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On Site and Laboratory Investigation on Some Churches Hit by a Recent Earthquake, in order to Assess the Damages to Materials and Structures

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Abstract

At the end of 2004, an earthquake (5.2 Richter scale) hit the eastern part of the Lombardy Region in Northern Italy. No casualties occurred luckily, but many buildings were damaged and particularly affected was the vast patrimony of Churches. The authors were asked by various parishes to carry out a preliminary after earthquake investigation on 10 Churches and 2 rectories, carefully chosen to be representative of the total number existing. The aim was to assess the state of damage of the structures and the properties of the materials as a base for the preservation and repair projects.

The investigation was carried out following the same procedure for all the Churches: archive documentary research, geometrical and crack pattern survey and interpretation, definition of the possible incipient collapse mechanisms, mechanical characterization of the masonry through flat-jack tests, use of sonic tests to define the density of the walls, individuation of the masonry section typology by sampling, ultrasonic tests on stone columns, vibration tests on tie rods, definition of mortar and stone properties sampled from the walls through chemical, physical and mechanical laboratory tests.

Keywords: churches**,** earthquake, failure mechanisms, masonry characterization.

Introduction

On November 2004 an earthquake hit the area of the lake of Garda, an international tourist area. Though its magnitude was not particularly high (5.2 Richter scale) and fortunately the event did not cause casualties, nevertheless many public and private buildings were damaged. The region is considered as a seismic area and a previous earthquake occurred in 1901.

In the province, around one thousand churches can be found; several were damaged by the earthquake at various levels and in some cases new damage was added to existing defects, due to lack of maintenance. The Dioceses of Brescia decided to provide designs for repair and strengthening of the damaged churches but also for prevention of future damages to all the others too. To this purpose, a preliminary investigation was needed in order to know the state of damage affecting the structures. To L. Binda and her collaborators were assigned the investigation of 10 churches and two rectories. The request was rather peculiar: a quick (within two months) and cheap investigation was needed as a support to the repair project. Architect M. Biasin was the designer and was supported for the structural analysis by the University of Genoa and Brescia and by some local structural engineers.

The investigation was based on a methodology which was proposed by the authors for the vulnerability study of historic centres in seismic areas. The chosen churches were built in different centuries, show several construction typologies and are representative of the numerous churches of the dioceses. The bearing walls of the churches were all made in stone masonry, frequently two leaf walls with irregular stones and apparently built with different construction techniques. On the contrary, the stones came from local quarries and are rather similar; the same can be said for the mortars.

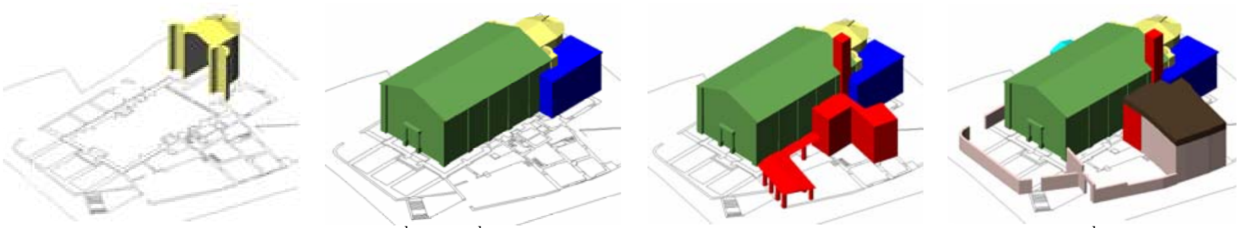
A preliminary assessment has been made to compare the different results in terms of collapse mechanisms and material properties as requested by the dioceses in order to understand which typology needs more attention for safety and prevention.

Methodology and level of investigation

The investigation methodology adopted by the Authors since the beginning of the '90s [1, 2] is based on the principle that knowledge is fundamental for the choice of suitable techniques and materials aimed to the preservation and damage prevention of the cultural heritage. This methodology has been well calibrated in different on site investigations on historic masonry buildings in the Umbria region after the earthquake of 1997 [3, 4, 5] and in the Liguria region [6 7] The earthquake that struck Umbria and Marche regions in '97 gave the occasion to learn that the lack of knowledge on the material and structural behaviour of the existing buildings was, and still is, the main cause of inappropriate choices for the intervention techniques.

