ASSESSMENT OF THE ST. GIUSTA CHURCH IN BAZZANO AFTER THE L'AQUILA EARTHQUAKE ON APRIL 6, 2009

Luigia Binda
Politecnico di Milano
Structural Engineering Dept.
piazza L. da Vinci, 32 - Milano
Italy
binda@stru.polimi.it

Giuliana Cardani
Politecnico di Milano
Structural Engineering Dept.
piazza L. da Vinci, 32 - Milano
Italy
cardani@stru.polimi.it

Christian Amigoni
Engineering firm
Corso Dante, 15
Calolziocorte (LC)
Italy
ufficiotecnico@studioamigoni.com

Fabio Maroldi
Politecnico di Milano
Structural Engineering Dept.
piazza L. da Vinci, 32 - Milano
Italy
fabio.maroldi@polimi.it

Filippo Lorenzoni
University of Padova
Dept. of Construction and Transportation Engineering
via Marzolo, 9 - Padova
Italy
filippo.lorenzoni@gmail.com

Claudio Modena
University of Padova
Dept. of Construction and Transportation Engineering
via Marzolo, 9 - Padova
Italy
modena@dic.unipd.it

KEYWORDS: cultural heritage, church, masonry structures, seismic vulnerability.

ABSTRACT
On April 6th 2009 an earthquake with a moment magnitude of 6.3 Mw hit the centre of Italy and especially the historical city of L'Aquila, causing the collapse of many buildings both modern and historic. An overview of the historical cultural heritage showed that the constructions built properly many centuries ago, although the strong seismic events of the past, did not collapse during this last event.
It is the case of St. Giusta church in Bazzano, built in the 13th cent and one of the most beautiful churches of the area. St. Giusta, already hit by different historic seismic events, had serious damages during this last earthquake to the facade, with the collapse of the bell tower, to the columns and to the pillars.
The paper will report the first investigation of damages carried out soon after the earthquake, the individuation of the mechanisms of failure and of their causes, the emergency provisional structures realized by the fire brigade and the characterisation of the masonry quality through non destructive tests (flat-jack, sonic, radar and thermography).

INTRODUCTION

The earthquake of April 6th 2009 involved a wide area among the cities of L'Aquila, Avezzano, Sulmona and Teramo, in the central part of Italy. The ground morphology had an important role in the structural damages distribution and the most catastrophic effects were observed along the Aterno river valley, involving, besides L'Aquila, many historical centres like Paganica, Onna, Fossa, Bazzano and others.
The seriousness and the extension of the damages on the cultural heritage due to the earthquake were without precedent in the recent seismic events mainly considering the dimension and the strategic importance of L'Aquila as capital of the Abruzzo region.
The activities organization of the Civil Protection Department (DPC) "Protection of Cultural Heritage" was carried out by the employers of the Cultural Heritage Ministry (MiBAC) with the help of the research centre of L'Aquila (CNR-ITC) and of a group of researchers from the University of Genoa, Padua and Milan. The first objective was to elaborate a preliminary list of the protected architectural heritage to be urgently surveyed in the damaged area and to verify their state of damage, while giving first indications of "emergency" for the safety works.
For the damage survey of the cultural heritage, dedicated survey forms were used, prepared by the Civil Protection respectively for churches and for the palaces. The used templates are made up of different sections covering: (i) general notions such as name, location, ownership and function; (ii) information on existing artistic heritage, main dimensions of the building, evaluation of both the structural damage and

the artistic heritage damage; (iii) certification fit for habitation; (iv) suggestions for emergency and safety propping; (v) economic quantification of the damage. The structural damage survey is based on the identification of macro-elements that constitute a masonry building.

One of the first surveyed historical buildings was the church St. Giusta in Bazzano, about 7 km from L'Aquila city, one of the most beautiful churches of the area.

The Church of St. Giusta was built in the 13th cent, probably over a previous Church of the 3rd century a.C.; the date 1238 appears on a stone of the facade.

The structure presented an irregular geometry and non homogeneity of the masonry walls also consequence of several reconstruction after the past earthquakes; these characteristics made the church vulnerable to the effect of the seismic actions, even if it was apparently in good state of conservation after the recent conservation interventions.

Serious damages were caused by the April 2009 earthquake to the facade (Fig. 2), with the collapse of the bell tower and of the top of the facade, the out of plane rotation of the facade and the in plane damage of the facade and of the lateral walls. Heavy damages also were caused to the columns and to the pillars under flexural actions.

