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# Structural Assessment and Seismic Vulnerability Analysis of the Reggio Emilia Cathedral, Italy

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ABSTRACT: The definition of "structural safety" of a historical masonry structure is still a concept which is somewhat difficult to interpret. While for new masonry structures it is possible to have useful indications on their structural behaviour, as the analysis turns to "historical" constructions such task became harder and harder. Furthermore, the needs of preservation of the historical, cultural and architectural essence of the building in many cases contrast with the needs of providing the "adequate" capacity to its structure, in order to withstand the design seismic loads. The study presented in the paper is related to the definition of a knowledge and safety assessment "path", concerning masonry religious buildings with a monumental character inserted in the historical centre of the cities. A complex building, the Cathedral of Reggio Emilia, is studied in order to evaluate its structural behaviour thus defining its seismic vulnerability, by using different investigation and analysis methodologies.

## 1 FOREWORD

### *1.1 Background*

The definition of interpretative models that can properly identify the actual seismic behaviour of different structural types of masonry Cultural Heritage Buildings, is currently a topic of great interest in Italy. It is currently accepted, from the structural damage observation after several seismic events recorded in recent decades, that the actual response of an existing masonry building to horizontal actions can not be correctly defined, in the majority of cases, by considering the *global* behavior of the structure. The vast observation of post seismic damage *local* characteristics indicated the necessity to also evaluate the seismic response of individual structural elements, thus implementing suitable structural models (Borri et al. 1999).

In particular, it was observed a pronounced seismic vulnerability related to religious buildings, since they generally present remarkable dimensions and masses, reduced horizontal connections, high masonry elements lacking orthogonal stabilizing walls and presence of vaults and arches that can increase their thrust following the seismic event. Damage in churches was in fact often detected also for low/moderate intensity earthquakes (Lagomarsino et al. 1999) indicating for this structural typology an actual safety problem.

Several pieces of research carried out in recent years indicated the necessity of a multidisciplinary approach to the seismic assessment of historical masonry buildings. On one side, the first concern is the achievement of a reliable structural diagnosis, considering the necessity of a sound knowledge of the fabric (building history and evolution, geometry, structural details, crack pattern and material decay map, wall construction techniques and materials, material properties and structure stability, if needed). To this purpose, on site and laboratory experimental investigations are required (Binda and Saisi 2005).

On the other side it is strongly suggested the application of *local* structural evaluation models considering the seismic response of individual building's structural elements (macroelements approach), rather than conventionally evaluate the overall structural behavior. Several *matrices* graphically depicting the more common failure modes, based on a vast damage classification work after the recent seismic events and referred to specific building typologies, were defined. Regarding the church typology, the data collection started in occasion of the Friuli 1976 earthquake, (Doglioni et al. 1994). The use of simplified models, (kinematic mechanisms) using the principles of limit analysis for the churches' seismic assessment, has been considered since then.

Other modeling strategies (numerical approaches) proven their usefulness in the analysis of historical structures, given the implementation of a correct modeling strategy (Lourenço 2001). For some years now, modeling strategies using numerical techniques as the Distinct Element Method, the Structural Element Method or the widespread Finite Element Method, considering non linear material properties, are becoming a standard procedure (Roca 2001; Rots 2001; Ramos and Lourenço 2004).

### *1.2 Adopted methodology*

Basic concepts of the assessment methodology considered in the present study are the achievement of an adequate knowledge of structure and materials and the successive use of the obtained data for seismic evaluation purposes. A salient feature of the proposed method is the combined application of two distinct modeling strategies (limit analysis and numerical approach). A preventive analysis of the Cathedral considered i) its constructive history and structural evolution, ii) damage manifested by the building after the historic seismic events and iii) the present day crack pattern. Subsequently iv) a wide on-site investigation campaign was carried out. Finally v) the seismic assessment of relevant parts of the structure, involving different modeling strategies, was carried out. Global linear elastic numerical models, calibrated on the basis of the results of the experimental phase, were used to feed local numerical models implementing material non linear constitutive laws. Push-over analyses were carried out on non linear models in order to obtain seismic capacity curves and to identify the actual seismic damage pattern. Limit analysis (kinematic mechanism approach) was comparatively used to define the seismic capacity of selected macroelements, defined in the numerical models corresponding areas. Data emerged from the different modeling approaches were finally compared.

