CODE 535

INSPECTION, DIAGNOSTIC ANALYSIS AND SEISMIC IMPROVEMENT OF BUILDINGS DAMAGED BY SEISMIC EVENTS: S. MARIA ASSUNTA CHURCH AT FABBRICO (ITALY)

Armanasco, Alessandro[1]; Foppoli, Dario[2]

1, 2: Construction, Restoration and NDT
Foppoli Moretta e Associati Counsulting Engineers, Tirano (SO) ITALY
e-mail: posta@foppolimoretta.it, web: http://www.foppolimoretta.it

ABSTRACT

Structural diagnosis can be usefully employed for the protection of existing buildings from the effects of earthquakes and is a useful device for risk prevention, assessment of the usability of buildings damaged by seismic events and for the planning of reparation and improvement interventions.
Each of these applications involves the use of specific methods and techniques that have to be known and standardized as far as possible.
In 2012, the Emilia region in Italy was affected by an earthquake of medium intensity, that therefore caused very extensive damage particularly to the historical and monumental heritage, due to the great sensitivity of its constructive typology to seismic loads. The paper aims to describe the overall approach to the intervention of damage reparation and seismic improvement with reference to the case history of the parish church of S. Maria Assunta at Fabbrico (RE).
The proper planning was based on the results of a careful diagnostic campaign aimed at identifying the damage kinematics activated by the earthquake and at achieving the structural identification of the building and the mechanical characterization of the masonry.
The building site set up that followed, meant the building could be observed with the finest detail in very systematic way, so confirming the results provided by the preliminary diagnostics. This was fundamental for the definition of the constructive details of the intervention, which had to be designed and implemented with great precision and operative attention. In particular, the very significant damage that affected the vaults of the church were shown to be mainly caused by the action of a heavy reinforced concrete beam built in recent years at the extrados of the vaults, evidently with the aim of providing a provisional reinforcement, that, in fact, proved to be harmful. Its removal through a very delicate operation, was therefore necessary.

KEYWORDS: Non-Destructive Testing, Numerical Modelling, Damage Reparation, Seismic Improvement.

1. INTRODUCTION

The Italian monumental heritage has an outstanding value, but it also suffers from its exceptional fragility. Its value is universally recognized and it lies in a unique coexistence of monuments and cultural landscapes that have maintained their absolute uniqueness over the course of several historical epochs, from pre-Roman to the Middle Ages, Renaissance to the Modern and Contemporary Age. Its fragility is due to two complementary aspects. On the one hand, its exceptional diffusion requires widespread and detailed maintenance that is very difficult to coordinate and support. On the other hand, the fragility of the territory, which is often subject to devastating events such as floods and landslides, but particularly earthquakes that have repeatedly destroyed areas of Italian territory for centuries. The sequence of

disasters over recent decades has been devastating, from the Friuli earthquake of 1976 to the last Amatrice / Norcia earthquake of 2016.
Although not generally of high intensity, these seismic events have had a relevant impact on the built heritage, causing massive damage that, especially from the historical point of view, are irreparable since the reconstruction of a monumental building is sure to result in the loss of its cultural value. Therefore, the issue of assessing the safety of existing buildings is of paramount importance, both in terms of the historical-architectural-artistic value of most of the historical buildings and because of their high vulnerability, especially under seismic actions.
The structural diagnosis can be usefully employed, with reference to the protection from the effects of earthquakes, in three complementary aspects:

- preliminary assessment of the seismic vulnerability of existing buildings;
- inspection of the state of damage immediately after the earthquake to assess the usability of buildings;
- assessment of the state of damage and of structural characteristics to plan reparation and improvement interventions.

Each of these applications involves the use of specific methods and techniques that have to be known and standardized as far as possible [1].
The paper will describe the overall approach to the intervention of damage reparation and seismic improvement of a monumental building that, both for historical-artistical and identity reasons, has a particular significance for its own community: the parish church of S. Maria Assunta at Fabbrico (RE). This building was affected by the earthquake that in 2012 caused widespread damage in the Emilia region (North Italy) especially to the historical and monumental heritage, because of the great sensitivity of the constructive typology to seismic loads.