After the first investigation of damages carried out soon after the earthquake, useful for the individuation of the mechanisms of failure and of their causes (Binda et al. 1999, Penazzi et al. 2000, Binda et al. 2007), the emergency provisional structures were realized as well as the characterisation of the masonry quality through non destructive tests, together with a vulnerability analysis based on the collapse local mechanisms according to the last seismic code.

DESCRIPTION OF THE CHURCH

The Church of St. Giusta in Bazzano (L'Aquila), was built in the 13th cent, probably over a previous Church of the 3rd century a.C.; the date 1238 appears on a stone of the facade. A peculiar decoration with arches, columns and pilasters makes the facade one of the most beautiful in the area (Figs.1 and 2). A beautiful crypt with frescoes is situated under the rectory.

The Church has a rectangular plan (about 38 x 20 m) and presents only two naves separated by arches with columns and pillars of different shapes (Figs.3 and 4). The third nave was actually substituted by a chapel and a rectory and it is separated from the central nave by a continuous wall in rubble stones. The roof presents visible wooden trusses.

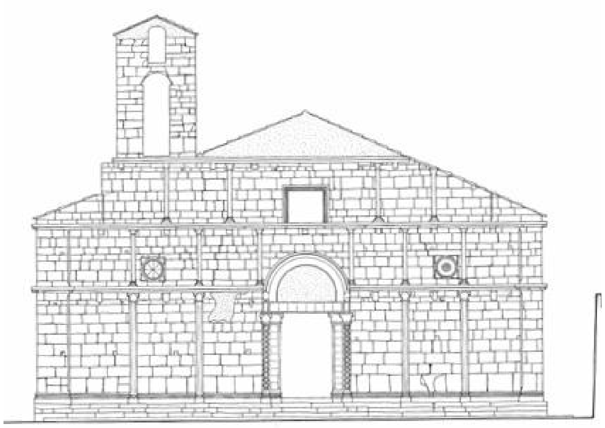


Figure 1: The façade of St. Giusta church.

Figure 2: The façade of St. Giusta church after the earthquake of 06.04.2009.

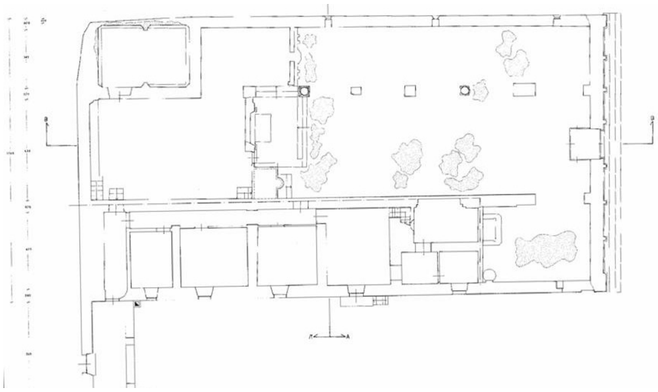


Figure 3: The plan of St. Giusta church.

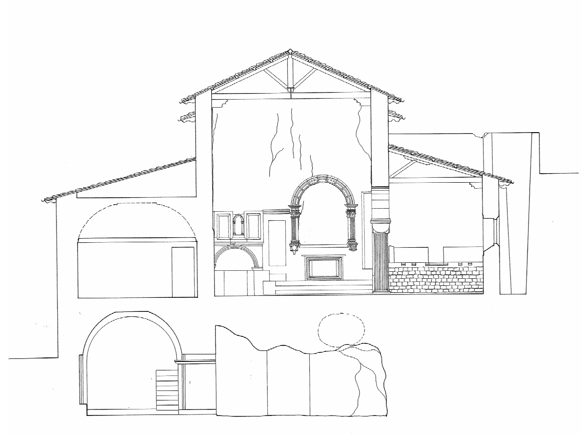


Figure 4: Transeversal section of St. Giusta church.

The actual shape is a result of subsequent repairs due to historic seismic events like in 1461 and 1703. The 1703 earthquake destroyed completely the apsidal wall and the right aisle, whose arches separating the nave remained closed with panels until 1910.
The structure presented therefore an irregular geometry and non homogeneity of the masonry walls also consequence of several reconstruction after the past earthquakes; these characteristics made difficult the identification of the original structural scheme and made the church vulnerable to the effect of the seismic actions, even if it was apparently in good state of conservation after the recent conservation interventions.