## 2 SANTA MARIA ASSUNTA CATHEDRAL, REGGIO EMILIA, ITALY

### *2.1 Introduction*

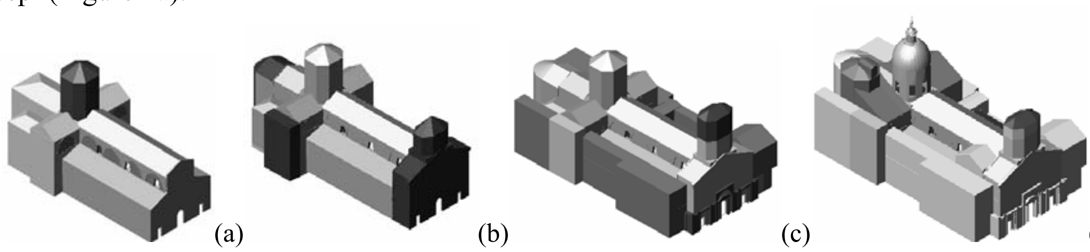
The proposed analysis methodology is applied to an existing Cultural Heritage building, the *Santa Maria Assunta* (Our Lady of the Assumption) Cathedral in Reggio Emilia, Italy, presenting characteristics of pronounced structural complexity (Casarin, 2006). The process of urban stratification comported the inclusion of the Cathedrals' structures between the surrounding buildings/palaces (Figure 1).

Figure 1 : The historic centre of Reggio Emilia, with indication (in the lighter spot) of the Cathedral inserted in the urban context

The structure of the Cathedral is mainly composed by clay brickwork masonry. The diversified constructive phases comported the use of different materials, and some structural elements or parts are made of stone. The Cathedral presents a Latin cross plan, with central nave, two aisles and transept. The length of the church is 77.40 m, the width is 33.80 m, the span of nave and aisles is 10.15 m and 6.50 m, respectively. The maximum height is reached at the top of the dome, with 44.60 m; the height of the façade dome lantern is 33.80 m and the height of the roof above the central nave is 22.25 m.

### 2.2 Historical notes

The origins of the Reggio Emilia Cathedral are to be found at the half of the IX century (Montorsi, 2002). The structure was based on the pre-existences of an early Christian church. The original plan of the church corresponds to a “Latin cross” typology, with three naves and transept (Figure 2a).



(a) (b) (c) (d)

Figure 2 : Constructive phases of the Cathedral: (a) the Romanesque church (IX-XIII c.); (b) XIII c. interventions; (c) XV-XVI c. interventions; (d) XVII-XIX c. interventions

Throughout the centuries the Cathedral underwent several interventions, which substantially altered the original construction. The principal modifications corresponded to: the extension of an atrium to the original façade, with a superimposed dome lantern (XIII c., Figure 2b); the erection of chapels along the aisles, between the mid XV century and the end of the XVI, and the raising of the dome lantern (1451) (Figure 2c); the raising of the aisles’ vaults, the elimination of the Romanesque women’s gallery (1551-1559) and the inclusion of the original Romanesque columns inside “new” massive cruciform pillars; the substitution of the ancient dome lantern positioned at the nave/transept crossing with a dome (1624-1626) (Figure 2d), and the complete substitution of the pre-existing cross-vaulted structures, both in the central nave and in the aisles, with the construction of barreled vaults (1777).