When dealing with churches as monumental buildings, a detailed investigation is needed in order to accomplish both the conservation demands due to their historic-artistic value, and the safety requirements connected with their public function. The past experience in seismic areas showed that this type of buildings is subjected to typical and repetitive damage mechanisms as: the out of plane rotation of the façade, the in plane damages of the lateral walls, the damage of the apse and of the bell tower, etc [8].

As a first step to provide a design for repair and preservation of the damaged churches a preliminary in-situ survey was considered useful to obtain details on the geometry of the structure, identifying irregularities (vertical deviations, rotations, etc.) and to single out the parts where more accurate investigations was needed. The building may have been subjected to the addition of several volumes in different times, and the possible discontinuities between the different volumes could affect the overall seismic behaviour. Therefore, for a reliable interpretation of the signs of damage, the geometrical survey is not enough but also the historical evolution of the structure in its complexity has to be investigated (Figure 1).



High Middle Age — 15th – 16th century — Napoleonic period — Early 20th century

Figure 1 - Construction phases of the church of S. Michele Arcangelo at Sabbio Chiese.

Based on the methodology proposed by the authors for historic centres [9], the investigation consisted of the following steps: (i) geometrical survey of the building and survey of the crack pattern, (ii) interpretation of the crack pattern and definition of the damage or collapse mechanisms affecting each building, (iii) survey of the masonry texture and of the morphology of the wall sections, (iv) detection of the connections wall to wall and roof and vaults to walls, (v) sampling and characterisation of mortars, plasters and stones in laboratory through chemical, physical and mechanical tests, (vi) on site characterisation of the masonry walls through sonic and flat-jack tests, (vii) detection of the tension values for steel tie rods.

It was also important for the authorities to distinguish between damage caused by the earthquake and damage of a different nature which could have been caused by excessive dead load or soil settlements, or simply by lack of maintenance.

Typology of the buildings and observed damage

Apart from the church of S.S. Crocifisso at Bogliaco di Gargnano, that was built in the 18th cent. and presents a central plane, and from S. Andrea Monumentale at Toscolano Maderno that was founded in Romanic style in 12th century, most of the churches surveyed during the research here described were built between 15th and 17th century and are characterized by a “basilica” plan. Generally they are organized in a unique nave, whereas only S. Pier d’Agrino and S. Andrea Monumentale are based on three naves, with no transept except from S. Antonio Abate at Morgnaga.

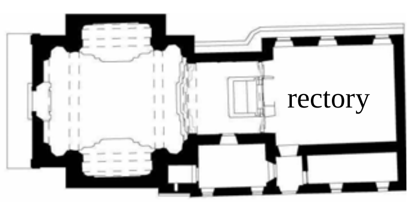


Figure 2a – S.S. Crocifisso at Bogliaco di Gargnano: central plane.

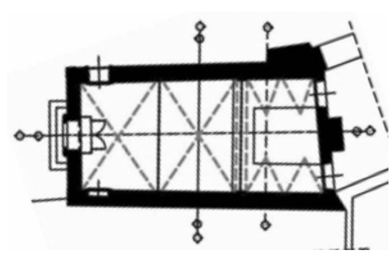


Figure 2b – Immacolata at Toscolano Maderno: one nave and no chapels.

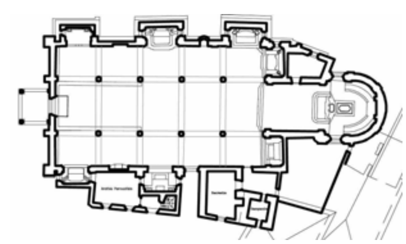


Figure 2c– S. Pier d’Agrino at Bogliaco di Gargnano: three naves and chapels.

