(Article begins on next page)

A structural analysis of the Modena Cathedral

Simonetta Baraccani [a], Stefano Silvestri [b], Giada Gasparini [c], Michele Palermo [d], Tomaso Trombetti [e], Elena Silvestri [f], Renato Lancellotta [g], Alessandro Capra [h]

Department of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna, Bologna, Italy

[a] *University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy, Tel.: +39 0512093232; fax: +39 0512093236, e-mail: simonetta.baraccani2@unibo.it*

[b] *University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy, Tel.: +39 0512093232; fax: +39 0512093236, e-mail: stefano.silvestri@unibo.it*

[c] *University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy, Tel.: +39 0512093232; fax: +39 0512093236, e-mail: giada.gasparini4@unibo.it*

[d] *University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy, Tel.: +39 0512093232; fax: +39 0512093236, e-mail: michele.palermo7@unibo.it*

[e] *University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy, Tel.: +39 0512093232; fax: +39 0512093236, e-mail: tomaso.trombetti@unibo.it*

[f] *Studio Tecnico Silvestri di Ingegneria e Architettura, Viale Caduti in Guerra 35, 41121 Modena, Italy, Tel.: +39 059216387; fax: +39 059211299, e-mail: elenasilvestri@studiotecnicosilvestri.it*

[g] *Politecnico of Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy, Tel.: +39 0110904841, e-mail: renato.lancellotta@polito.it*

[h] *University of Modena, Via Università 4, 41121 Modena, Italy, Tel.: 0592056511,; fax 059 245156, e-mail: alessandro.capra@unimore.it*

THE STRUCTURAL ANALYSIS OF THE MODENA CATHEDRAL

Simonetta Baraccani [1], Stefano Silvestri [1], Giada Gasparini [1], Michele Palermo [1], Tomaso Trombetti [1], Elena Silvestri [2], Renato Lancellotta[3], Alessandro Capra[4]

[1] *University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy*

[2] *Studio Tecnico Silvestri, Viale Caduti in Guerra 35, 41121 Modena, Italy*

[3] *Politecnico of Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy*

[4] *University of Modena, Via Università 4, 41121 Modena, Italy*

Historical monuments, by its own features and time evolution, represent a "unicum" characterized by large uncertainties. To reduce the uncertainties and lead to a more robust assessment it is of fundamental importance to carry out a preliminary, but comprehensive, study with the integration of different fields. The scope of this paper is to present a preliminary assessment of the structural “health” of the Modena Cathedral making use of a multi-disciplinary multi-analysis approach. The approach is based on the development of a multi-disciplinary research able to providing an “integrated knowledge” of the building and a kind of multi-analysis method, which seeks to integrate the results of analyses based on different approaches (from simple but more reliable limit schematizations, to more complex but, usually less robust, computer-based models).

KEY WORDS: historic monuments, integrated knowledge, structural behaviour, limit schematizations, finite element models.

1. INTRODUCTION

The architectural heritage represents a considerable portion of the Italian cultural heritage, which has to be preserved for future generations. Historical monuments are built and modified during the centuries by using various construction techniques, workmanships of different expertise, with the result of a complex fabric, characterized by a high degree of uncertainties, quite far from our modern buildings (Bucur et al.2008). In most cases, their actual configuration and state of conservation is not only the result of the natural degradation due to ageing effects, but also the consequence of the impact of past extreme natural events (such as earthquakes, floodings), which may have caused partial or total collapses.

The inherent complexity of historical buildings (due to the complex geometrical configuration, the use of different construction techniques, different materials), together with the natural material decay and the effects of natural hazards, make the assessment of the "structural health” extremely challenging. Furthermore, all the uncertainties due to this complexity render each monument a "unique"(Roca et al. 2010). This means that the approach commonly used for the assessment of ordinary buildings (largely based on the use of computer software and well established protocols) cannot be simply adopted for complex monumental buildings.

In fact, it clearly appears the need of an integrated approach for the assessment of monuments vulnerabilities in order to plan effective interventions. In this respect, in the case of ordinary structures, a common strategy to reduce the uncertainties and provide a reliable assessment of the “structural health” is based on the use of extended in situ experimental tests. In most cases when dealing with historical buildings this strategy is not feasible and only limited non-destructive teste can be performed.

A possible approach to reduce the uncertainties in the knowledge of historical buildings is based on the development of a multi-disciplinary research aimed at providing an "integrated knowledge" through the mutual exchange of expertise and capabilities of different sectors and a real-time monitoring of the state of the buildings (ICOMOS 2003). According to the principles of restoration, only with a thorough knowledge it is possible to conceive intervention solutions targeted at preserving the original integrity of the architectural heritage.

Similarly, as already briefly mentioned, approaches and tools commonly used for the structural analysis of ordinary buildings, extensively based on the development of finite element models, do not always seem to be appropriate for historical monuments of unique features. More reliable results can be obtained by employing a multi-analysis method which seeks to integrate the results of a number of structural analyses based on different approaches (from simple but more reliable limit schematizations, to more complex but, usually more sensible, finite element models, Lourenço 2002).

A multidisciplinary Committee has been established in the year 2008 with the purpose of assisting the local authorities in charge for the management of the Cathedral of Modena. A deep knowledge and the structural behaviour of this monument has been therefore evaluated through a multi-disciplinary multi-analysis approach.

The present work is focused on the development of a preliminary structural analysis aimed at identifying the main vulnerabilities and criticalities to be mitigated. Therefore, some of the studies carried out by the Committee, including the identification of the main phases of construction, the topographic surveys, the geotechnical investigations will be here briefly summarized provided that they were fundamental for the development of the structural assessment. An extensive summary of all the studies conducted by the Committee will be available in a volume entirely dedicated to the Cathedral of Modena.

2. THE CATHEDRAL OF MODENA

The Cathedral of Modena, a masterpiece of Romanesque architecture and sculpture of northern Italy, represents the main architectural reference site of the Catholic community of Modena (Figure 1). The Cathedral, consecrated in 1184, was declared as “UNESCO World Heritage in the 1997. Its construction began in 1099 under the coordination of the architect Lanfranco and sculptor Wiligelmo. The actual Cathedral was constructed in the same location of pre-existent churches whose ruins were discovered during past interventions (Acidini et al.1984).

The in-plan geometry is approximately 25 m wide (in the transversal direction) times 66 m long (in the longitudinal direction), for an area of roughly 1650 m^2. The maximum roof height is approximately 24 m (Figure 2). The Cathedral has a Latin cross plant with three naves, a false transept and the chancel (the area of the liturgical altar) in an elevated position, due to the presence of a crypt containing the corpse of the city's patron, Saint Geminianus.

The structural configuration consists of heavy masonry walls and sturdy masonry and stone pillars supporting the weight of impressive thin masonry vaults, added in the XV century. Both the central nave and the side aisles have four spans. The vaults of the central nave have double length span with respect to the vaults of the aisles. The maximum height of the vaults of the central nave is around 20 m, while that of the side aisles is approximately 13 m. Next to Cathedral erects a high tower (86 m high), the Ghirlandina Tower whose construction proceeded in parallel with that of the Cathedral up to the fourth level. The upper part of the tower was built later, between 1261 and 1319 (Cadignani 2009).

3. THE INTEGRETED KNOWLEDGE

3.1.The construction phases and the main interventions

The first fundamental step toward a reliable assessment of the structural behaviour of a monument relies in the study of its construction phases, including the damages suffered during the history and the strengthening interventions carried out to repair theme. All this information are also very important for a better understanding and interpretation of the present cracking pattern.

The current configuration of the Cathedral is the result of various changes, transformations and interventions that occurred on the structure during the centuries. These continues transformations not only affected the architecture of the Cathedral but also significantly influenced its structural behaviour. In the light of this, it is of fundamental importance to have a clear view of the most significant construction phases.

Three cathedrals were built on the necropolis containing the tomb of St. Geminiano (the founder of the church of Modena), before the current one (Labate 2007). The tombstone is the only remaining evidence of the first cathedral. A second cathedral was erected in the same place around the VIII-IX century. The remains indicate that the church had a length of around 32 m and width of 18 m. The presence of polylobate pillars (Bertoni 1914), discovered during past excavations, allow supposing the existence of another cathedral, presumably built around the XI century (Figure 3) (Frankl 1927).