### 2.3 Damage pattern

Considering the past seismic events as full scale tests on the structure (latest events happened in 1996 - Richter magnitude 5.4 – and in 2000 - Richter magnitude 4.5), the present damage pattern shown by the Cathedral is highly indicative of the structural response of the building, and clearly denounces the areas of the complex manifesting higher seismic vulnerability.

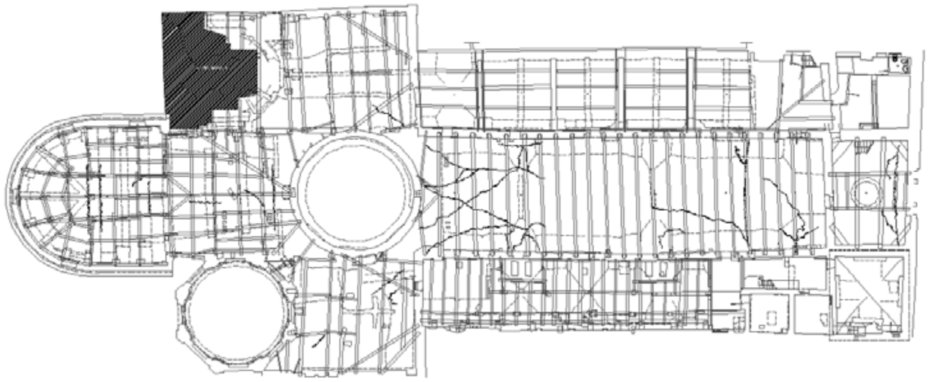


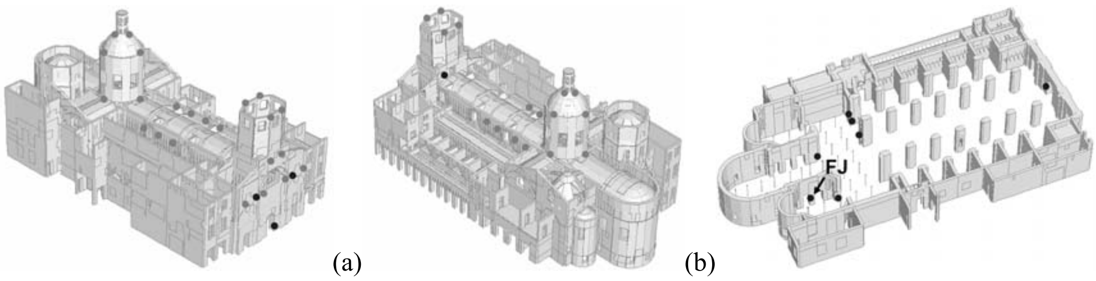
Figure 3 : View of the damage pattern reported on the vaults, mainly localized at the crossing between main nave and transept and in the façade area

In a global sense, the Cathedral did not present worrying damage patterns in its vertical elements. Almost the totality of masonry walls and pillars did not present remarkable damage, except local moderate cracks in correspondence of the pillars sustaining the dome. Damage seems to localize maximally in correspondence of the dome and the façade dome lantern, being massive structures presenting relevant heights. In fact, the vaulted system of the nave mainly suffered in correspondence with these last (Figure 3).

## 3 EXPERIMENTAL INVESTIGATIONS

### *3.1 Introduction*

A sonic characterization of wide portions of the complex was carried out on different parts of the Cathedral, related to different constructional phases. Subsequently, ambient vibration tests were performed to define the dynamic response of relevant portions of the complex, considered indicative of the overall seismic behavior. Technical data on the acquisition systems/sensors and information on the testing methodology are reported in Casarin (2006). A graphic layout of the tested positions is shown in Figure 4.




(a) (b) (c)

Figure 4 : Tests positioning, external view from North (a) South (b) and axonometric view, from East. Darker spots correspond to points of execution of direct sonic tests, lighter spots to dynamic identification sensors' positions.