Some of them have been provided with lateral chapels that are original or have been added according to the *Instructiones* given by C. Borromeo on 1580 to the Milan diocese. In many cases they rise on the place of a previous construction and often have been subjected to later interventions for decoration or strengthening purposes.

The churches studied are not isolated buildings, but they generally are annexed to the sacristy, the bell-tower and in some case the rectory. Figure 2a, 2b, 2c show some typical plans.

Collapse mechanisms

The interpretation of the crack patterns observed on the churches tried first of all to distinguish between the damage caused by the earthquake and that previously present on the constructions for other reasons. Considering the former, some of the mechanisms, for instance those involving the lateral naves, the chapels or the transept, were only relevant to single churches according to the building typology, since these elements are not always present. Other failure mechanisms, like the out of plane rotation of the façade and the hammering action of the roof structure on the lateral walls have only been observed in a couple of cases, probably because of the good connection between orthogonal parts. In the following, only the most diffused collapse mechanisms will be illustrated.

In plane mechanism of the façade

This mechanism has been observed in six cases; it is the most frequent one and always involves simple façades, i.e. plane front only connected to the lateral bearing walls. In all the studied cases, the crack pattern has developed along few well defined lines, indicating a good quality of the masonry [8, 9]. The crack position is obviously influenced by the openings too. In figure 3 the church of S. Antonio Abate at Morgnaga is presented: on the central part of the façade a series of cracks are visible corresponding to the windows.
In figure 4 the Church of SS. Crocifisso at Bogliaco di Gargnano can be seen: from the photograph a failure line basically vertical and in central position can be noticed. The cracks are probably generated by the out of plane displacement of the lateral walls and are exacerbated by the presence of the openings.

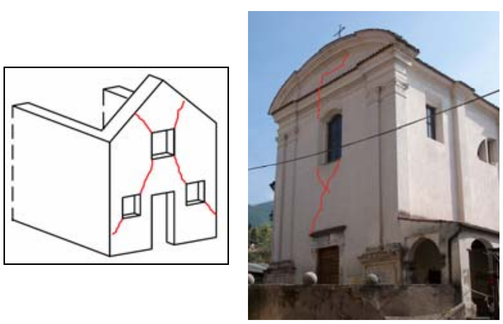


Figure 3 - S. Antonio at Morgnaga

Figure 4 - SS. Crocifisso at Bogliaco

Failure of the triumphal arch

Because of the out of plane confinement on both sides, the triumphal arches only showed in plane failure that has been detected in four cases. In Figure 5 the triumphal arch of the church of S. Giovanni Pavone at Sabbio Chiese shows a particularly evident crack pattern that required supporting structures. A similar problem is evident in Figure 6 at the arch of the apse, where the movement of the keystone also required the use of props.

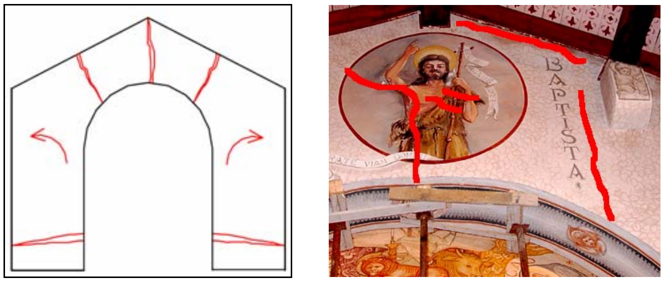


Figure 5 – S. Giovanni Pavone at Sabbio Chiese; triumphal arch.

Figure 6 – S. Giovanni Pavone at Sabbio Chiese; arch of the apse.

Behavior of the vaults of the central nave

In four cases the vaults of the central nave looked cracked, often due to the heavy load of the re-built roof (Figures 7 and 8).

In the case of S. Benedetto da Norcia at Pompegnino di Vobarno (Figure 9) the central nave looks severely cracked, probably because of the presence of a rigid plaster that makes the cracks more evident. The structure has been completely propped to guarantee safety.