DESCRIPTION OF THE MASONRY QUALITY

For the evaluation of the mechanical behaviour of a masonry wall, it is important a thorough knowledge of the various masonry typologies surveyed in relation to (i) the nature and shape of the constituent elements (stone blocks, irregularly shaped stones, bricks), (ii) the presence of mortar and assembly techniques, (iii) the detection of their cross section (Binda et al. 2009).
Therefore a construction code can be defined, a measure of quality that not only allows the identification of typologies belonging to a single local structural and technological vocabulary and giving the opportunity to perform comparisons, but also allowing an estimation, from a construction point of view, of the eventual vulnerability of a loadbearing masonry wall.
The structural efficiency of a masonry in fact depends directly from the construction quality.
For the definition of the masonry walls quality of St. Giusta church, five survey points were selected (Fig.5).
The choice of points had to cover all the different textures found in the church walls in order to compare them with data from historical sources and understand the evolution of the building construction. In reality the choice of the points could only fall on the walls without plaster or partially collapsed, in accessible areas and where it is possible to work in security. Walls without plaster show clearly the many changes that took place over time.
As shown in figure 6, the external leaf of the facade wall is made of calcareous regular stone blocks and, as in many other cases in the region, the internal leaf is less regular, while in the middle a third leaf is made in small irregular stones. Connections among the leaves are not visible; this explains both the high vulnerability of the top of the facade. In the other selected point the masonry has irregular texture and irregular calcareous stones.
This analysis was also used to detect the points where diagnostic investigations should be carried out.

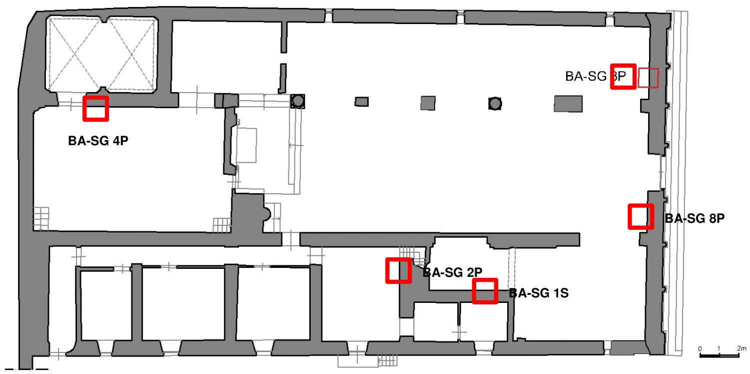


Figura 5: Localization of the surveyed poins for the definition of the masonry qualità.