### *3.2 Sonic pulse velocity tests*

Sonic tests, considering a total of over 350 sonic paths analyzed in different parts of the Cathedral, were aimed at the qualitative evaluation of the physical characteristics of masonry. Tests were carried out in direct configuration. Generally, fair/good velocity results were detected, indicating possible fair masonry mechanical characteristics. In terms of minimum values encountered, seldom the velocity was lower than 800 m/s. No odd velocity values were found, denoting absence of macroscopic inconsistencies within the tested masonry portions investigated. Several masonry walls tested denoted a general velocity uniformity, indicating a possible uniformity also in terms of mechanical characteristics. This was particularly evident in the façade tests, where a horizontal *slice* 17 m long was analyzed at the same height, denoting rather regular velocity values.

### *3.3 Dynamic tests*

The aim of the dynamic acquisitions was to define the structural modal parameters (natural frequencies, mode shapes), for model updating purposes. The investigation process was intimately connected with the evaluation of a preliminary FE model, indicating the possible sensors' locations. The experimental analysis focused on the Cathedral's portions considered more representative from a dynamic point of view, as the dome, the façade (Figure 5) and the upper parts of the main nave. Reference sensors (one or two axes) were positioned at meaningful points, allowing the possibility to use a limited number of transducers to characterize wider portions, by means of different setups. In the façade setups, sensors were positioned at different heights, both on the octagonal structure of the dome lantern, and on the façade's wall. Several peaks were noticed within the frequency range of interest (Figure 5b).

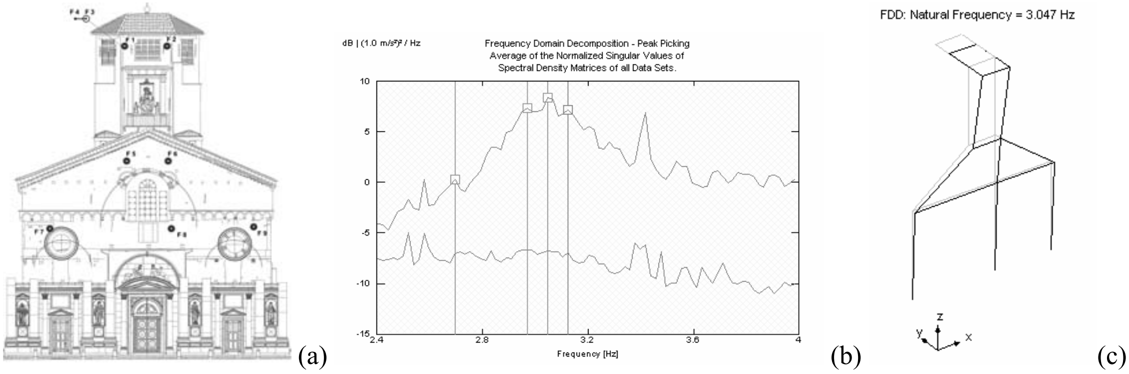



Figure 5 : Façade dynamic identification: (a) sensors positioning,; (b) Frequency Domain Decomposition Peak Picking method, selected frequencies; (c) defined mode shape, first (bending) resonant frequency

To obtain reliable data, cross correlations were established between the spectral density obtained from different sensors, comparing coherence and phase angle. In the façade, it was observed that just a couple of identified frequencies are indicative of global modes (Figure 5c), presenting good coherence values between the reference sensors.

## 4 STRUCTURAL ANALYSIS

### *4.1 Introduction*

In a first instance, a kinematic limit analysis approach was selected, considering the seismic individual response of defined portions of the complex. Several numerical simulations were then performed, starting with linear elastic models comprehending the global structure. Such first models were calibrated on the basis of the results emerged from the experimental investigations. According to the results achieved, reduced models considering the material non linear properties were implemented. In the next sections, the analysis of-the-out of plane seismic behavior of the façade will be presented.