2. AIMS AND METHODS

2.1. Description and background

Figure 1: front view of the church of S. Maria Assunta in Fabbrico (RE)

The church (Fig. 1) is located on the site of two previous churches, the first, mentioned since 772 AD, and the second dating back to the Renaissance period, both within the nucleus of an old fortification. The current building maintains their position and direction towards the East / West axe, even if the orientation has been reversed and the building has been extended. It was built as its present appearance, a single nave with side chapels and a deep presbytery and apse, by the architect Girolamo Beltrami from Reggio Emilia in the penultimate decade of the 17^{th} c., in compliance with the style disseminated between the 17^{th} and 18^{th} c. which refers to the post-tridentine Roman architectural style.
Its simple geometry, symmetrical in the plant and in the apparatus, combines the classical taste with baroque elements. The richness of the interior surprises as itis in contrast with the sobriety of the exterior.

Its imposing, unfinished façade, stands out against the large churchyard, which extends over a part of the pit of the fortification, filled at the period of construction of the church to connect the fortified nucleus to the ancient village, according to the urban development direction determined by the position of the church itself.

2.2. Aims of the designed interventions

The designed intervention had to take into account the relevant boundary conditions:
- the structure's damage due to the seismic event of 20 and 29 May 2012;
- the huge amount of damage due to previous seismic events (Friuli 1976 and Emilia 1996), reported in the documentation found, which demonstrated that the building, due to its considerable slenderness, is intrinsically sensitive to the seismic action;
- the conservative and maintenance needs of the building, which play a primary role in the maintenance design that must necessarily be developed within a long-term strategy.

Since the church is a listed building the improvement, restoration or localized interventions are limited by the Italian guidelines [2] that specify that "often it's appropriate to consciously accept a higher level of seismic risk than the one of ordinary structures, rather than acting in a way not proper for the criteria of cultural heritage conservation". With the necessary priority of restoring earthquake damage, specific design choices aimed at increasing the building's safety without upsetting its structural behaviour have been taken. They were based on the following principles:
- respect of the original structure of the building, increasing the resistance of the elements rather than the implementation of new seismic-resistant structures;
- reversibility, as far as possible, of the interventions;
- guarantee of long-term technical performance of the materials;
- simplicity of the techniques in order to allow the use of easily available materials and the foreseeing of interventions that can also be carried out by local companies without specialized training.

The greater effectiveness of the consolidation intervention is obtained by respecting the original structural behaviour, which means working to correct the detected structural deficiencies. From the analysis of the available documentation, it was possible to deduce both the intrinsic vulnerability of the building, which has already been mentioned, and the fact that in the past the church has gone through, at least, two interventions of dubious efficacy:
- the R.C. beam is placed at the key of the extrados of the vault of the nave, connected to the vault itself by means of tie rods, whose effectiveness is, at the very least, doubtful;
- the concrete roofing of the sacristy, which is unnecessarily heavy and, as it has no connectors, causes dangerous horizontal loads.

It was therefore planned to eliminate these incongruous and harmful interventions and operating in such a way as to consolidate the structures in compliance with their original structural behaviour.

2.3. Path of knowledge

The restoration work on a monumental building needs to move from the knowledge of the intervention's objective, which follows the in-depth understanding of its historical, technical, architectural and artistic peculiarities. This requires a delicate cognitive phase framed in the path of knowledge, explicitly outlined by the Italian guidelines [2] as a fundamental assumption for the purpose of a reliable evaluation of the current safety and also for the choice of effective improvement interventions.
This path must be articulated according to the following activities:
- identification of the construction;
- historical-critical survey of the building, of its crack and deformation pattern;
- interpretation of the historical evolution;
- structural identification of the building and its construction details;
- evaluation of the materials' mechanical properties and their conservation state;
- evaluation of the soil-foundation behaviour.