The first construction of the present cathedral took place in three phases, starting from the 1099 to conclude around 1120 -1130 (Peroni 1989 and 1999; Lomartire 1989; Armandi 1999). According to the hypothesis of Porter (1917), later also confirmed by other researchers, the construction began, almost in parallel, from the apses (phase A) and, just few years later, from the main façade (phase B). Later on, starting from the 1130, the clerestory was built and the lateral naves were joined at the points where, according to critics (Peroni 1989 and 1999; Lomartire 1989), the initial construction was interrupted in order to maintained the portions of the pre-existing cathedral (phase C). According to more recent historical studies (Silvestri 2013), the construction did not proceed in parallel from the two sides, namely the main façade and the apsis, but started from the apses to end with the main façade (phases A and B). In light of this alternative hypothesis, the phase C was necessary to repair some damages due to early soil settlements manifested during the first two phases. Figure 4 graphically represent the three construction phases according to the last hypothesis.

Several interventions after the end of the construction (end of XXII century) were carried out during the years. According to most critics, the roof system, initially made of wooden trusses system arranged in the transversal direction, was rebuilt starting from the 1413. The orientation of the principal beams were changed when the vaults of the naves were constructed. Probably during this phase, the wooden beams have been renewed. This intervention probably caused further deformations of the longitudinal walls. Later, other interventions were necessary to retrofit the Cathedral after the earthquakes occurred in the 1501, 1505 1671 and 1832. The main interventions affected the vaults, the arches, the façade and the portions of walls adjacent to the Ghirlandina tower (Dondi 1896). In the following years, additional strengthening interventions were performed, such as refilling the main cracks, repairing the roof (new wood structures connected to the masonry wall trough tie-rods) and better connecting the walls through iron tie-rods in the naves at different heights (Figure 5).

3.2. The accurate reconstruction of the geometric configuration through laser scanner and geotechnical investigations

A 3D laser scanner of the Cathedral have been carry out in order to precisely identify walls dimensions and eventual not-verticality (Castagnetti et al. 2011). In more details, the study revealed that the main overhanging are localized in the walls closest to the Ghirlandina Tower, thus indicating a strong interaction between the Tower and the Cathedral. It has to be noted that the Tower and the Cathedral are connected by strong arches, which tend to contrast the rotation of the apses.

A geotechnical investigation aimed at identifying the main soil properties as well as indication the presence of foundations of the pre-existing cathedrals has been carried out. Those ruins are localized in the area below the aisles. The presence of the pre-existing foundations may further justify differential settlements. As a consequence, the foundation soil is characterized by different levels of consolidation due to the weights transmitted to the ground from previous cathedrals.

3.3. The material properties

The knowledge of the material properties is the starting point of any reliable structural analysis. If for new constructions this phase is quite straightforward, for the case of a complex monument the evaluation of the material properties may become one of the major challenge. Extensive non-destructive tests are typically used to evaluate material properties of ordinary existing buildings. Nonetheless, for important monuments, only limited tests are usually allowed by the local authorities in charge of the conservation of the monument. Moreover, the mechanical parameters as obtained from few non-destructive tests, provide only partial or punctual information. This means that these few data should be critically analyzed given that they may be affected by large uncertainties.

A simple method to critically analysed the materials mechanical characterization based on limited experimental tests have been recently proposed by the authors and applied for the case on an ancient masonry Tower located in Bologna (known as the "Asinelli" Tower). In that study (Palermo et al.2014), experimental values have been compared/validated with typically values suggested by codes or literature and values based on material models. A similar approach has been used for the Cathedral of Modena in order to estimate materials elastic properties and strengths. For masonry and stones, Young's modulus (E) of E_m =180000 MPa and E_s=250000 MPa have been assumed, respectively. For the wooden beams, considering ageing effects, the lower bounds mechanical properties as suggested by CNR-DT 206/2007 have been used.

3.4. The actual state of degradation

A first detailed survey of the cracking pattern were carried out in the 2010. After the 2012 Emilia Earthquake the Cathedral suffered minor damages, mainly localized in the vault. Therefore, a second survey were carried out to detect in detail the damages cause by the earthquake. After this detailed survey, a strengthening intervention has been planned. The design is actually under development.

The initial crack pattern (2010) has been identified not only to monitor the state of the main cracks but also to correlate their location within the construction phases and main interventions. The analyses of past studies also helped in the classification of the cracks. In particular, the correlation between the damage and the past interventions allow to identify probable causes and distinguish between stable cracks and still evolutionary situation. The major cracks are displayed in Figure 6. The main cracks are indicated in red, while grey areas indicates concentration of cracks, i.e. portions of potential high vulnerabilities. It can be noted:

- a large vertical crack is located in the main facade, just below the big rose window;
- a concentration of cracks has been identified in the connection between the walls, all along the portion of the building constructed during the phase C, in the fourth span from the west;
- another cracks concentration appears near the main facade, along a line parallel to the façade, in the second span from the west;
- vertical cracks along the main transversal walls and arches separating the central naves from the lateral naves;
- the grey areas are mainly located in the portion of the cathedral coinciding with the location of the old ones.

During the survey after the 2012 Emilia Earthquake, new cracks appeared in the intrados of the main vaults. Moreover, also an evolution of some existing cracks has been observed (Figure 7).

3.5. The monitoring system

In 2003, a static Structural Health Monitoring (SHM) system has been installed aimed at monitoring the "structural health" of the monument (Sohn et al.2004, Worden et al. 2007) for its efficient conservation (Rossi 1997). Typically, a static SHM is composed of several devices, which monitor the evolution of strain and stress state of structural elements, the opening of specific existing cracks, the change in the inclination of walls, and correlate the acquired data with weather conditions. The information are generally plotted against time. A stationary (in time) condition reasonably suggests that the structure is in a stable condition, whilst a non-stationary response (especially in the cases where a clear trend is observed in the data) may indicates a significant evolution of the state of damage, which may preclude the structural safety of the monument. Clearly, especially for an old monument, the information obtained from a SHM system can improve the knowledge of the structure. Moreover, the data obtained from the monitoring may be integrated with the results of structural analysis and also used to check in real time the effectiveness of strengthening interventions.

The monitoring system installed in the Cathedral is composed of biaxial and triaxial joint meters (MGB-MGT), inclinometers (FP), deformometers (D) and thermometers (T) to monitor the main cracks across the walls and vaults, the inclination of the external longitudinal walls, the relative displacements between the cathedral and the tower and the internal temperature, respectively (Baraccani et al. 2014). A plan view with the indication of all installed instruments is provided in figure 8. For instance, the record of a biaxial joint meter (MGB1) is displayed in Figure 9a together with the record of the thermometer. A strong correlation of the oscillations with the thermal excursions may be noted. For the sake of conciseness, only the most significant results as obtained from the 10 years of monitoring by the joint meter can be summarized as follows (see also Figure 10):

- the average daily oscillation is around $1\text{-}7 \cdot 10^{-3}$ mm;
- the average annual oscillation is around $1\text{-}40 \cdot 10^{-2}$ mm;
- in general a quite stationary response is observed, with the exception of few instruments (such as MGB2, see Figure 9b), which show a slightly increasing trend (average annual rate around 10^{-2} mm/year).

4. MULTY- ANALYSIS METHOD FOR THE ASSESMENT OF THE STRUCTURAL BEHAVIOUR

4.1. The applied loads

Generally speaking, the actions on a building can be classified into: (i) dead loads (i.e. permanent loads such as the structure self-weight and non structural self-weight); (ii) live loads (i.e. loads due to the use and occupancy of the building); (iii) environmental loads (such as wind pressure, effect of snow, rain, effect of extreme events such as earthquake, hurricanes, floods, fires…). The geometrical properties of the roof system and masonry walls have been identified through the accurate geometric surveys of above (see section 3.2).

In this work, only the effect of the vertical loads will be considered in the structural analysis. The assessment of the monument against the other possible environmental loads is out of the scope of the present work and will be the objective of future specific studies.

The vertical load due to snow has been estimated equal to 120 kg/m^2 according to the Italian building code (NTC08 2008). In addition to the above described loads also the interaction between the Cathedral and the adjacent Ghirlandina tower has been accounted for (even if, at this stage, in a rather simple way) by applying a path of differential vertical displacements at the base of the Cathedral (values of imposed displacement were provided by the geotechnical investigations mentioned in section 3.2). In detail, the differential displacements have been imposed in the portion of the base closest to the Ghirlandina Tower (Figure 11). The imposed vertical displacements are equal to 20 cm at corner H, 27 cm at corner G, and 30 cm at corner F. Linear variations of vertical imposed displacements have been assumed between the above mentioned points, as well as moving from the side to the center of the cathedral.

4.2.Structural analysis with simple schematizations

In light of the integrated approach, the structural behaviour of the Cathedral has been analyzed by employing different structural models. First, simple limit schematizations (i.e. substructures) have been developed for a preliminary structural analysis of the roof system and the main vertical resisting elements (i.e. walls and stone pillars). Each substructure is analyzed with the purpose of obtaining the stress state of the main structural elements. In more details, for the case of the single walls, both simple hand-made schematization and planar Finite Element (FE) models have been developed.