### *4.2 Limit Analysis*

The analyzed portion is composed by the structural elements of the first Cathedral's bay, considering the façade wall, the dome lantern, the first couple of pillars and the longitudinal walls. The damage pattern encountered did not allow a simple interpretation of the envisaged collapse mechanism, as there are cracks denoting several failure possibilities. For this reason, a number of collapse scenarios were evaluated, and the corresponding safety factors ($\alpha_0$) and capacity curves were defined, according to the methodology proposed by the Italian seismic standards. Figure 6 indicates the considered collapse mechanisms for the out-of-plane seismic action.

| Mech. | $\alpha_0$ (g) |
|---|---|
| (a) | 0,457 |
| (b) | 0,215 |
| (c) | 0,183 |
| (d) | 0,189 |
| (e) | 0,205 |

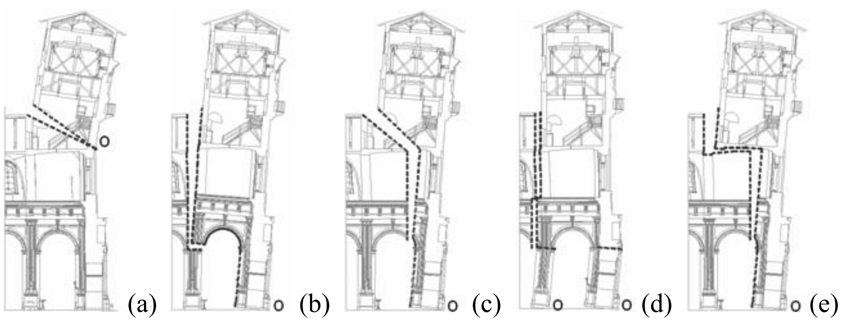
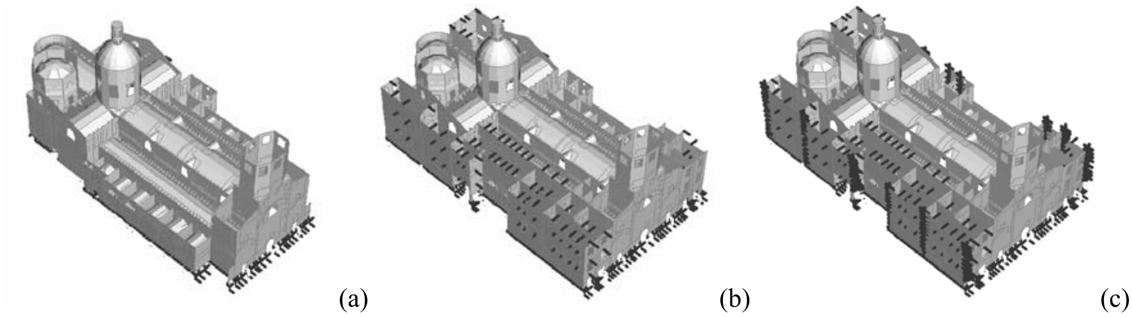



Figure 6 : (a) to (e): Considered façade out-of-plane overturning mechanisms, detail of the separation surfaces and hinge positioning, and obtained $\alpha_0$ values.

### 4.3 Finite Element Method analysis

The numerical simulation of the Reggio Emilia Cathedral considered in the first instance several linear elastic Finite Element models, representing the global Cathedral's structure, being aimed at the comparison with the experimental dynamic outcomes. In addition, relevant parts of the surrounding buildings were subsequently included in the models, since their presence modifies in a significant manner the dynamic behavior of the Cathedral (Figure 7). To validate the definitive linear elastic numerical model on the basis of the experimental results, the Modal Assurance Criterion was used.