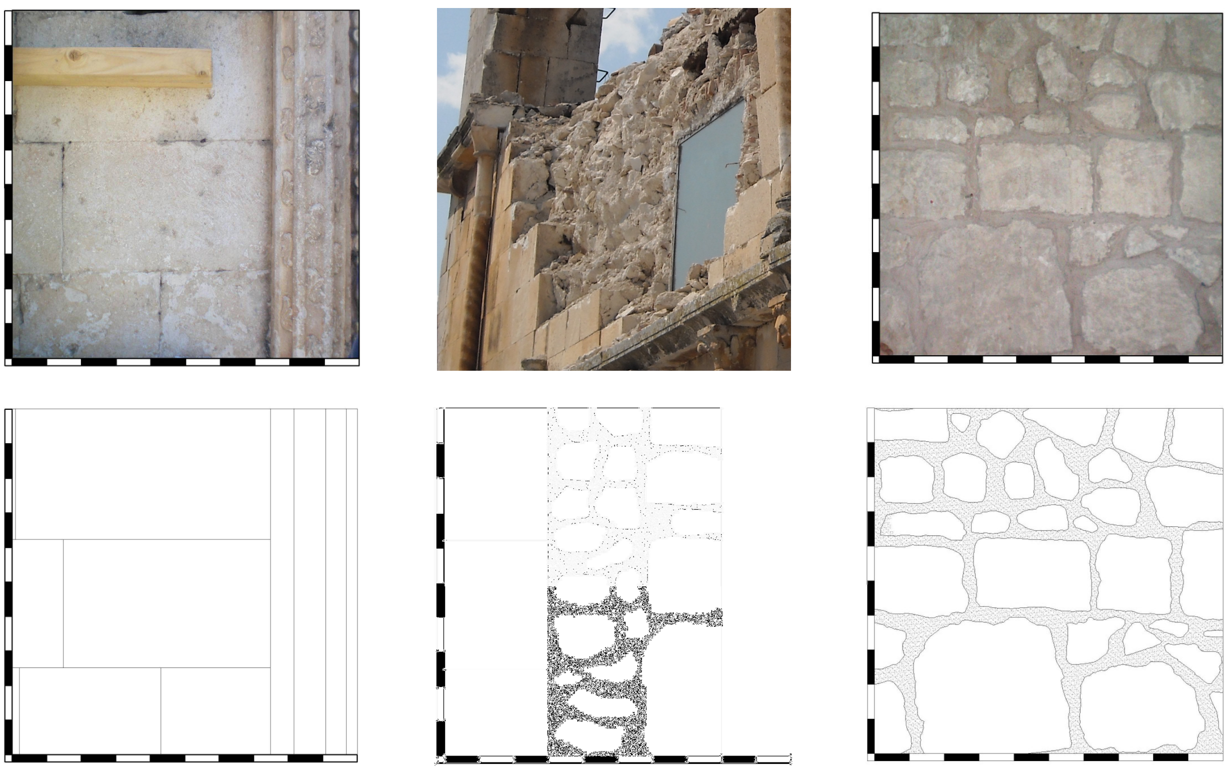


Figure 6: Masonry (prospect and cross section) of the facade.

DIAGNOSTIC INVESTIGATION TESTS

Some preliminary diagnostic tests were carried out on the masonry structure, where allowed (Anzani et al. 2007). In particular sonic pulse velocity tests and flat-jack tests were carried out in two places: on the internal wall of the left aisle, where there is the chapel, and on the internal side of the facade.

The local state of stress, measured with the single flat-jack test, was difficult to evaluate due to the irregularity of the masonry and the movement of some stones during the wall cut, but it was estimated about 0,04 MPa. The mechanical behaviour due to compression measured with the double flat-jack test, show a high non-homogeneous deformable masonry without a linear behaviour (Fig.7), due to the irregular not cut stones and high presence of mortar. With the double flat-jack test the modulus of elasticity results lower than 200 MPa.

Also sonic pulse velocity test by transparency measured on the same area of the wall shows a masonry with low values of velocity, 637 m/s, while on façade wall the measured values are the double (Fig.8),

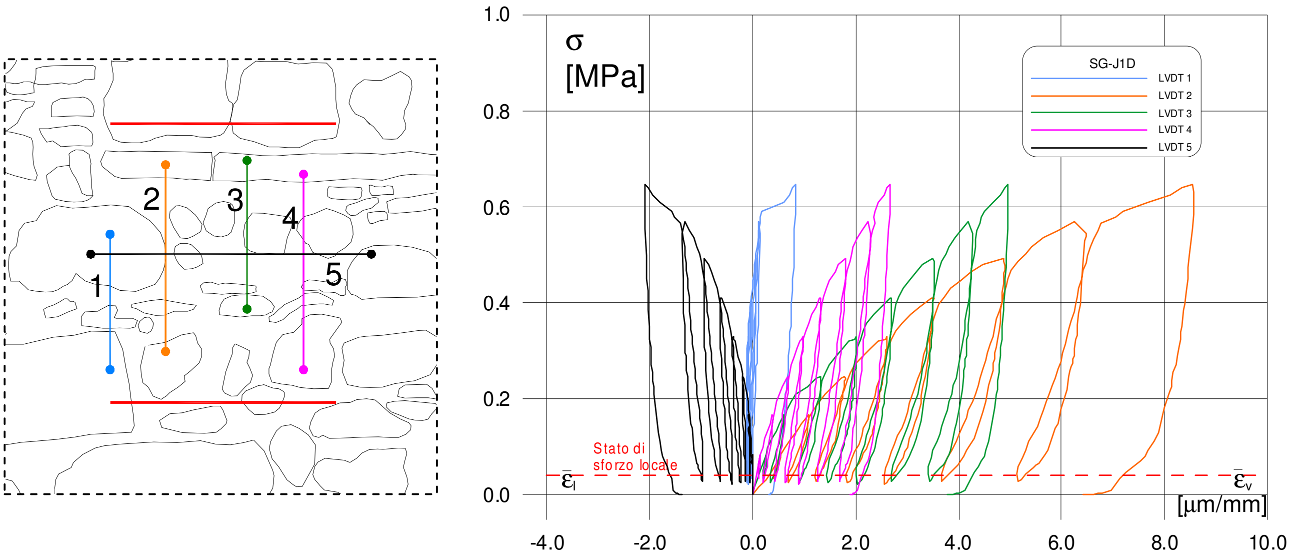


Figure 7: Double flat jack test on the masonry wall dividing the nave from the left aisle.