4.2.1. The roof system

The actual roof geometrical configuration is made of principal beams arranged in the longitudinal direction, which rest on secondary beams or transversal trusses systems (indicated as *Ti* and *ti* respectively, in Figure 12).
Making use of this geometry a simple static analysis has been performed in order to get the stress levels and the reactions at the base of the roof (which are then used as applied loads for the resisting elements).

Maximum normal stresses for the main beams due to self-weight only are around: 50 kg/cm^2 for the central nave, 80 kg/cm^2 for the area of transept, 100 kg/cm^2 for the aisles. The addition of the snow load lead to an increase in the maximum stresses of about 35% leading to maximum stresses close to material strengths. In detail, Figure 13 shows the stress levels (in a colour scale) of the roof beams. The stress levels in the secondary elements (trusses) are of the order of 10-15 kg/cm^2, well below material strengths. It is worth to note that, due to the absence of specific tests performed on the wood elements, the assumed strength is conservative.

4.2.2. The vertical resisting elements

The vertical resisting elements of the Cathedral are masonry walls and stone pillars and characterized by along the height irregularities in both the geometry (changing in thickness) and mechanical properties (variation of material). These discontinuities may lead to significant stress concentrations. Therefore, in order to account for the presence of those discontinuities, in addition to homogeneous regular hand-made schematization, 2D FE models of each single wall have been also developed, assuming an ideal vertical configuration.

The following assumptions are considered for the hand-made schematizations: (i) two limiting conditions: full cross section and hallow cross section (or "a sacco", i.e. two exterior masonry layer plus an interior layer composed of chaotic stones and filling materials); (ii) constant wall thickness equal to the average wall thickness; (iii) the presence of architectural elements is neglected; (iv) each wall is subdivided into homogeneous portions (i.e. same cross section, referred to as a_i, i=1,…,28) in order to calculate the normal average stresses at the base.

First, the results of the simple hand-made schematizations in terms of stress levels at the base (Figure 14) are compared with those of the ideal perfectly vertical FE models (Figure 15). Then the influence of the actual geometrical configuration is accounted for.

In the case of full masonry, the normal stresses due to only self-weights only are between 3-8 kg/cm^2 for the exterior walls and between 10-14 kg/cm^2 for the masonry pillars. Assuming an "a sacco" masonry (the contribution of the internal fill in terms of strength is neglected), the normal stresses due to the self-weights only doubled, when compared to the limit case of the full masonry.

The stresses at the base of the stone pillars due to the self weight only are around 32 kg/cm^2. If the effects of the snow load are included, a small increase (of about 2.5%) is obtained. Contour maps of the normal stresses, as obtained from the 2D FE models, are displayed in Figure 15. Comparisons of the stress levels as displayed in Figures 14 and 15 indicates a good agreement between the two kinds of models.

To account for the walls overhanging, in a simplified way, the thrusts transmitted by the internal arches have been calculated and applied at the top of the walls to estimate the increase in the normal stresses. Figure 16 provides a schematic plan indicating the percentage increment of the normal stresses at the base of the walls and pillars due to their inclination. The green color represents increments below 30%; the yellow color increments between 30% and 70%, while the red color represents increments larger than 70%. The ranges of the normal stresses at the base of the walls and pillars by also including the effect of walls inclinations are provided in the plan schematization displayed in Figure 17. Maximum stresses are around 15 kg/cm^2 for the masonry walls and 90 kg/ cm^2 for the stone pillars. All values are well below material strenghts.

The lateral forces due to the arches thrusts have been also used to evaluate the out-of-plane displacements and compare them with the measurements from 3D laser scanning. The comparison revealed some not negligible discrepancies (even one order of magnitude) probably due to the effect of other relevant factors, such as: differential settlements (related to the discovered ruins of the foundations of pre-existing churches) and due to the interaction between the Cathedral and the Ghirlandina Tower.

4.3.Structural analysis with finite element models

In addition to the simple models described in the previous sections, FE models of the entire Cathedral have been developed by using the commercial software Strauss 7 (www.strand7.com).

It is known that structural response obtained from global finite element models of complex ancient monuments, typically made of masonry and stones, are affected by several limitations, such as the material behavior (almost no tensile strength), the actual effectiveness of the connections, the effectiveness of the chains, the restrain provided by the soil. In addition, the dynamic properties of global models in terms of fundamental frequencies and modal shapes are very far from the real ones, provided that based on linear elastic analysis (Blasi and Coisson 2006). All this issues, in addition to the large variabilities associated to material properties, the actions, the geometry, require the developments of a number of FE models based on limit schematizations in order to simulate the real behavior and make a robust assessment of the structural behavior.

In this study, 3D FE models of increasing complexity have been developed. The rationale is to identify and study individually the main effects influencing the static behavior such as: (i) soil-structure interaction (considering different vertical constraints at the base), (ii) the presence of the main cracks, and (iii) the effects of different load cases.

All the models have been developed assuming: (i) homogeneous and elastic material characterized by the properties summarized in section 3.3. (ii) walls made of full masonry, (ii) average thickness for each wall, (iii) architectural elements are not included in the model (iv) the roof system is not directly modeled (it is considered in terms of applied loads).

The following restrains at the base have been considered to account for the soil-structure interaction:

- Fixed base condition (F): soil is assumed to be rigid;
- Roller (R): the soil is assumed to be rigid in the vertical direction and with negligible lateral stiffness;
- Winkler 1 (W1): the soil is assumed to have a constant vertical stiffness (see figure 18(a)) while the lateral stiffness is assumed to be proportional to the applied axial load
- Winkler 2 (W2): two different vertical stiffness are used to account for the presence of the ancient cathedral of the XI century (see figure18 (b)), while the lateral stiffness is assumed to be proportional to the applied axial load.

Two geometrical configurations have been developed:

- Undamaged configuration (UD-C)
- Cracked configuration (C-C)

The response to the following single load cases have been evaluated for both models:

- Vertical loads (V),
- Thermal effects (T),
- imposed differential Displacements (D) at the base representing the interaction between the Cathedral and the Ghirlandina Tower.

The analysis of the single load cases allows a more in-depth interpretation of the possible causes of the main cracks. Then, the single effects have been combined. Table 1 summarizes the different models, constraints imposed at the base and the different load cases used to perform the static analyses. For instance, the response of the undamaged configuration with the fixed based condition subjected to vertical loads will be referred to as UD-C+F+V. For the sake of conciseness, only selected relevant responses will be here commented.

As expected, the restrain at the base which better simulate the actual behavior of the Cathedral is the one referred to as W2. In general, the models, which account for the initial presence of the main cracks does not lead to significant discrepancies in terms of maximum stresses.

The stress state for a specific longitudinal wall and transversal wall as obtained from the UD-C and the W2 restrain considering all the single load cases is summarized in Figures 19 and 20. It can be noted that the locations of the peaks of the tensile stresses are in good agreement with the location of the main cracks.

The in plane and out-of-plane deformed shapes for a specific longitudinal wall are represented in Figure 21 and compared with the results of the 3D laser scanning. The deformed shapes are consistent with the 3D laser scanning indicating that: (i) the presence of the ancient ruins of the pre-existing churches reduces the deformations within the zone A (as indicated in figure 21(a)); (ii) the interaction between the Cathedral and the Ghirlandina Tower causes significant out of plane displacements (Figure 21(b)) of the longitudinal walls, especially for those walls closer to the tower. These out-of-plane- displacements are quite larger than those caused by the arches thrust.

5. THE MAIN VULNERABILITIES

The process leading to the integrated knowledge together with the results of the structural analyses presented in the paper allowed to identify the main vulnerabilities of the structure. In detail, they can be recognized in:

- the tendency of the perimeter longitudinal walls of developing out-of-plane movements, as revealed by the 3D laser scanner, probably due to the unconstrained thrusts of the arches and differential settlements, as confirmed by the results of the structural analysis;
- global building rotation towards the Ghirlandina Tower, as revealed by the 3D laser scanner, probably caused by the strong interaction between the cathedral and the Tower, connected by strong arches, and also due to differential soil settlements (note that the portion of the apses is significantly heavier than the other portions);
- the concentration of cracks in the portion of the building which was subjected to the so called phase C of construction;
- the vaults are very vulnerable as revealed by the damages occurred during the Emilia 2012 earthquakes.

A sketch which schematically represent some of the highlighted vulnerabilities is represented in Figure 22.

6. CONCLUSIONS

In this paper, a multi-disciplinary multi-analysis approach is adopted for the preliminary assessment of the structural health of the Cathedral of Modena, northern Italy. The approach is aimed at providing an “integrated knowledge” of the building through the interaction of experts in various fields. Based on the comprehensive knowledge acquired during almost 10 years of study a first structural analysis of the monument has been carried out. The analysis of the results together with the information gathered from the integrated knowledge allowed the identification of the main structural vulnerabilities and criticalities. Those results will be used to develop effective strategies of interventions to improve the safety of the monument, respecting its historical and cultural integrity.