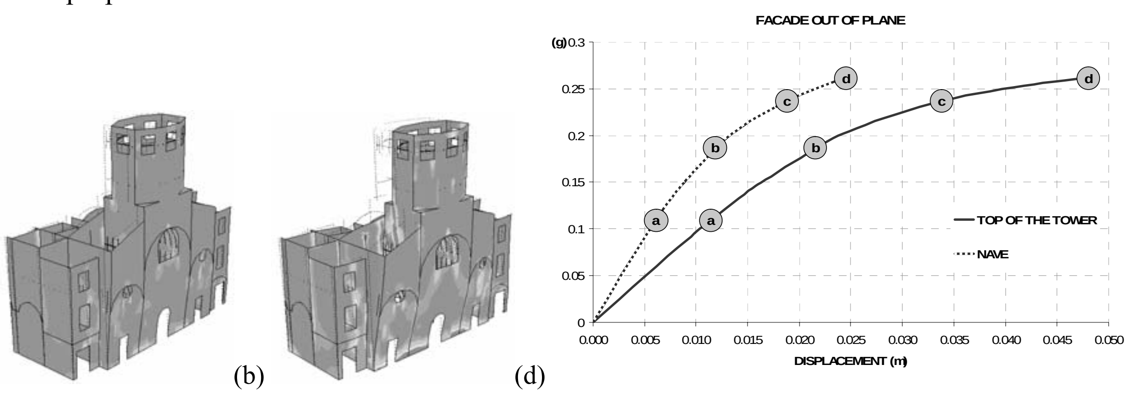


(a) (b) (c)

Figure 7 : From the first model (a) to the definitive (c) through successive boundary conditions variation.

Subsequently, a global model considering the whole Cathedral and part of the surrounding buildings, based on the elastic model previously calibrated on the basis of the experimental results, was implemented by using the software package DIANA™, considering non linear material properties. To the purposes of the study, significant portions of the full model were extracted and separately analyzed. The Cathedral's parts considered in the sub-models were selected on the basis of geometrical, historical-constructive and damage pattern preventive evaluations. The façade model considers the front part of the Cathedral, included reduced parts of the surrounding structures. The deep transversal crack present in the nave vault at the end of the 2nd bay is considered as a discontinuity joint, being the model separated from the rest of the Cathedral's structures in this position. A wide vertical crack that separates the Cathedral's front from the adjacent building was taken into account. The model (38959 nodes, 14683 elements) implements 2D rectangular/triangular curved shell quadratic elements. A total strain rotating crack based criterion was selected (Feenstra et al. 1998, Rots 2002). The Young's modulus conferred to the structural elements derives from the calibration analyses carried out for the global FE linear elastic model (2100 MPa).

In absence of direct experimental determination, a tensile strength of 0.10 MPa was adopted. A simple material elasto-plastic constitutive law (in tension), with no material softening and an elastic compressive behavior were considered. Loads applied in the analyses were the self weight and the seismic action, introduced by the application of a set of equivalent horizontal loads proportional to the mass of the structure.




(b) (d)

Figure 8 : Façade model, damage progression, maximum principal strains: the damage pattern denoted by the models in (b) – $\alpha$=0,19g - to (d) - $\alpha$=0,26g - is related to the corresponding points of the capacity curves (control points at the top of the tower and at the nave's level) in the diagram.

Figure 8 illustrate the progression of the damage mechanism. Damage starts with crack opening at the corner between the Cathedral's façade and the orthogonal walls, followed by consequent cracking in the first bay aisle vaults. The damage process continues with the involvement of the dome lantern sustaining walls (appreciable diagonal cracks), with the beginning of a separation crack between the first bay central vault and the façade wall and the façade overturning, denounced by the crack opening in the rear part of the wall.

The analysis stopped at a value of horizontal acceleration equal to 0.26 g, following a significant reduction (down to 13% of the initial) of the system's stiffness. It is worth stressing that the damage pattern predicted by the analysis finds a remarkable correspondence with the effective damage observed in the Cathedral, in several positions.

### *4.4 Comparative results, limit analysis and non linear FE model*

Results emerged from the comparative analyses carried out on the façade model are reported in Figure 9. Evaluating the obtained results, it seems that the most likely collapse mode is the one indicated by the mechanism in Figure 9c. Nonetheless, also a translational component of the central nave respect the aisles, as supposed in mechanism (d) (pillars overturning), is fully appreciable (Figure 9b, d). In terms of values comparison, it has to be stressed that the numerical simulation did not take into account a softening law for the tensile behavior.