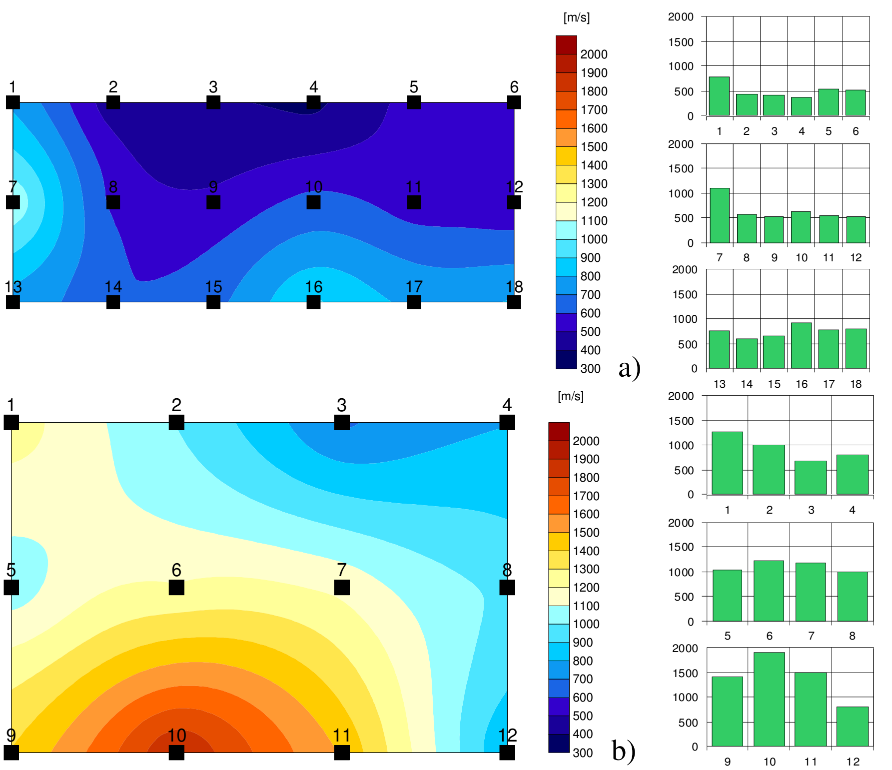


Figure 8:Sonic pulse velocity tests on: a) the masonry wall dividing the nave from the left aisle and b) façade masonry.

DAMAGE DUE TO THE EARTHQUAKE

The structural damage survey is based on the identification of macro-elements that constitute a masonry building and on the evaluation of the level of activation of the kinematic mechanisms associated to the macro-element itself (Giuffrè, 1991).

The crack pattern of S. Giusta in Bazzano is rather serious and easily described by subdividing the structure in its macro-elements.

The façade, while showing signs of past interventions, presents at the top a span-roof, although this termination seems to be successive the construction. Consequently the upper part of the facade presents

the greatest damage (Fig.9a): the façade has indeed lost the gable at the ridge beam and in front of the central nave, with detachment of the external leaf around the central window to the second cornice. The outer leaf and its decoration have a clear out of plumb and are in unsafe conditions (Fig.9b).
Looking at the side elevations of the church it is clearly visible how the entire facade is overturning, with maximum opening at the top, at the corner front-nave, with major emphasis on the right side to the east, at the aisle (Fig.10).
Even in the lower part the damage is larger on the right side (East) than on the left (west) and this could be due to differences in planimetric shape of the two aisles, with or without transverse bracing walls.
The detachment of the masonry façade from transversal walls is visible from inside the church.


a)

b)

Figure 9: a) Crack pattern of the façade and b) out of plumb of external leaf of the masonry wall.


a)

b)

Figure 10: Detachment of the longitudinal masonry walls from the façade: a) higher part and b) lower part.