Finally, the experience grown by the authors trough the study of this important monument, based on continues exchanging ideas with experts in various fields, revealed the fundamental importance of the phase of the knowledge of the structure, which is commonly trivial for the case of ordinary buildings. Such approach could be generalized and used as a guide for reliable assessment of the structural behaviour of complex historical buildings.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge all the members of the Scientific Committee of the Modena Cathedral: Carlo Blasi (restoration, University of Parma), Giovanni Carbonara (restoration, University La Sapienza of Roma), Stefano Casciu (Soprintendenza per i Beni Storici, Artistici e Etnoantropologici of Modena and Reggio Emilia), Carla Di Francesco (Direzione Regionale per i Beni Culturali e Paesaggistici dell’Emilia Romagna), Paola Grifoni (Soprintendenza per i beni Architettonici e Paesaggistici per le province di Bologna, Modena e Reggio Emilia), Donato Labate (Soprintendenza per i Beni Archeologici dell’Emilia Romagna), Stefano Lugli (geology, University of Modena e Reggio Emilia), Graziella Polidori (Soprintendenza per i beni Architettonici e Paesaggistici per le province di Bologna, Modena e Reggio Emilia) and Mario Silvestri (civil engineering, Studio Tecnico Silvestri). Finally, the authors would also like to acknowledge priest Giacomo Morandi (high priest Maggiore of the Modena Cathedral).

REFERENCES

I. Bucur-Horvath, I.Papa, M. Bulbuk, J. Virag, *Historical constructions- Authenticity and adaptation to modern demands*, Structural Analysis of Historic Construction, 2008.

P. Roca, M. Cervera, G. Gariup, L. Pelà, *Structural Analysis of Mansory Historical Constructions. Classical and Advanced Approaches.* Arch Comput Methods Eng, Springer, 2010

ICOMOS/ISCARSAH, *Recommendations for the analysis, conservation and structural restoration of architectural heritage.* Committee (2005). See www.icomos.org

P. Lourenço, *Computations of historic masonry structures*. Progress in Structural Engineering and Materials, 2002.

C. Acidini Luchinat, S. Piconi, L. Serchia, *I restauri del Duomo di Modena 1875-1984*. Panini Editore, Modena, 1984

R. Cadigliani, *La torre Ghirlandina. Un progetto per la Conservazione*, Luca Sossella Editore, Modena, 2009

D. Labate. Il *contributo dell'archeologia alla lettura di un monumento, in La torre Ghirlandina. Un progetto per la Conservazione*, a cura di CADIGNANI R., Luca Sossella Editore, Modena, 2009.

G. Bertoni, *La cattedrale modenese preesistente all'attuale: primo ragguaglio sugli scavi del Duomo, agosto-settembre 1913 / Giulio Bertoni.* - 2. Edizione - Modena: Orlandini, 1914

P. Frankl, *Der Dom in Modena*, in "Jahrbuch fur Kunstwissenschaft", IV, 1927

A. Peroni, *Architettura e scultura: aggiornamenti, in Wiligelmo e Lanfranco nell'Europa romanica*. (Atti del convegno, Modena1985), Modena, 1989

A. Peroni, *Il Duomo di Modena. L'architettura, in Il Duomo di Modena*, 1999, a cura di C. Frugoni, *Il Duomo di Modena*. Franco Cosimo Panini, Mirabilia Italiae 9, 1999.

S. Lomartire, *Paramenti murari del Duomo di Modena. Materiali per un 'edizione critica, in Wiligelmo e Lanfranco nell'Europa romanica* (Atti del convegno, Modena 1985), Modena, 1989

M. Armandi, Copie e originali. Il repertorio di mensole figurate del Duomo di Modena, in Il Duomo di Modena, a cura di C.FRUGONI, Franco Cosimo Panini, Modena, 1999

A.K. Porter. *Lombard Architecture*, New Haven, Yale Univ., 1915-17

E. Silvestri, *Una rilettura delle fasi costruttive del Duomo di Modena*, in "Atti e memorie", Deputazione di storia patria per le antiche provincie modenesi, s. XI, XXXV, 2013.

A. Dondi, *Il Duomo di Modena, notizie storiche ed artistiche*. Modena, 1896.

C. Castagnetti, E. Bertacchini, A. Capra, M.Dubbini. *Il laser scanning terrestre per l'analisi di edifici di interesse storico ed artistico*. In: Ambrogio Manzino e Anna Spalla. Geomatica - le radici del futuro (tributo a Sergio Dequal & Riccardo Galetto), Cagliari:Edizioni, 2011.

M. Palermo, S. Silvestri, G. Gasparini, S. Baraccani, T. Trombetti, An approach for the mechanical characterization of the Asinelli Tower (Bologna) in presence of insufficient experimental data. Accepted for publication in the Journal of Cultural Heritage, 2014.

Istruzioni CNR-DT 206/2007, Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Strutture di Legno, Cons. Nazionale delle Ricerche – Commissione di studio per la predisposizione e l'analisi di norme tecniche relative alle costruzioni.

M.Armandi, *Il Duomo di Modena: Atlante fotografico*. Modena, Panini 1985.

C. Frugoni, *Il Duomo di Modena*. Franco Cosimo Panini, Mirabilia Italiae 9, 1999.

H. Sohn, C. R. Farrar, F. M. Hemez, D.D. Shunk, D.W. Stinemates, B.R. Nadler, J.J. Czarnecki, "*A Review of Structural Health Monitoring Literature: 1996–2001*", Los Alamos, NM: Los Alamos National Laboratories, 2004.

K. Worden, C.R. Farrar, G. Manson, G. Park, "*The fundamental axioms of structural health monitoring*". Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science, 463(2082), 1639-1664, 2007.

P.P Rossi, "The importance of monitoring for structural analysis of monumental buildings", Keynote lecture International Colloquium IABSE, Bergamo, Italy, 1997.

S. Baraccani, T. Trombetti, M. Palermo, G. Gasparini, S. Silvestri,A. Dib, *A methodology of analysis for a critique interpretation of the data acquired from monitoring system of historical buildings*. 7th European Workshop on Structural Health Monitoring July 8-11, La Cité, Nantes, France, 2014.

Norme Tecniche per le Costruzioni", *Italian building code, adopted with D.M. 14/01/2008,* published on S.O. n. 30 G.U. n. 29, 2008.

C. Blasi, E. Coïsson,*The importance of historical documents for the study of stability in ancient buildings: the french Panthéon case study*. Asian journal of civil engineering (building and housing), 7(4), 359-368, 2006

a) b)

Figure 1. Photographs of Cathedral of Modena: a) view of the apses and b) view of the facade.

a) b)

Figure 2. a) A 3D view of the Modena Cathedral (Google Earth); b) Cross-section of the Cathedral of Modena