The level of knowledge reached on these bases determines the choice of confidence factors (F_c) to be applied in the safety assessment process.

3. INSPECTION AND DIAGNOSIS

3.1. Historical-critical survey

The Italian guidelines [2] emphasize the fact that the knowledge of the building, deriving from the survey and diagnosis activities, cannot be separated from adequate understanding of the historical evolution of the construction itself. It is evident that the fact that a historical building (that in the past was subject to differential soil subsidence, winds and earthquakes) still standing today is already the demonstration that the building structure is adequate to guarantee long term structural stability. It can be assumed that history has constituted a full-scale experiment on the artefact and that the cracks, distortions and stress states are the results of this experiment; that's why it is important to get their measurement in order to obtain a model which is as close as possible to the current structural behaviour of the building.

For the church in Fabbrico, the succession of past events, that in some way may have affected the current state of conservation of the building, was investigated on the basis of archival research with the examination of the available manuscripts, design documents, and photographic documentation and of the feedback on the same artefact. The information was then usefully implemented including during the construction phase, allowing to go deeper into the morphological structure of the decorative furnishing and its evolution over time. Thus, it was possible to reach an adequate understanding of the construction phases and of their succession, so determining the building's structural conception and also the intrinsic weaknesses that are not always detectable through diagnostics alone.

3.2. Inspection

Simultaneously, a detailed inspection of the building was carried out by personnel with specific qualification and returned on the basis of standardized survey forms. This inspection was aimed at locating, identifying and filing seismic damage and kinematic mechanisms activated by the earthquake, so highlighting the structural weaknesses.

The analysis and representation of the damage of the 2012 earthquake was also fundamental, flanked by the recognition of previous interventions, in particular the repairs carried out following the seismic events of the past (1697) and those more recent (1976 and 1996). It was implemented through the execution of GPR surveys on the church walls, in order to identify the perimeter tie-rod positions that were indicated by the documents but no trace of which was found (and which were actually identified, with keyholes made undercut and hidden in the masonry).

3.3. Diagnostic survey

The Italian guidelines [2] state that the Non-Destructive Test (NDT) techniques of indirect type can evaluate the homogeneity of the mechanical parameters in the different parts of the construction, but they don't provide reliable quantitative estimation of their values; the direct measurement of the parameters of the masonry, in particular those of resistance, cannot be performed therefore except through Minor Destructive Tests (MDT), which may also be useful in calibrating NDT in order to reduce the number and invasiveness of the investigations.

The mechanical properties of the materials, in particular of the masonry, have been determined, together with their state of stress, through flat jack tests (MDT) [3] [4] [5] (Fig. 2) which have been appropriately calibrated through the measuring of sonic wave velocities (NDT) [6] carried out extensively on the structure. Tomographic cross sections were drawn to analyse specific elements (Fig. 3). In order to fully identify the geometry of the masonry, the stratigraphy of the elevation and foundation structures were analysed by carrying out core drilling of small diameter which were subsequently inspected with an endoscopic probe. From the same cores, and from the surface in the accessible areas (to obtain undisturbed samples), the bedding mortars were sampled and subjected to chemical, physical and petrographic characterization.

An overall Ground Penetrating Radar (GPR) survey campaign was also conducted on the entire floor area of the church, in order to identify buried tombs and any existing walls that could affect the construction of the internal scaffolding. In order to determine the geotechnical characteristics of the surrounding area to define the data necessary for the seismic vulnerability evaluation, geo-mechanical and geo-seismic surveys were carried out according to the following steps

- dynamic penetrometric tests to identify the soil stratigraphy;
- MASW - ReMi tests in order to calculate the parameter V_{S30};
- H/V measurements in order to highlight the presence of seismic resonance phenomena and allow the estimation of the frequencies of amplification of the ground motion.

