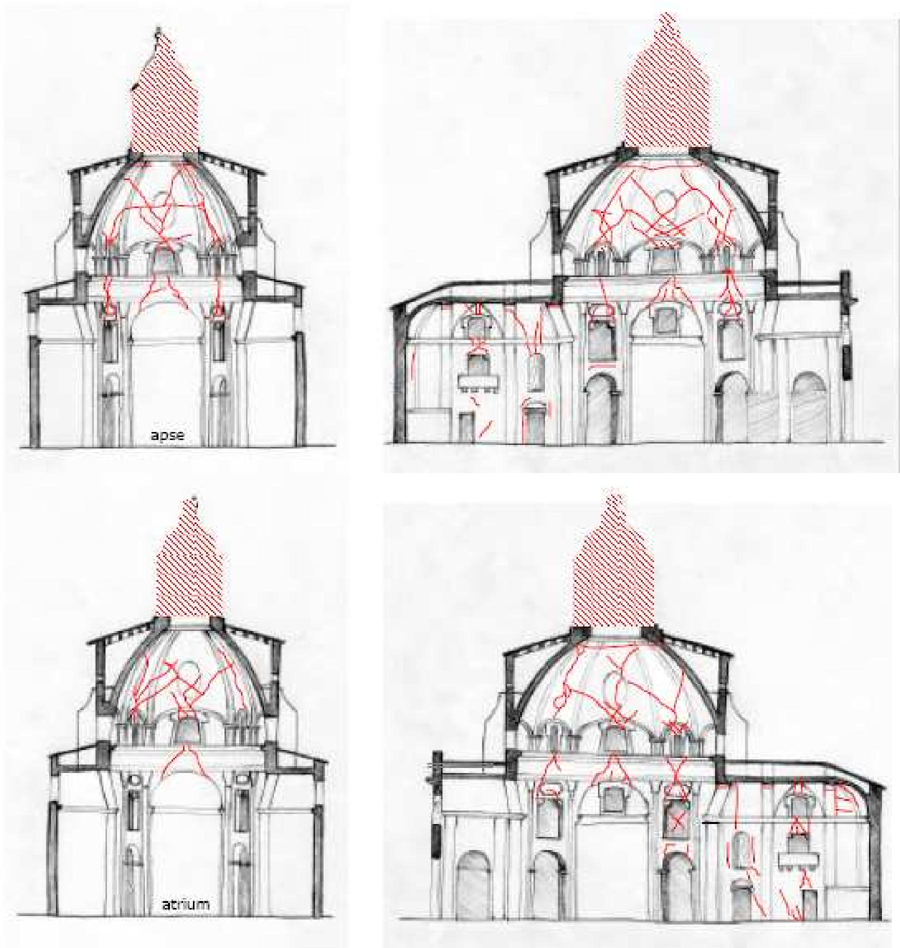

Figure 5: Crack pattern of the church.

Figure 6: Crack in the dome and in the dome cladding

Detailed Vulnerability and Damage Assessment

The vulnerability assessment of the church has been carried out according to the procedure proposed by the Italian "Guidelines for the evaluation and mitigation of seismic risk to cultural heritage" (Guidelines for evaluation and mitigation of seismic risk to cultural heritage 2008). The methodology is based on the identification of 28 possible damage mechanisms of a set of macro-elements of the church (e.g. façade, apse, dome, bell tower, etc.) and on the assessment of those factors which may promote or inhibit them. It leads to the evaluation of a vulnerability score i_v (varying from 0 to 1), calculated as:

$$i_v = \frac{1}{6}\frac{\sum_{k=1}^{28}(v_{ki} - v_{kp})}{\sum_{k=1}^{n}\rho_k} + \frac{1}{2} \quad (1)$$

where: k is the number of mechanism (k=1,28); v_{kp} is an integer (0= v_{kp} =3) evaluating the vulnerability of the structure with respect to the k-th mechanism; v_{ki} is an integer (0= v_{ki} =3) evaluating the effectiveness of anti-seismic factors of the structure with respect to the k-th mechanism; ρ_k is a parameter (varying from 0.5 to 1) weighting the relevance of each mechanism with respect to overall building collapse.