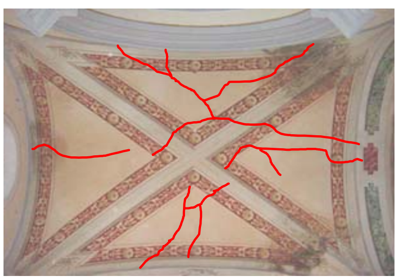


Figure 7 – S. Pier d'Agrino at Bogliaco di Gargnano

Figure 8 – S.S. Crocifisso at Bogliaco di Gargnano

Figure 9 – S. Benedetto at Pompegnino di Vobarno

Mechanism of the apse

Four churches are affected by the rotation mechanism of the ending part of the apse. In Figure 10 the church of S. Michele Arcangelo at Sabbio Chiese is illustrated. Two long cracks can be seen in symmetrical position, sometimes cutting the whole wall thickness, indicating a detachment of the ending part of the apse due to out of plane rotation.

Figure 10 – S. Michele Arcangelo at Sabbio Chiese

In plane mechanism of the lateral bearing walls

Because of the good transversal connection offered by the roofs and by the lateral chapels when present, no out of plane rotation of the lateral bearing walls has been observed, except that in the case of the central plane church of SS. Crocifisso, where the vertical cracks in the façade is prsumably due to a rotation of the lateral walls. On the contrary, shear cracks showed in the case of three churches. The phenomenon is less frequent than the in-plane mechanism of the façade, probably because of the higher in-plane flexural stiffness of the lateral walls and to the higher slenderness of the façade. In Figure 11 the crack patterns appeared on the north and south walls of the church of S. Antonio Abate at Morgnaga are shown**.**

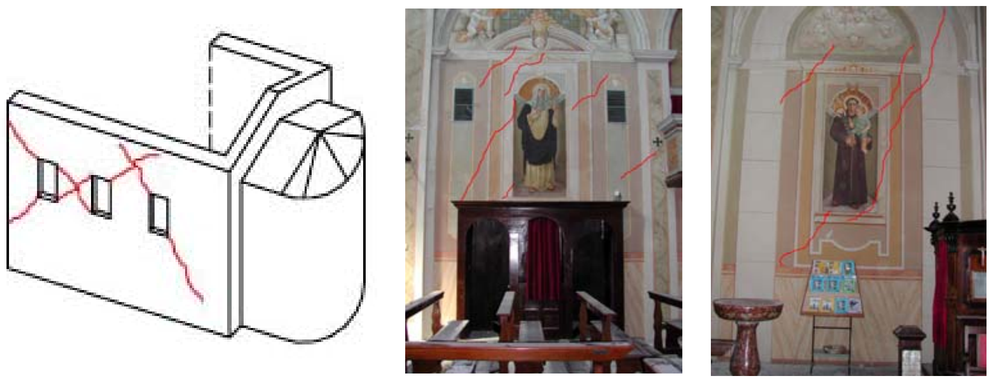


Figure 11 - S. Antonio Abate at Morgnaga

Failure mechanisms of the bell-tower

The bell-tower was not present in all the case studies. In general its failure mechanisms are influenced by its position with respect to the church and by the kind of connections, considering that it may be particularly vulnerable because of its slenderness. In Figure 12 the bell-tower of S. Michele Arcangelo at Sabbio Chiese is shown, which is affected by severe crack patterns. In particular, the cracks on the east and west fronts indicate a movement of the tower in the north-south direction. In fact, the upper part of the tower can freely move whereas the lower part is well constrained by the church and the rectory. East and west faces of the belfry show a crack corresponding to the keystone, probably due to an out of plane rotation of north and south walls.