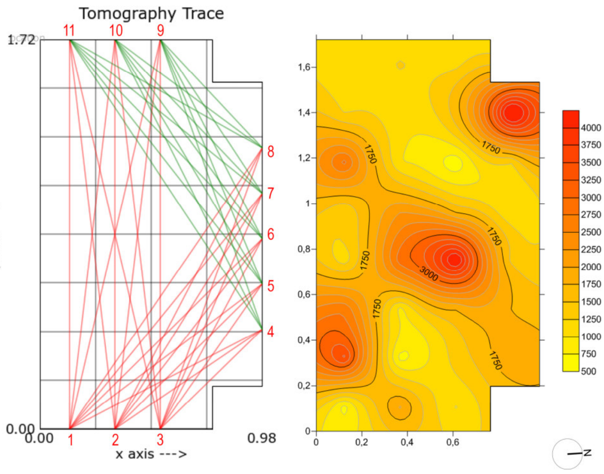


Figure 2: Tests with flat jacks Figure 3: Tomographic horizontal section

The survey carried out made it possible to reach the maximum level of knowledge and so the minimum value of the Confidence Factor (F_c = 1.00) was used in the following analysis.

4. DESIGN

4.1. Design principles

The structure modelling requires its schematization according to a set of relationships that can be expressed with mathematical instruments. For ancient structures, there is consolidated belief, taken from the observation of the damage caused by the many seismic events that have occurred in Italy, that, in many cases, the real response of a building to seismic action cannot be evaluated exclusively considering the global structural behaviour. Furthermore it is necessary take into account the response of single structural elements (called macro-elements) that, by themselves, are sufficient to justify a wide range of seismic damage. It is therefore necessary to use (in a complementary way) models suitable for a limit analysis, particularly representative of the seismic response of macro elements experimentally observed on structures, and finite element models that can take into account the overall behaviour of the structure, but whose results must be carefully calibrated as they are particularly sensitive to the variation of the parameters used for the calculations.
The design process then develops starting from the feedback of the inspections and from the diagnostic information gathered, according to the methods described in the previous points. On the basis of this data, the building was analysed both in its structural macro-elements and in its overall behaviour, allowing the determination of the Resistance Indices (I.R.) that provide the structural safety assessment. Effective consolidation interventions were therefore designed and the I.R. were restated and compared with the previous ones in order to determine the effectiveness of the foreseen interventions.

4.2. Modelling and vulnerability evaluation

To capture the global structural behaviour, a three-dimensional numerical model of the building has been developed and implemented using information and mechanical characteristics collected from experimental data. In order to adequately represent the real behaviour of the structure, the model has been validated not only with regard to the adequacy of the numerical calculation code, but also with reference to its accuracy in representing the actual structural behaviour. Also in this back analysis phase, it was, therefore, necessary to use experimental data that was compared with the numerical results provided by the model in order to guarantee the adequacy of the model prepared, thus confirming the validity of the modelling procedure. The validation was indeed carried out by comparing [7]:

- the crack pattern detected with the calculated tensile stresses;
- the deformation detected with the calculated deformation state;
- the stress state of the walls measured through single flat jack with the calculated stress state.