The evaluation of damage has been carried out by adopting the survey form of the Italian Department of Civil Protection for the seismic damage assessment of churches (Scheda di Rilievo del Danno ai Beni Culturali – Chiese 2006). This form has been defined in the same framework adopted for the vulnerability assessment. For this reason, the same macro-elements and the same damage mechanisms of (Guidelines for evaluation and mitigation of seismic risk to cultural heritage 2008) are considered in this form. The damage score id (varying from 0 to 1) is defined in this case as:

$$i_d = \frac{1}{5}\frac{\sum_{k=1}^{N}(\rho_k d_k)}{\sum_{k=1}^{n}\rho_k} \quad (2)$$

where d_k is an integer evaluating the damage related to the k-th mechanism (0=d_k =5).

The vulnerability and damage scores assigned to the church, defined on the basis of the visual vulnerability and damage assessment described in previous paragraphs, are collected in Table 1.

Table 7: Summary of damage and vulnerability scores assigned

*Macroelements and associated failure mechanism**	*Weight mechanism* ρ_k	*Damage level* d_k	*Anti-seismic measure score* v_{ki}	*Vulnerability factors score* v_{kp}
Overturning of facade	1	3	2	1
Damage to the top of façade	1	0	2	0
In-plane shear damage of façade	1	2	1	0
Transversal response of the hall	1	3	3	1
In-plane shear damage of side walls	1	3	3	1
Dome, drum and tiburio	1	4	3	0
Lantern	1	5	2	1
Overturning of apse	1	3	2	1
In-plane shear damage of presbitery or apse	1	3	2	1
Vaults of presbitery or apse	0,5	3	2	0
Roof damage: side walls	1	2	0	0
Roof damage: apse, presbitery	0,5	1	0	0
Overturning of chapels	1	2	2	0
In-plane shear damage of walls of chapels	1	2	2	0
Vaults of chapels	1	2	1	0
Interaction with adjacent buildings	1	4	0	1
Bell tower	1	3	3	2
Belfly	1	4	2	0

*Among the 28 possible macrolements, only those which are actually present in the church are illustrated

The resulting vulnerability index is i_v = 0.29, while the resulting damage index is i_d = 0.54.

In order to assess whether the damage occurred to the church was predictable, and therefore whether it was avoidable through preventive interventions, the simplified model LV1proposed in

(Guidelines for evaluation and mitigation of seismic risk to cultural heritage 2008) was applied. This model, based on statistical data collected in previous Italian earthquakes, allows to estimate the peak round acceleration for the ultimate limit state (a_{SLU}) and for the damage limit state (a_{SLD}) on the basis of the vulnerability index i_v as:

$$a_{SLU} = 0.025 \cdot 1.8^{5.10-3.44 i_v} \tag{3}$$

$$a_{SLD} = 0.025 \cdot 1.8^{2.75-3.44 i_v} \tag{4}$$

The safety index of the structure for the limit state i (i=U or D, depending on the limit state considered) represents the ratio between the capacity of the structure and the seismic demand and may be calculated as:

$$I_{si} = \frac{a_{SLi}}{\gamma_I S_i a_{gi}} \tag{5}$$

where: a_{gi} is the peak round acceleration of the site; S is a parameter taking into account soil and morphological effects; γ_I is the "relevance" ratio, taking into account the exposition and the cultural relevance of the monument.

The following parameters have been defined for the church of *S.* Agostino on the basis of the Italian code (NTC 2008): a_{gU} =0.260 [g] and a_{gD} =0.104 [g]; S_U = 1.16 and S_D= 1.20; γ_I =1.20.

The calculated safety indexes is I_{sU} = 0.77 and I_{sD} = 0.48. The damage was largely predictable.

Conclusions

The church was seriously damaged by the earthquake. Main damages occurred to the dome-drum system and to the lantern. The lantern, which was rebuilt in early '80, collapsed (the light steel structure was found at the base of the building after the earthquake). A complete analysis of the crack pattern shows a prevailing response along the longitudinal axis, along which the stiffness of the structure is lower. The calculation of the safety index showed that preventive analyses concerning the vulnerability of the structure and site hazard could have suggested the adoption of interventions to improve its seismic response. At present, possible interventions are: the injection of cracks and the external cerclage of the dome-drum system with FRP strings. The reconstruction of the lantern will require an accurate study to define its optimal weight and stiffness. Longitudinal steel ties should be finally inserted along the apse, presbytery and atrium walls.

Acknowledgments

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