For this reason, the overall FE response did not manifest a softening branch after the peak attainment, but a tendency to an asymptotic value, as can be considered the reached value (0.26 g) in consideration of the structural stiffness decrease (Figure 9a). The importance of the comparative FE model evaluations lies however in the possibility to reassert that the assumed limit analysis failure mode (c) is supposedly correct, also in consideration of the proposed FE model damage pattern experimental verification.

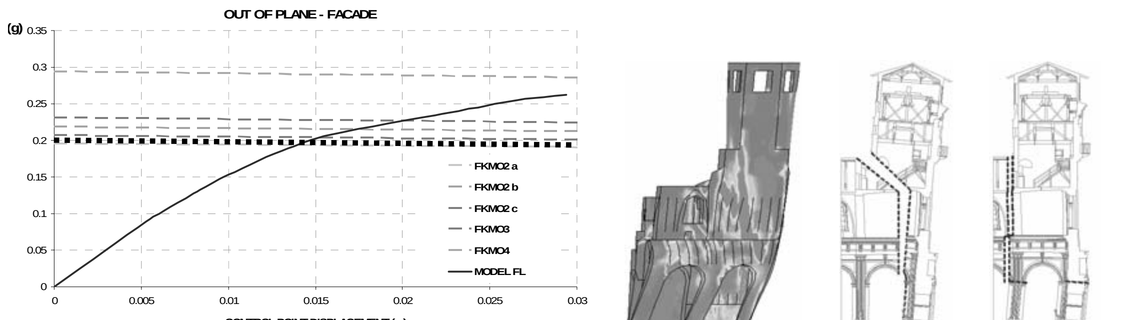



Figure 9 : Façade model, (a) FE and limit analysis capacity curves, the bold dotted black line corresponds to the almost coinciding kinematic models (c) and (d) capacity curves; (b) numerical outcomes at the last step of the non linear analysis (0.26 g); comparison with the limit analysis mechanisms (c) and (d).

## 5 CONCLUSIONS

Considering the structural assessment of a historical masonry building, the study carried out reasserted the importance of a multidisciplinary approach to the problem. The in situ survey, the evaluation of the damage pattern suffered by the structure, the historical analysis have been essential in defining in a correct way the structural layout of the fabric.

Sonic investigation tests showed that the overall *quality* of the masonry is fairly good, presenting average velocity values that can be considered satisfactory for the analyzed masonry typology and thickness. This observation allowed a confident adoption of the limit analysis method, that considers masonry portions as rigid bodies, not presenting e.g. preventive collapse by masonry crumbling. Dynamic investigation was noted to be a powerful tool for the characterization of wide structural portions. With relatively few test setups it was possible to define the dynamic behavior of almost all of the structural complex of the Cathedral, thus properly calibrating the reference FE linear model to be used for the seismic assessment.

Limit analysis (macroelement approach) proven to be a valid and useful tool in the seismic assessment of existing masonry buildings, requiring the knowledge of few parameters (geometry, connections) and a meticulous damage observation. Limits of the method emerge when the analysis must take into account complex structures, for which the failure mode definition is not trivial. The combined application of numerical models was critical in the correct definition of non ordinary kinematic schemes, since the analysis considered composite mechanisms. The preventive implementation of elastic global models can be considered an important step for the definition of the overall structural properties. The adoption of non linear material constitutive laws represented however a key issue in the proper evaluation of masonry structures.

As a conclusive remark, it can be said that results have a conventional nature, in absence of a deep knowledge on the constitutive materials and on the process that drives the structure to failure. It has then to be reasserted the extreme importance of the observation of the damage pattern left by previous seismic events, considered as the historic real scale test on the structure.

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