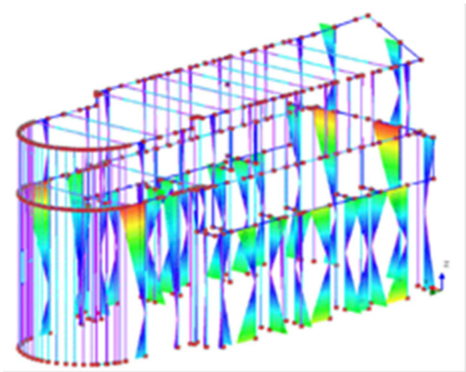


Figure 4: LV3 analysis, shear assessment

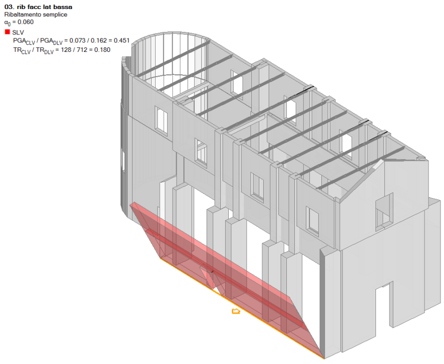


Figure 5: LV2 analysis, collapse mechanisms

The analysis was carried out by means of three-dimensional numerical modelling (Fig.4); the seismic verification was carried out by linear static analysis. The intrinsic non-linearity effects in the structural behaviour of the masonry have been taken into account by identifying the crack pattern and by modelling the consequent discontinuities verified by recursive comparison with the calculated tensile stresses. The analysis was integrated by the LV2 analysis of local collapse mechanisms (Fig. 5).

4.3. Repair and improvement drafting

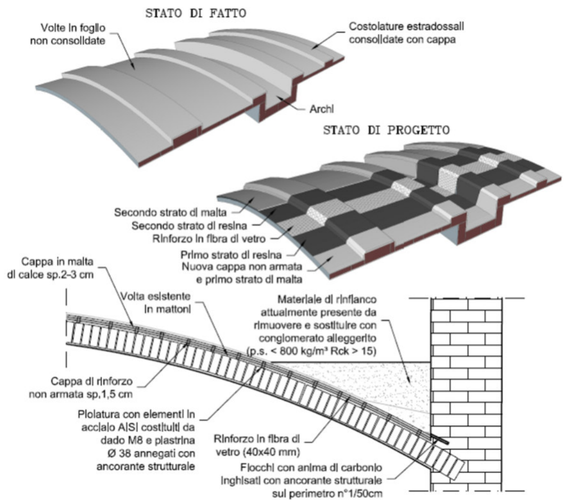
The structural project was based on the analysis of possible damage mechanisms, paying particular attention to those activated during the earthquake: the damage suffered by the structures was analysed, correlated to the above-mentioned damage mechanisms and taken into consideration depending on their intensity. Appropriate structural interventions were therefore planned to repair the damage and to improve the local and overall response of the building to seismic loads. The design was aimed at making minimal resolutive intervention in compliance with the conservative criteria. In the drafting of the project, it was necessary to evaluate the impact caused by the required repairs to the structure of the walls, of the slabs and of the vaults. Therefore, it was necessary to evaluate and to modulate its implementation with specific regard to the architectural aspects, in order to determine the best possible solution and, in the meantime, to preserve surface finishing apparatus, furnishings and decorations.

The vault of the nave is shaped like a “sheet” barrel vault (about 8 cm thickness), with lunettes corresponding to the side wall windows, stiffened at the extrados through ribs made with bricks placed on the side. The intrados arches protrude and divide the spans of the hall and present tie-rods placed at the springs. At the extrados of the ribs and of the arches, a thin reinforced concrete coating was placed (without steel connectors) during a previous intervention of consolidation; in addition an R.C. beam was constructed at the key of the vault, thereby incorporating the chords of the trusses, aiming to suspend the vault through metal tie-rods. This system is of dubious effectiveness, as evidenced by the significant crack pattern caused by the recent earthquake, that was not counteracted by the described reinforcements. The main damage occurred in correspondence with the first and the last span, resulting in shear cracks arranged at 45 °.

Therefore, the elimination of the R.C. beam with its tie-rods was drawn up and its replacement with a reticular metal beam to counteract the tilting of the front façade implemented. Subsequently, the intervention has seen the application of a covering of Fibre-Reinforced Inorganic Matrix material

(FRCM) reinforced with fiberglass fabric (fig. 6) and connected to the vault with metal connectors glued to the extrados of the vault (drilling connecting holes in the bricks is impossible because of their limited thickness). For the execution of the foreseen operations, it was indispensable to carry out the preliminary shoring of the vault by a scaffolding on the top of which a worktop was built on which metal adjustable props were placed to support a system of wooden ribs.