Externally, the longitudinal walls of the aisles are in good condition with a recent repointing intervention. Long shear cracks are more visible from the inside and on the right side of the church.
Especially, the wall that divides the nave from the right aisle, consists of arches and columns / pillars different from each other, made of material probably coming from previous constructions. On the contrary the corresponding wall on the other side (on the left) has only an opening arch towards the front, at the entrance to the chapel, while the rest of the wall is blind, as separating the church from the pastor's home.
Therefore, the most damaged wall is the one on the right, with arches, columns and pillars. All columns and pillars present an overturning with cracks due to compression to the foot toward the center of the church and with loss of material (Fig.11a).
The larger pillar to the façade presents crushing cracks in all his full height (Fig.11b).

In addition, the dividing walls between the nave and the aisles presents wood trusses elements that moved out from the wall (Fig.12).
The apse wall already had a crack pattern before the earthquake of 06/04/2009, but this event has generated new cracks.
The crypt reported no damage following the earthquake, thanks to the fact of being buried.


a)

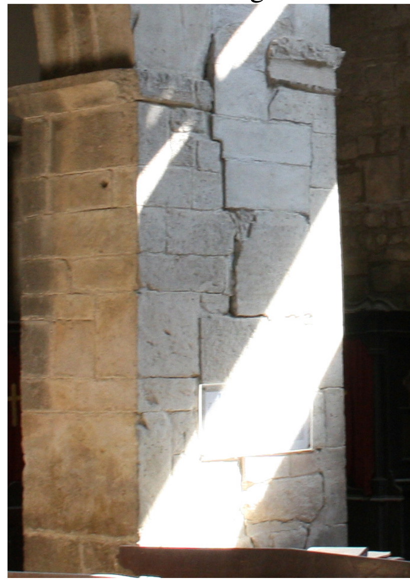

b)

Figure 11: The damage of the pillars: a) a stone lintel used as a pillar due to overturning and b) the largest pillar damage by crushing.

Figure 12: Wood trusses went out from the wall.

Figure 13: the collapse of the masonry wall behind the lateral chapel.

The transversal walls of the left aisle, in the pastor's house and in correspondence of the chapel, are badly damaged due to shear actions (Fig.13). Some vaults in bricks partially collapsed.

VULNERABILITY ANALYSIS

For the identification of activated damage mechanisms, the vulnerability analysis was carried out referred to the national code (NTC 2008, OPCM 2003 and OPCM 2005), Annex C of the Guidelines - "Model for assessing the seismic vulnerability of churches."

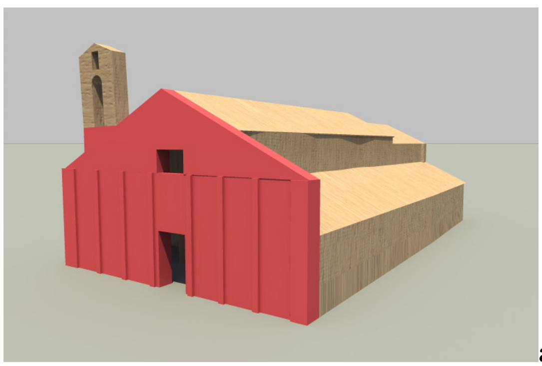
First action was to verify the presence in the church of kinematic mechanisms, among the 28 kinematic mechanisms, typically detectable in this building typology, presented in the Guidelines, associated to different macro-elements.

The kinematic mechanisms approach under the seismic evaluation of existing historic buildings, is based on the monolithic behaviour of the masonry structural elements. The damage survey in Abruzzo region has shown since the beginning that the monolithic behaviour in many cases was not realized because of the composition and the intrinsic structure of the masonry, which has often presented poor quality causing the collapse of entire masonry walls.

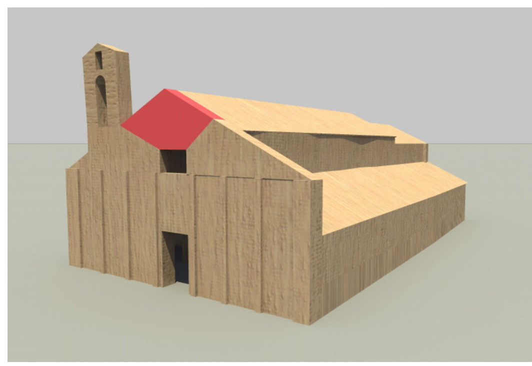
The safety in St. Giusta church results as verified, in case of earthquake, for the facade of the church and of the right side of the facade (assuming the seismic acceleration direction perpendicular to the facade) (Fig.14a,c).