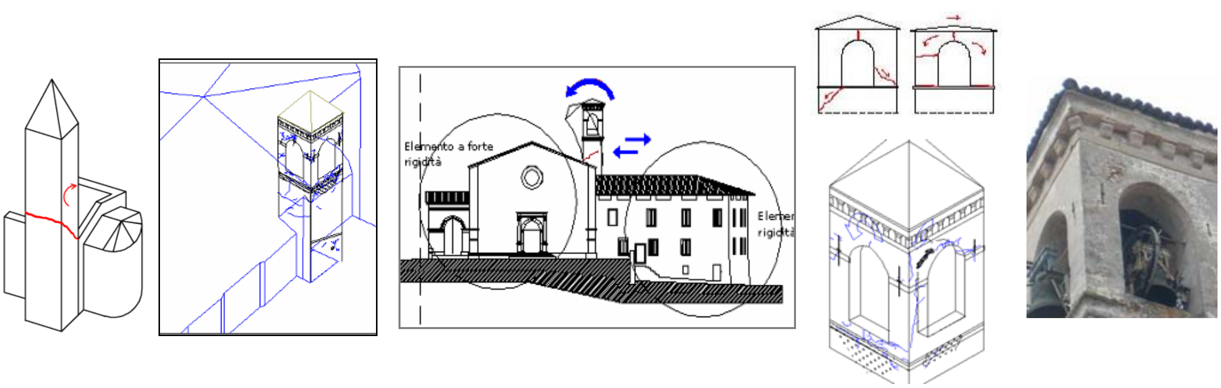


Figure l2 – Bell-tower of S. Michele Arcangelo at Sabbio Chiese

Damage survey by NDT and masonry characterization on site

According to the low budget allocated by the single churches, only a few flat-jack and sonic tests were carried out after a very accurate choice of the test positions and some ultrasonic tests for detecting the columns integrity (Figure 13). Systematically, the testing points were chosen in the most representative parts of the bearing walls: taking into account that the façade is usually made of better masonry, the lateral bearing walls were chosen. The tests were carried out mainly on the outer face of the wall, since the inner one was usually decorated with frescos and paintings which could not be damaged.

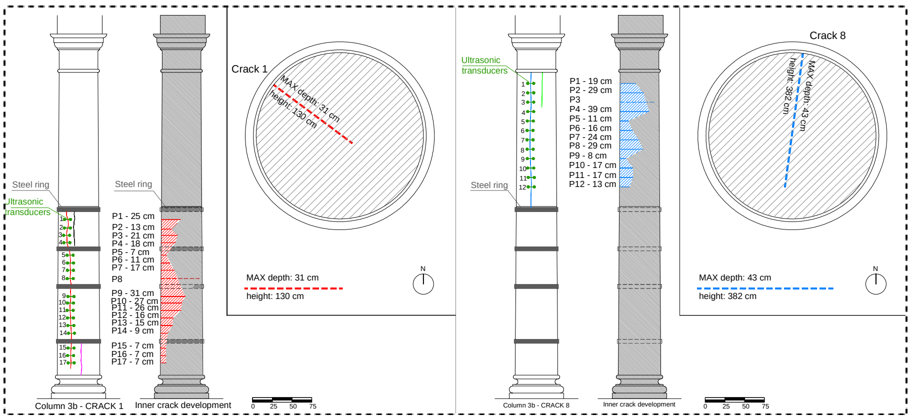


Figure 13 - Ultrasonic tests to characterize the inner crack development into a column.

Dynamic tests on tie rods were also carried out in order to detect the level of tension. A complete characterization of the wall was achieved by measuring the sonic velocity, the state of stress, the modulus of elasticity, the coefficient of lateral expansion, the mortar and stones chemical, physical and mechanical properties and by surveying the morphology of the wall cross section, understanding whether the masonry was made of one or two leaf and the leaves were connected in some way [10, 11, 12]. This survey was carried out by drilling and taking off several stones in order to visually investigate the wall texture, sketch the inner aspect of the wall (Figure 14), and sample stones and mortars for laboratory testing.

In particular, four subsequent steps were followed in the same area: (i) sonic tests by transparency on a grid of 75x75cm, (ii) single and double flat-jack test, (iii) survey of the masonry morphology and material sampling, (iv) repositioning of the stones in the wall.