The overall behaviour of the building under horizontal loads was improved by connecting the main structure of the roof to the trusses and to the secondary framework through metal elements. The forces in the plan will then be taken up by a light stringing, placed along the top perimeter of the main nave, built in reinforced masonry and connected to the underlying masonry by grooved bars. The existing metal tie-rods placed inside the masonry that connect the front façade with the buttresses on the side of the presbytery, were located through NDT, thermographic survey and GPR investigations, and were then re-tightened.



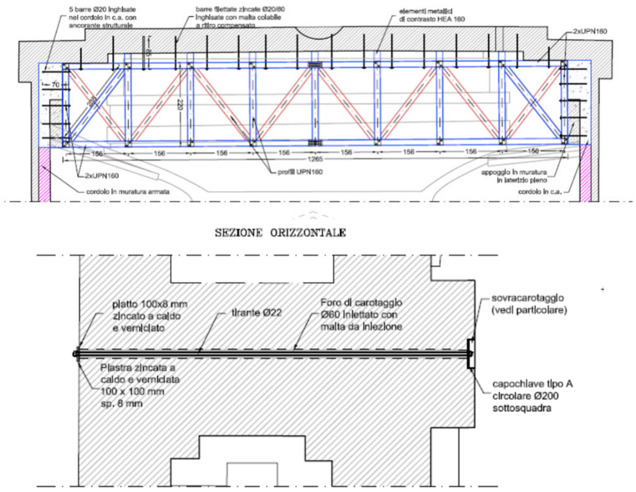


Figure 6: Interventions on the main vault Figure 7: Stiffness of the front facade

The earthquake also underlined the possibility of overturning the front façade, as evidenced by the wide crack between the vault of the hall and the internal façade. This proved also the ineffectiveness of the system of metal tie-rods connected to the R.C. beam. The re-tightening of the tie-rods of the side walls previously described is instead effective also in counteracting the façade's tilting. To inhibit such mechanisms, a metal truss was inserted at the extrados of the vault of the nave so connecting the front façade in a distributed way (Fig. 7) and spreading the horizontal seismic loads to the reinforced support curb. The vertical cracks in the façade were finally repaired by means of localized interventions ("*cuci-scuci*") .

The triumphal arch has key cracks but this problem is well compensated by the presence of lateral buttresses and tie-rods at the springs. Many vertical and shear cracks on the side walls of the apse were found, partially due to shear mechanisms and partially to the overturn tendency of the semi-circular element; the strength of the walls of the apse was improved through the deep re-filling the of the mortar joints, which can be particularly effective with respect to the poor consistency of the mortar observed during the inspections. Two level hoop insertion was also planned to connect the apse masonry to the triumphal arch.

The presbytery's vaults required interventions similar to the one already described for the vaults of the hall; in this case, the connection to the underlying structure through carbon flakes inserted in holes of limited depth was foreseen. The horizontal loads were counteracted in this case through a wooden curb connected to the masonry and to the roof elements.

The side chapels were poorly connected to the walls of the hall, so allowing the tilting of the same elements; shear and cracking problems of the covering vaults of these chapels were also highlighted. The plan foresaw operation through the restoration of the cracks. On the vaults, repairs were performed through the use of grouting from the extrados, to safeguard the altar's decorative apparatus. The cracks

close to decorative elements were repaired through sewing interventions with stainless steel bars. The back walls of the chapels were finally connected through external metal plates connected with tie rods inserted in the thickness of the buttresses.
The additional interventions required for the external volumes leaning against the church of the sacristy and of the stores, will not be described as they fall outside the aim of the present paper.