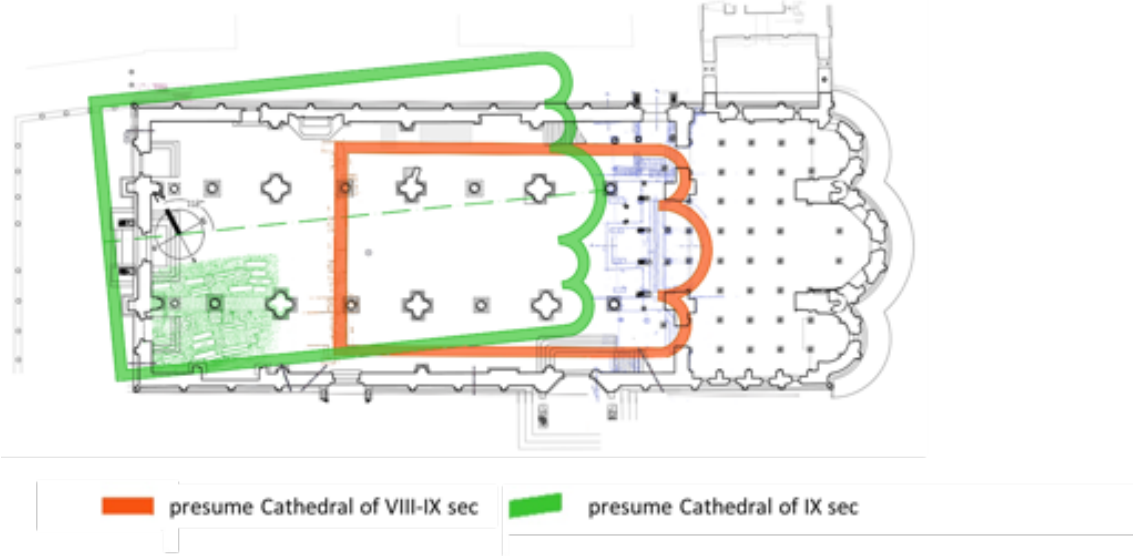


Figure 3. The pre-existing cathedrals

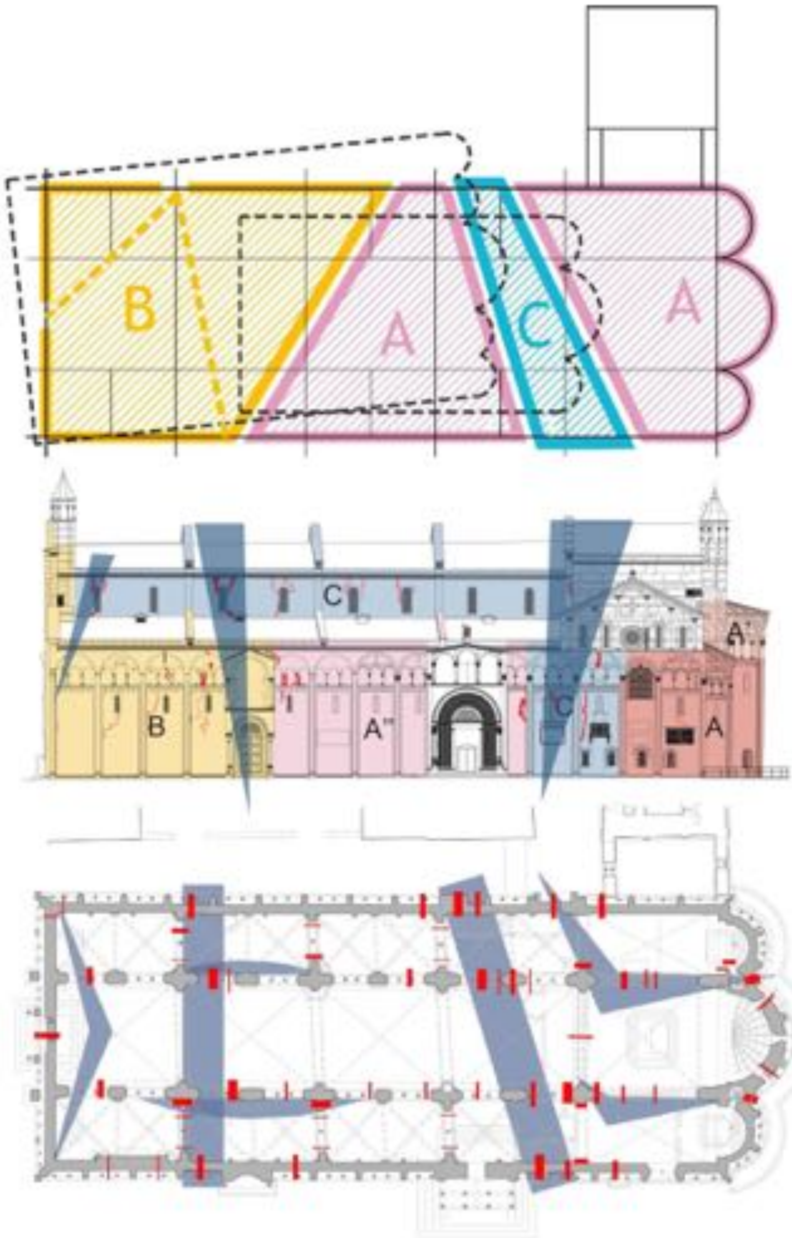
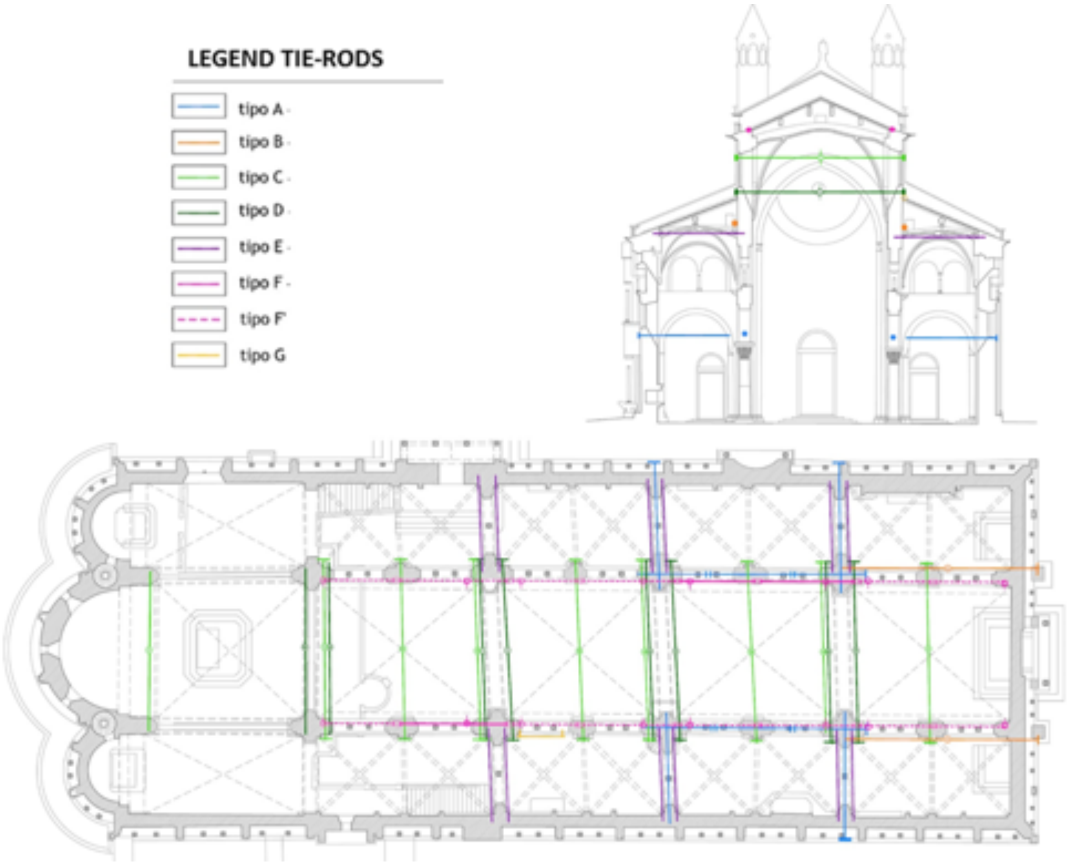