While the safety results as not verified, in case of earthquake, for the top of the facade, with horizontal crack on the tympanum with an opening and for the wall between the central nave and the right aisle, isolated or with lateral constraint, (assuming the seismic acceleration direction perpendicular to the facade) (Fig.14b,d).

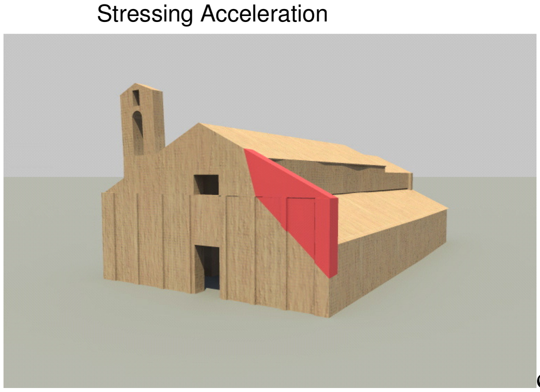
The seismic evaluation, referring to the Limit State of Damage (SLD), is satisfied if the spectral acceleration of mechanism activation is higher than the peak acceleration of seismic demand.


a)

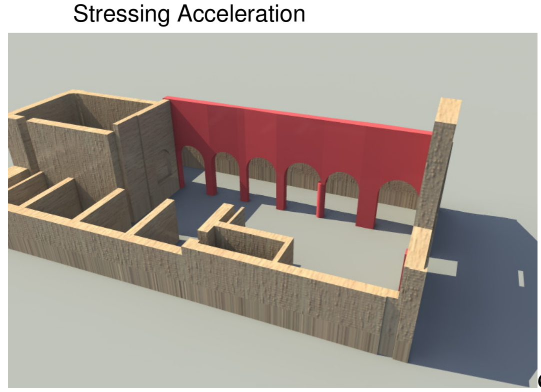
$$SLD = \frac{\text{Resistant Acceleration}}{\text{Stressing Acceleration}} = 1{,}1 > 1 \text{ verified}$$


b)

$$SLD = \frac{\text{Resistant Acceleration}}{\text{Stressing Acceleration}} = 0{,}85 < 1 \textbf{ not verified}$$


c)

$$SLD = \frac{\text{Resistant Acceleration}}{\text{Stressing Acceleration}} = 1{,}05 > 1 \text{ verified}$$


d)

$$SLD = \frac{\text{Resistant Acceleration}}{\text{Stressing Acceleration}} = 0{,}22 < 1 \textbf{ not verified}$$

Figure 14: The four main kinematic mechanisms selected for the vulnerability analysis.

Unlike the continuous full wall dividing the left aisle (now the pastor’s house), the wall between the nave and the right aisle has a high vulnerability due to the absence of transverse bracing walls. Furthermore, the macro-elements consists of pillars and stone elements of different sizes and geometry. These pillars support a masonry wall with an important mass. This macro-element clearly presents a very high instability out of its plane.

SAFETY MEASUREMENTS

Safety works carried out are as much as possible respectful of the conservation principles, efficient from the structural point of view and feasible by operators, who initially were exclusively technicians of the Fire Brigade.

Figure 15: Propping of the buildings facades

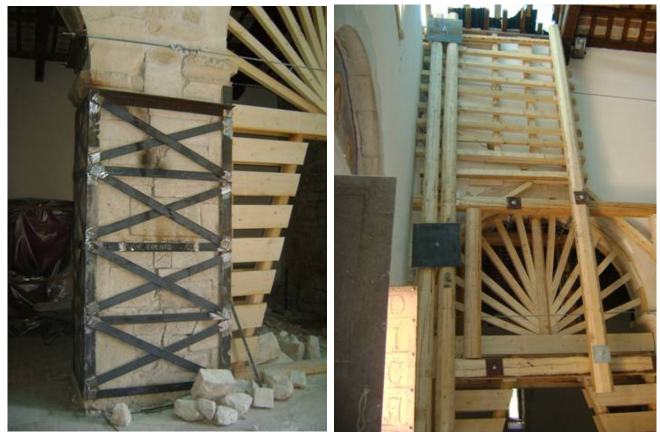


Figure 16: the encircled main pillar and bending of the aches.