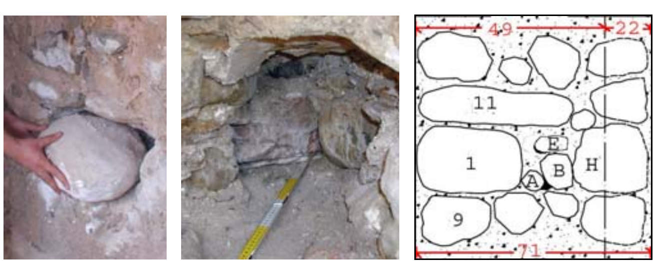


Figure 14 – Study of the masonry morphology

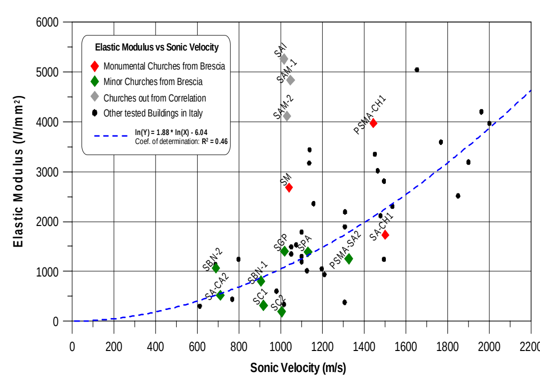


Figure 15 - E vs. sonic velocity

Figure 15 shows the relationship between the sonic velocity and the modulus of elasticity, compared to other values previously obtained from tests on different stone-masonry walls in historic centers.

The calculated values of the elasticity modulus allows for the subdivision of the churches into three categories: 1) from 189 to 803 N/mm^2, corresponding to a very weak masonry with internal voids and no connection between the masonry leaves, 2) from 1063 to 1732 N/mm^2, corresponding to a better masonry but with poor connections between the leaves, 3) from 2860 to 5260 N/mm^2 a definitely compact masonry well connected transversally. Figures 16 - 18 show some typical diagrams obtained with the double flat-jack test. It is interesting to notice that in these diagrams the previous categories of masonries can be recognised. Figure 16 shows a bilinear repsonse with low stiffness, Figure 17 is typical ofmedium stiffness, and Figure 18 shows high stiffness of the masonry.

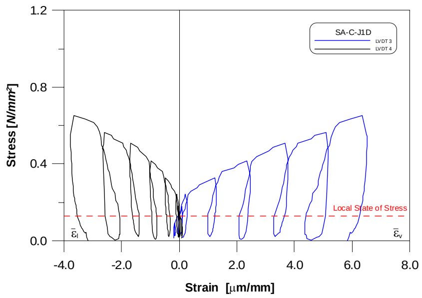


Figure 16 - S. Antonio in Morgnaga, rectory

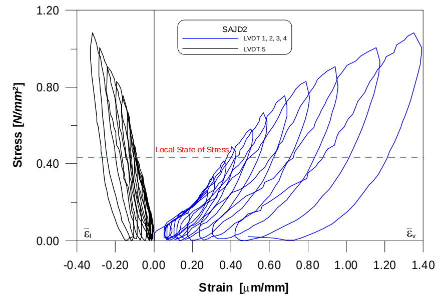


Figure 17 - S. Antonio in Morgnaga, church

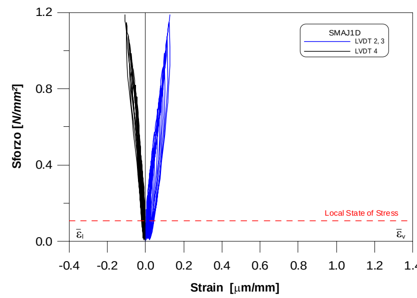


Figure 18 - S. Michele in Sabbio Chiese, church

Material characterization

The sampled stones and mortars were tested in laboratory. The mortars were submitted to chemical and physical analyses. The binder was separated from the aggregate by thermal attack and the grain size distribution was calculated as shown in Figure 19. Since the aggregate was mainly calcareous, it was not possible to determine the ratio binder/aggregate ratio chemically. Figure 20 shows the results of the chemical analyses: most of the mortars were similar, with the binder being hydrated lime.

The stones belonged to several lithotypes but limestone was the most frequent one. In Table 1 the results of physical and mechanical tests are reported.