B
A
C
A
C
B
A'''
C
A'
A

Figure 4. Relationship between the construction phases and the cracking pattern


LEGEND TIE-RODS
tipo A
tipo B
tipo C
tipo D
tipo E
tipo F
tipo F'
tipo G

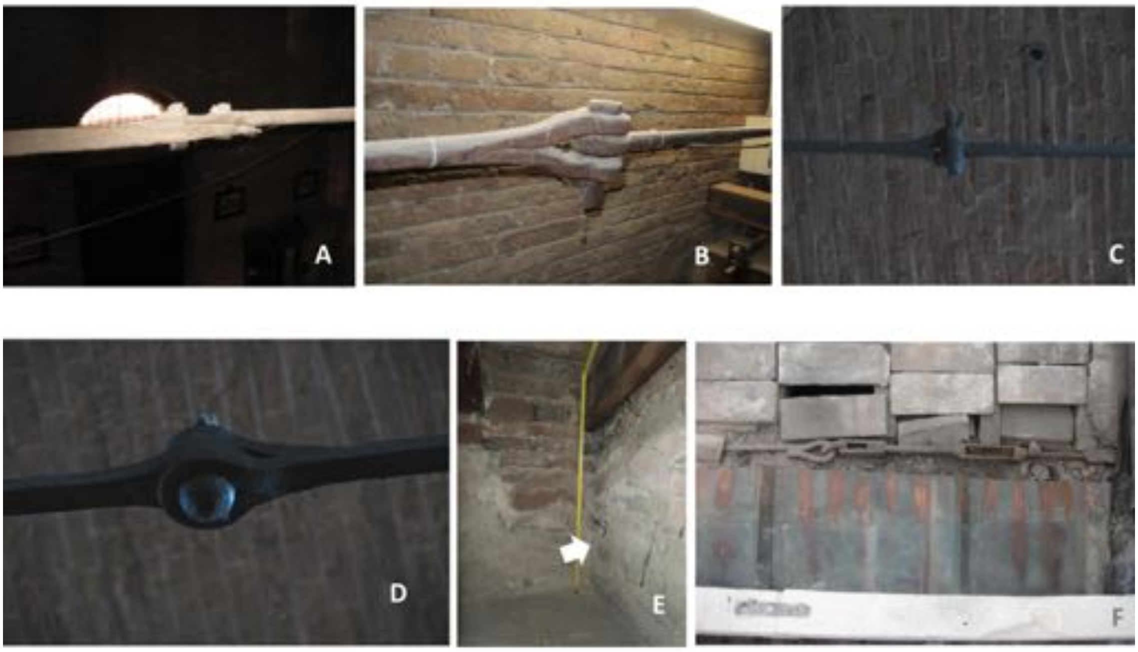
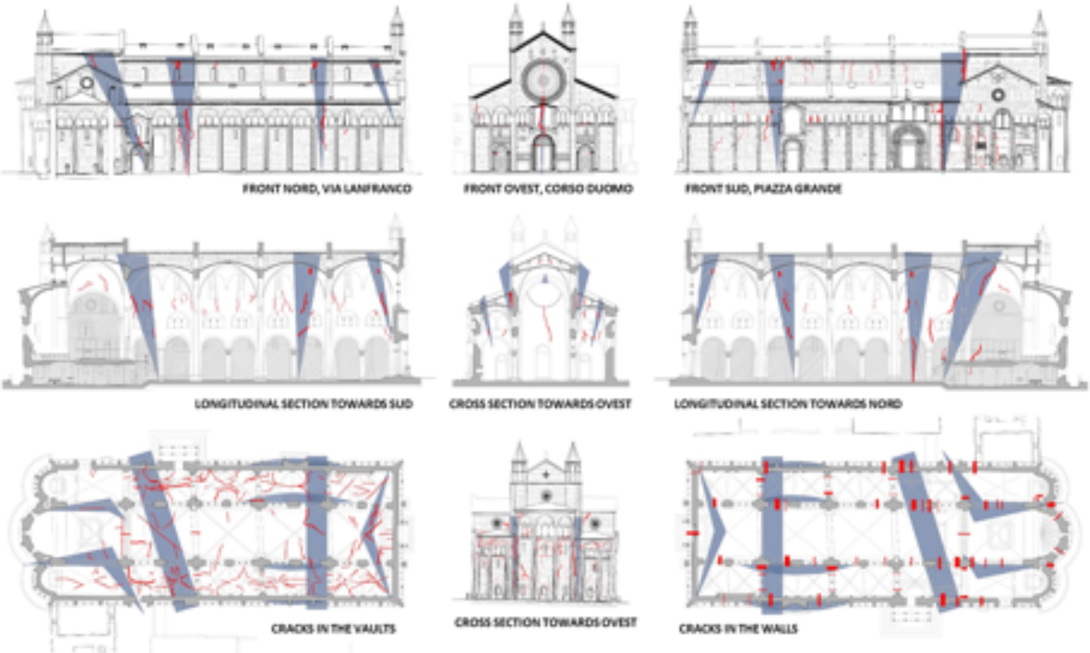
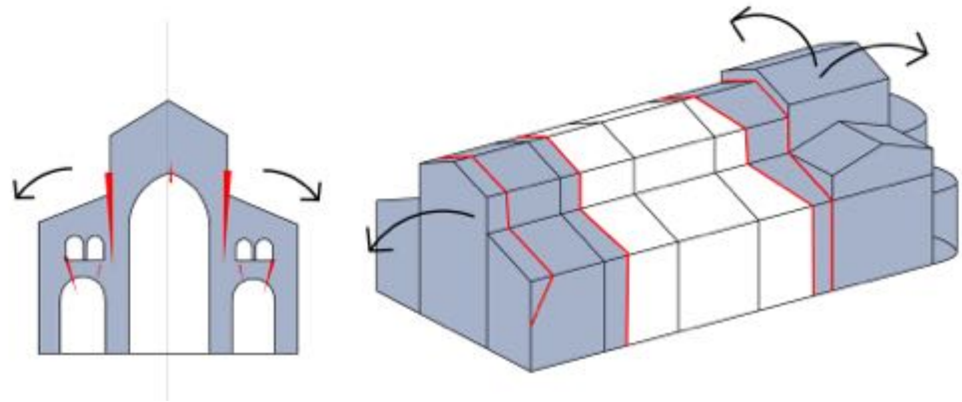


Figure 5. Survey of the tie-rods installed on the Cathedral during the years and respective photographers.

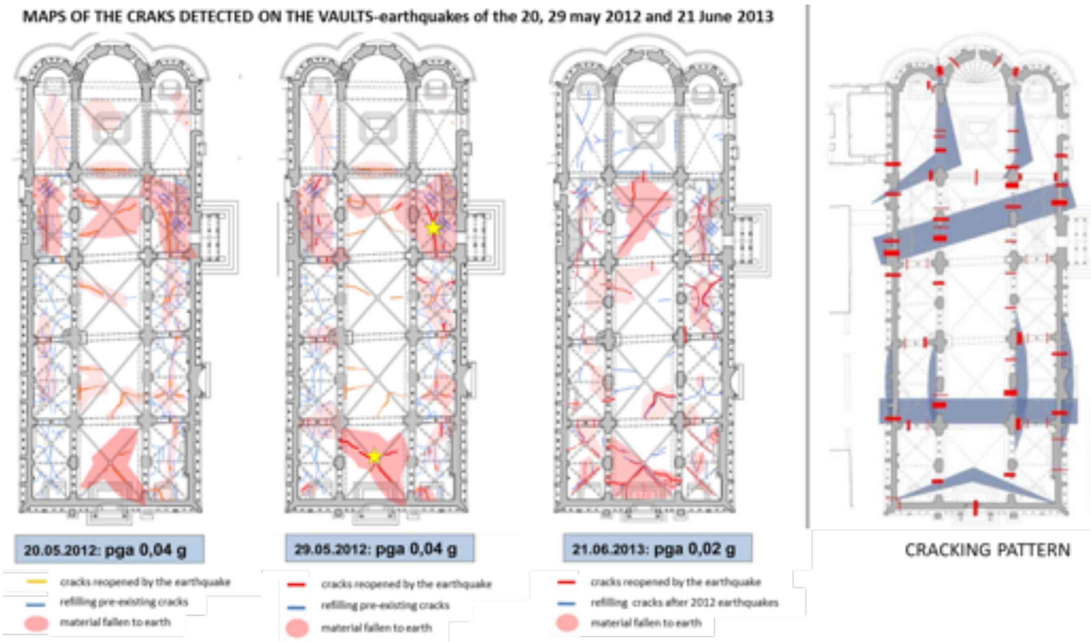

FRONT NORD, VIA LANFRANCO
FRONT OVEST, CORSO DUOMO
FRONT SUD, PIAZZA GRANDE
LONGITUDINAL SECTION TOWARDS SUD
CROSS SECTION TOWARDS OVEST
LONGITUDINAL SECTION TOWARDS NORD
CRACKS IN THE VAULTS
CROSS SECTION TOWARDS OVEST
CRACKS IN THE WALLS

a)



b)

Figure 6. a) Crack pattern of the Cathedral of Modena and b) main failure mechanisms of the Cathedral on the longitudinal and transverse direction


MAPS OF THE CRAKS DETECTED ON THE VAULTS-earthquakes of the 20, 29 may 2012 and 21 June 2013
20.05.2012: pga 0,04 g
cracks reopened by the earthquake
refilling pre-existing cracks
material fallen to earth
29.05.2012: pga 0,04 g
cracks reopened by the earthquake
refilling pre-existing cracks
material fallen to earth
21.06.2013: pga 0,02 g
cracks reopened by the earthquake
refilling cracks after 2012 earthquakes
material fallen to earth
CRACKING PATTERN

a)

b)

Figure 7. a) Maps of the cracks detected on the vaults after the earthquakes of the 20 and 29 May 2012 and 21 June 2013 and comparison with the crack pattern and b) photographs on the damage caused by recent earthquakes.