Propping of the building facade made with contrasting elements was immediately realised (Fig.15), braced and anchored to the ground by steel rod. This intervention was possible thanks to the free space in front of the church. A double level of tie-rods on the facade anchored to the openings was realised. The most damaged pillar was encircled with flat steel bars (Fig.16) and the internal arches near the façade were bended.

CONCLUSION

The seismic vulnerability assessment of historical buildings should consist of an articulated procedure based on indirect and direct sources of information, leading to the identification of the most typical failure mechanisms activated by the earthquake and allowing for appropriate analytical models. The paper has described the procedure adopted for the St. Giusta church in Bazzano in the emergency, soon after the earthquake, addressed to an articulated knowledge of morphological and constructive aspects of the masonry structures.

The damage was serious but clear to be analysed, so to adopt the most proper safety measurements against another seismic event.

The wooden roof, structurally deformable, had not cooperated to give the structure a box behavior. Invasive and not compatible interventions, increasing stiffness and weight of the church (such as concrete horizontal layers and concrete tie-rods) were not detected.

An analysis of the masonry quality showed a quite peculiar masonry constructive technique, which is very poor and weak but historically common all around the area, considering its seismicity.

Nevertheless during the double flat jack tests on masonry wall, unexpected displacements distribution was observed in the masonry. Comparing this aspect with the historical one (many heavy seismic events in the same buildings over centuries) teaches us to consider other aspects, such as the intrinsic ductility of that poor masonry. This parameter maybe should also be considered in the vulnerability analysis. More research should be carried out on this masonry typology and mainly on the contribution of the mortar in the general behaviour.

Observing the vertical cracks on the dividing wall, between nave and right aisle, and the other damages on the church, it is conceivable that the seismic component was perpendicular to the axis of the church and it was of important entity.

ACKNOWLEDGEMENTS
The authors wish to thank arch. C. Marsili and M. Marchetti, employers of the Cultural Heritage Ministry (MiBAC) for their continuous assistance, arch. L. Cantini, S. Giuffrida and the technicians M. Antico, M. Cucchi for the diagnostic investigations.

REFERENCES

- Anzani, A., Binda, L., Cantini, L. Cardani, G., Saisi, A., Tedeschi, C. (2007). "On site and laboratory investigation to assess material and structural damage on some churches hit by an earthquake", *Proc. of the 12th Conference ANIDIS - L'ingegneria sismica in Italia*, Pisa.
- Binda, L., Baronio, G., Gambarotta, L., Lagomarsino, S., Modena, C. (1999). "Masonry constructions in seismic areas of central Italy: a multi-level approach to conservation", *Proc. of the 8th North American Masonry Conference*, Austin, U.S.A., 44-55.
- Binda, L., Cardani, G., Saisi, A., Valluzzi, M.R., Munari, M., Modena, C. (2007). "Multilevel Approach to the Vulnerability Analysis of Historic Buildings in Seismic Areas Part 1: Detection of Parameters for Vulnerability Analysis through on Site and laboratory Investigations" and "Part 2: Analytical Interpretation of Mechanisms for Vulnerability Analysis and Structural Improvement". *Restoration of Buildings and Monuments*. vol. 13 - 6.
- Binda L., Cardani G., Saisi A. (2009) "Caratterizzazione sperimentale della qualità muraria", in: *XIII Conv. Naz. L'Ingegneria Sismica, ANIDIS*. 28/06-02/07/2009, Bologna, pp. 1- 10.
- Giuffrè A., (1991), Letture sulla meccanica delle murature storiche. Kappa Ed., Roma
- NTC 2008, Decreto Ministeriale 14/01/2008. "Norme Tecniche per le Costruzioni" - in Italian.
- OPCM 2003, Ordinanza del Presidente del Consiglio dei Ministri n. 3274 (2003). "Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica" - in Italian.
- OPCM2005, Ordinanza del Presidente del Consiglio dei Ministri n. 3431 (2005). "Ulteriori modifiche ed integrazioni all'Ordinanza del Presidente del Consiglio dei Ministri n. 3274" - in Italian.
- Penazzi, D., Valluzzi, M.R., Cardani, G., Binda, L., Baronio, G., Modena, C. (2000). "Behavior of historic masonry buildings in seismic areas: lessons learned from the Umbria-Marche earthquake", *Proc. of the 12th IBMaC*, Madrid, Spain.