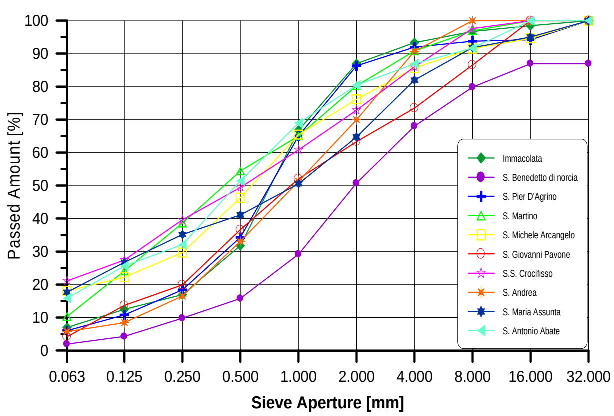


Figure 19 – Grain size distribution of the tested mortar

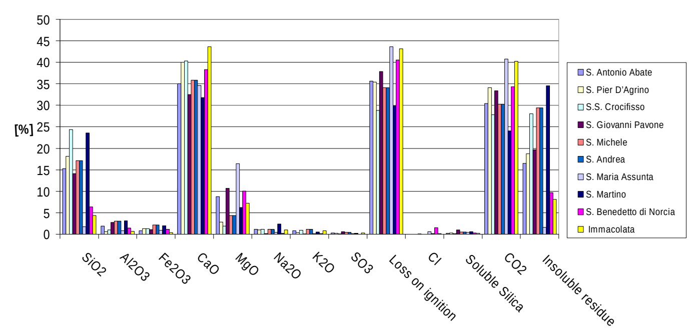


Figure 20 – Results of chemical analysis on mortars

Table 1: results of physical and mechanical tests on the stones

Building	Lithotype	bulk density Kg/m^3	absorption by total immersion [%]	capillary rise coefficient [%]	compressive strength *N/mm^2*	indirect tensile strength *N/mm^2*
S. Antonio	Microcrystalline limestone	2675	0.40	2.02	103.78	11.82
S. Benedetto		2486,71	0.77	3.60	87.3	10.3
Immacolata		2684,62	0.38	0.81	154	11.02
S. Andrea		2433	0.24	0.065	7.18	9.73
S. Andrea	Saccharoidal limestone	2593	1.12	2.21	171.8	8.8
S. Giovanni		2641	0.76	2.67	98.2	5.7
S. Martino	porphyrite	2679,69	0,17	4.52	12.33	7.12
S. Michele		2495	3.14	8.63	9.99	7.44
Immacolata	Marly limestone	2659	0.18	0.60	295	17.31
S. Andrea		2569	1.33	19.68	116	7.1
S. Crocifisso		2687,84	0.86	1.45	125	14.90
S. Giovanni	Dolomyte	2597	1.23	2.64	110.6	6.5
S. Pier d'A.	Limestone	2583	0.84	16.40	93.1	7.3
S. Pier d'A.	Pure limestone	2351.98	0.56	1,42	7.30	4.70

Discussion of the results and conclusions

After the investigation here described, the following considerations can be done: according to the church typology, mainly characterized by a unique nave, the most commonly observed failure mechanism is the in plane mechanism of the façade, with a crack pattern influenced by the opening position.

Cracks on the vaults of the central nave mainly occurred due to the heavy load of the re-built roof. Because of the good transversal connection offered by the roofs and by the lateral chapels when present, no out of plane rotation of the lateral bearing walls has been observed, whereas shear cracks showed in some case.

In a few cases, the out of plane rotation of the façade took place, probably because of the low masonry quality and the bad connection between orthogonal walls.

The failure mechanisms of the bell tower, when present, are generally influenced by its position and connections toward the church, being also particularly vulnerable because of its slenderness.

Sonic tests, flatjack, small disassembling and laboratory tests in sequence are essential to characterize the masonry typology and mechanical behaviour and the masonry material. The survey of the wall section is also useful to detect the masonry injectability, for repair by grout injection.

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