5. BUILDING SITE

The anamnesis of the building, matched with historical research and critical survey, as well as with diagnostic investigations, in the drafting phase, allowed us to evaluate the repair methods, in compliance with the peculiarities of the building. Correct interventions were identified, suitable for reducing the vulnerability which makes the fragility of the building stand out, should exceptional (but recurrent in the area) events occur, such as the earthquakes.
The following building site also allowed us to observe the building in a close and systematic way, so confirming the results provided by the diagnostic activity. This fact was fundamental for the definition of the executive details of the intervention, which could be designed and implemented with great precision and operative attention. Indeed, the careful diagnosis and design phases prevented making any major adjustments from the planning to the site (Fig. 8 vs. Fig. 7).

Figure 8: horizontal metal truss of the front façade Figure 9: Pull-out test on the connectors with the façade

The historically important artistic furnishing of the church, partly integrated with the structure of the walls, furthermore requires specific attention and protection. Thus, it was also necessary to carefully plan the temporary removal of the furnishing of the church and especially the liturgical decoration. For the not removable elements (strictly connected to the masonry) it was necessary to provide suitable protection, whose feasibility had to be carefully analysed during the definition of the repair methods and restoration interventions.
A major commitment was the construction of the shoring structure of the vault of the nave and of the apse area with a provisional structure that also provided the support of the vault while consolidation work was in progress; the subsequent use of a platform allowed the repair of damage at the intradox and the subsequent restoration of the plaster.
Another on site key operation was the correct selection of the technique adopted for the demolition of the R.C. beam of the vault of the nave. A micro-destructive method was used: the drilling of tiny holes with a pre-defined distance and their filling with expansive mortar. This allowed the cracking of the existing beam making the removal of the split elements easier.
In the works supervision phase, additional on-site tests were also prescribed to prove the effectiveness of the designed reinforcement elements, such as pull-out tests to assess the tensile strength of the connectors between the metal truss and the façade (Fig. 9).

6. CONCLUSIONS

The reported case histories presented some recurring problems for the structural characterization of monumental buildings stressing the need of NDT and showing the results that can be obtained. This is crucial to achieve a high level of knowledge in compliance with the path that the Italian Guidelines for Heritage Buildings draw in order to define the deepening level at which the diagnostic data has to be collected. This creates the conditions to achieve the highest reliability of the input data for the structural model even at low knowledge factor levels.
The case of the church in Fabbrico shows the complete path from the preliminary approach to diagnostic tests to modeling and seismic assessment to drafting to the execution of the intervention of repair of seismic damage underlining that some substantial problems can be faced and solved during the intervention.

7. ACKNOWLEDGMENTS

The authors would like to thank the *Ufficio Beni Culturali* of Reggio Emila - Guastalla Dioceses, particularly mons. Tiziano Ghirelli, arch. Mauro Pifferi e arch. Gian Lorenzo Inghirami, who coordinated the work, and the pool of local architects who managed the architectural aspects: arch. Alessandro Ribaldi, arch. Sandra Losi and arch. Lisa Accorsi.

8. BIBLIOGRAPHY

[1] Foppoli D., Inspections and NDT for the Characterization of Historical Buildings after Seismic Events: 2012 Emilia Earthquake, Proceedings of 10th International Conference Structural Analysis for Historical Constructions (SAHC 2016), Leuven, 2016, pp. 1497-1504

[2] D.P.C.M. 09/02/2011, Valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle norme tecniche per le costruzioni di cui al D.M. 14/01/2008 (Guidelines for Assessment and Reduction of Seismic Hazard of Heritage Buildings in Compliance with the 2008 Structural Code).

[3] Rossi P.P. L'impiego della prova con martinetti piatti per lo studio delle murature, Quaderni dell'ISMES, 1994

[4] ASTM C 1196-09 Standard test method for in situ measurement of masonry deformability proprieties using the flat jack method.

[5] ASTM C 1197-09 Standard test method for in situ compressive stress within solid unit masonry estimated using flat jack measurements.

[6] UNI EN 12504-4:2005 Testing concrete – determination of ultrasonic pulse velocity.

[7] Armanasco A. & Foppoli D. 2014. Diagnostic tests vs structural models: the utility of the comparison, Proceedings of 11th International conference on non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage (Art'14), Madrid, 2014.