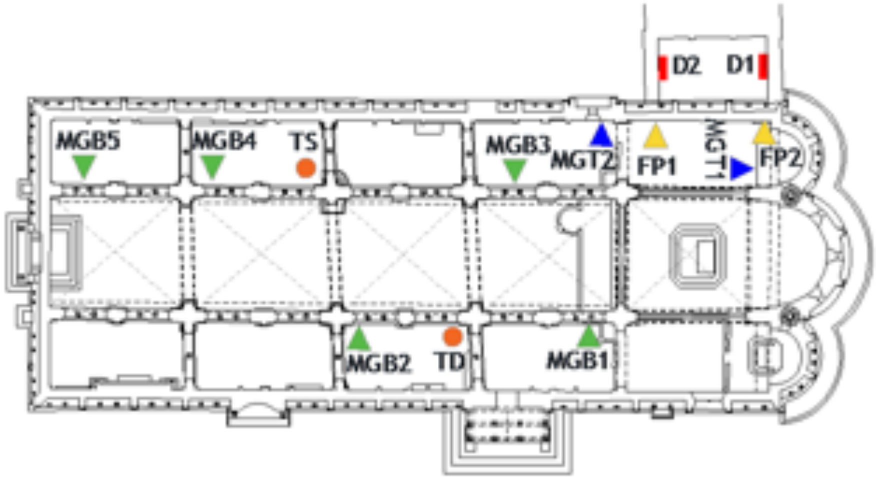
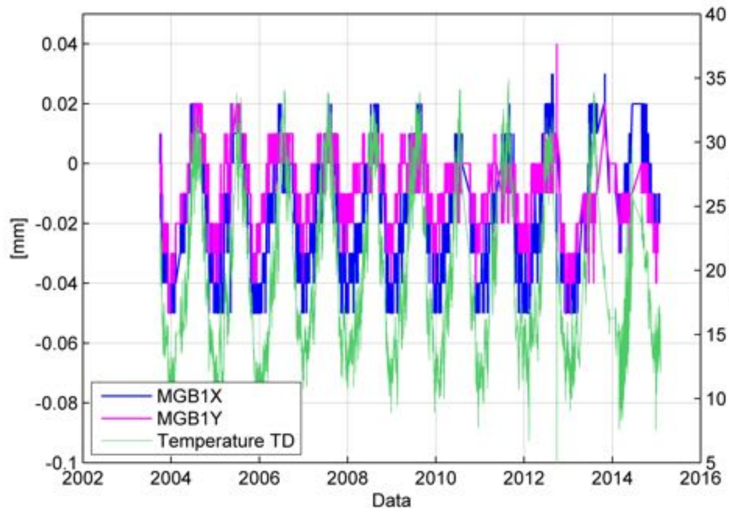
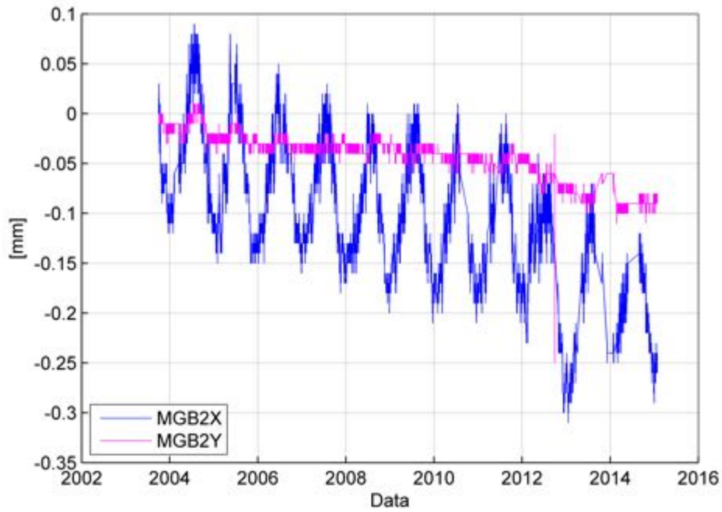


Figure 8. Location of the device installed on the Cathedral



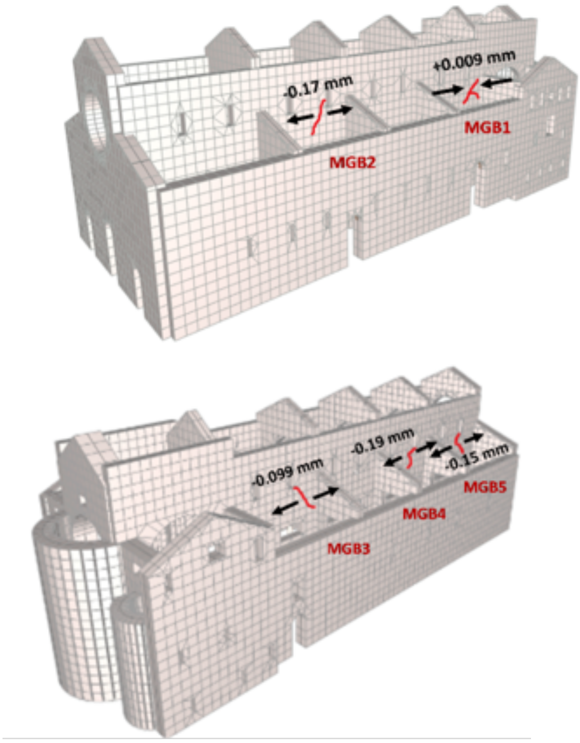
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
[mm]
40
35
30
25
20
15
10
5
Temperature °C
2002
2004
2006
2008
2010
2012
2014
2016
Data
MGB1X
MGB1Y
Temperature TD

a)

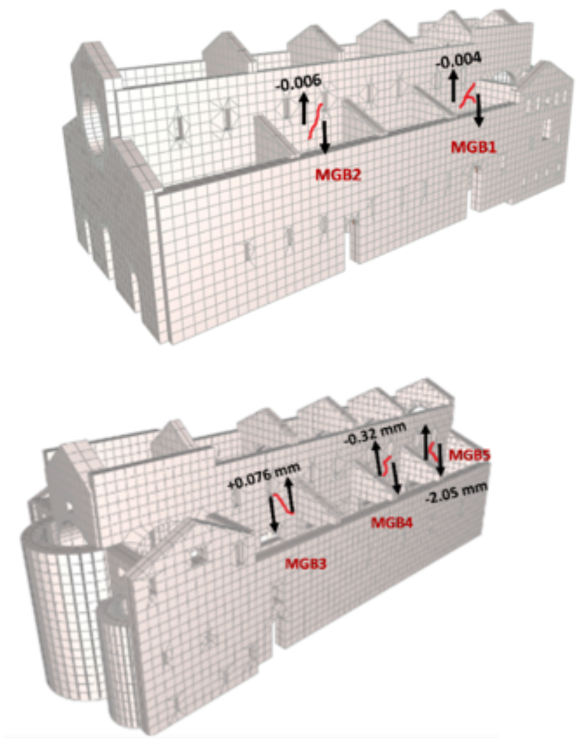


b)

Figure 9. a) Trend recorded by the biaxial joint meter MGB1 and the temperature TD, b) Trend recorded by the biaxial joint meter MGB2



a)



b)

Figure 10- a) Amplitude variations in the X direction of the cracks observed by MGB1-2-3-4-5, b) Movements in the Y direction of the cracks observed by MGB1-2-3-4-5

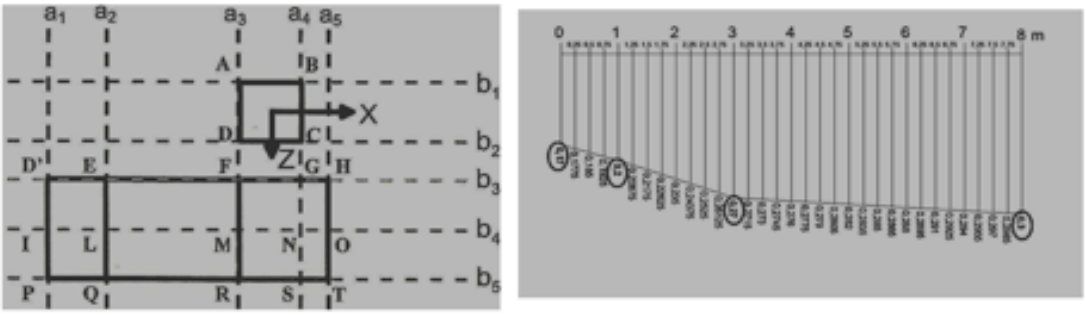
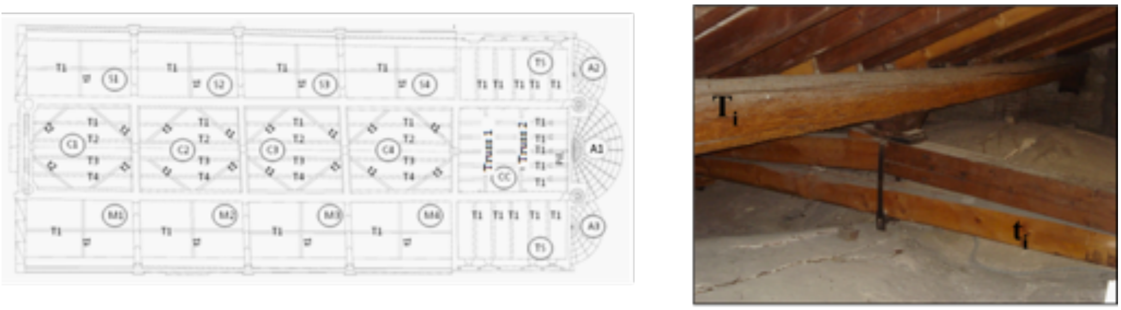


Figure 11. Imposed vertical differential displacements at the base due to the interaction between the Cathedral and the Ghirlandina Tower



a) b)

Figure 12. a) Structural roof elements and b) Main beams (T_i) and trusses system (t_i)

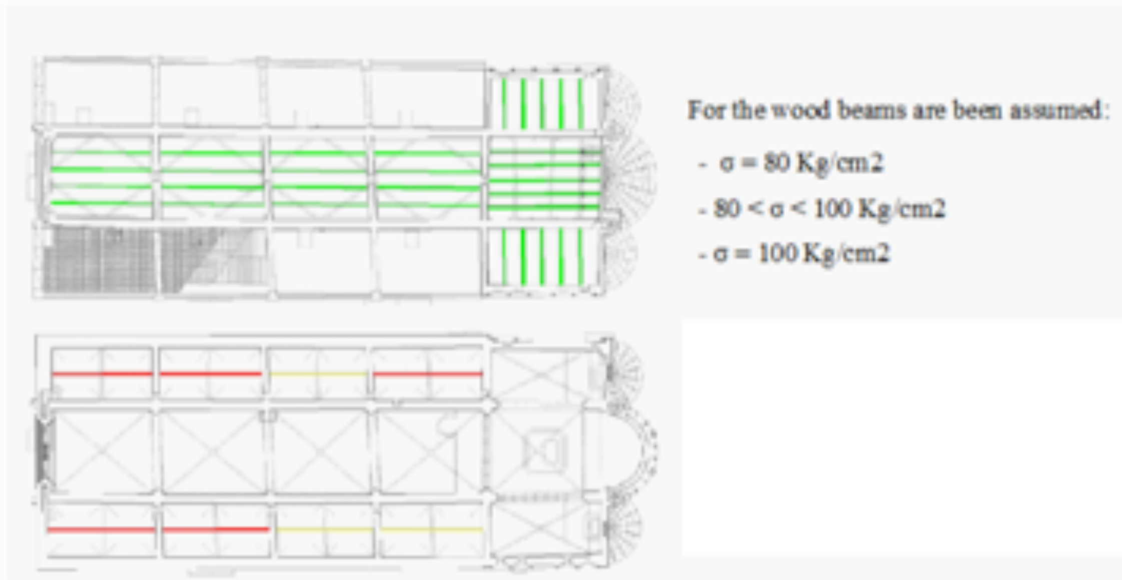


Figure 13. Stress level of the roof elements

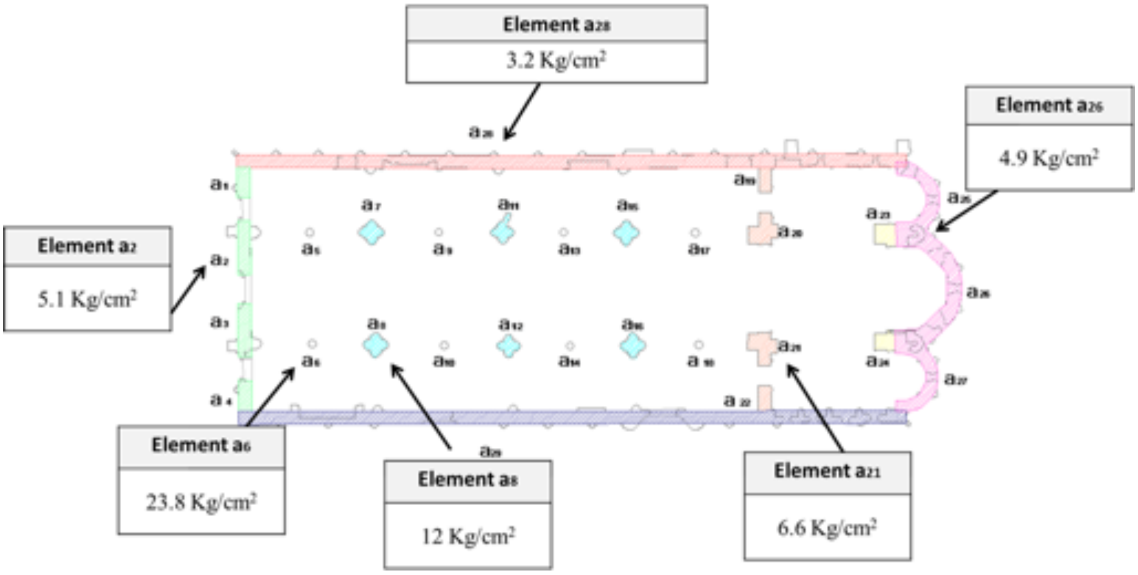


Figure 14. Reference values of the stress level at the base of the principal structural elements.

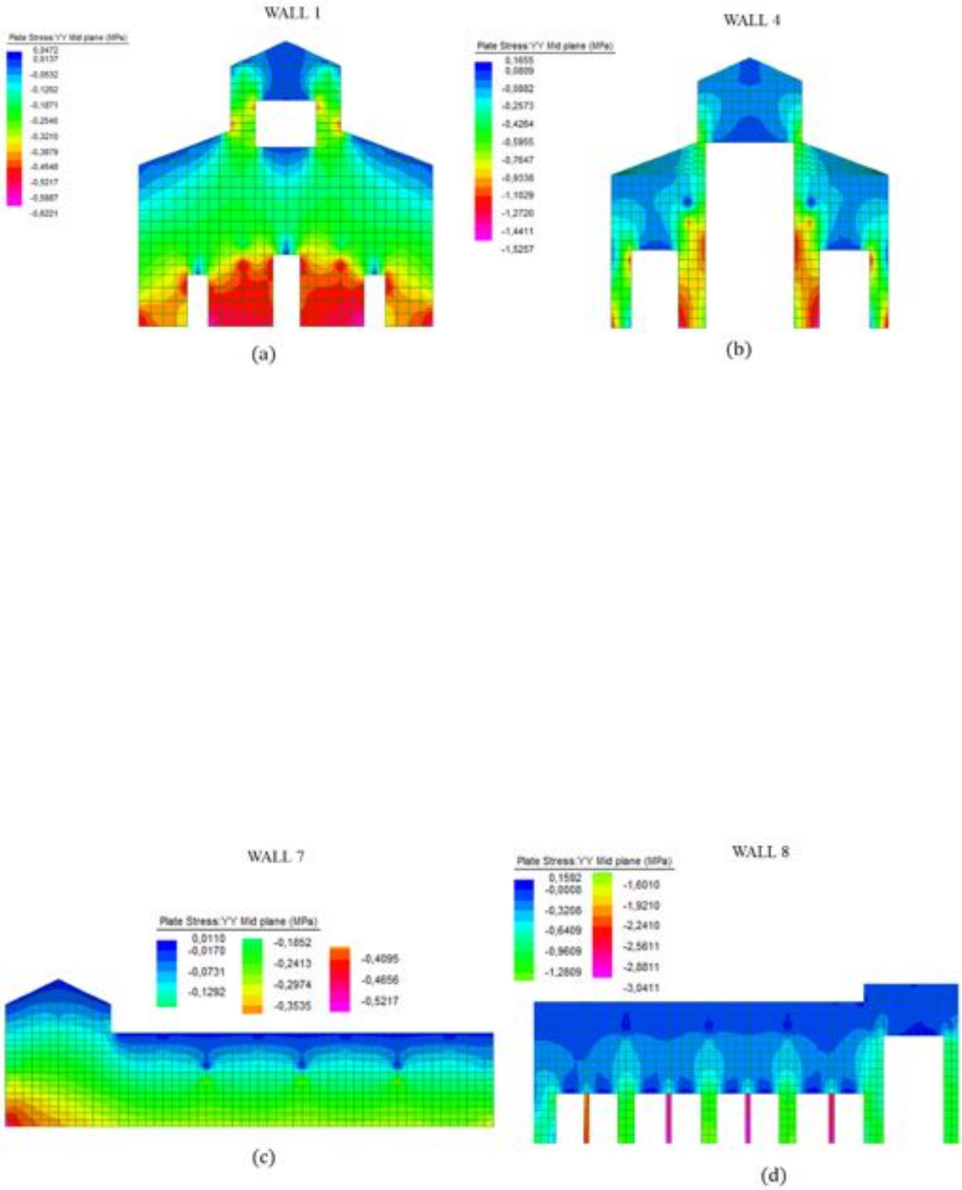


Figure 15. Contour maps of the normal stresses at the base of some walls obtained with two-dimensional FE models: (a) Wall 1; (b) Wall 4; (c) Wall 7; (d) Wall 8;

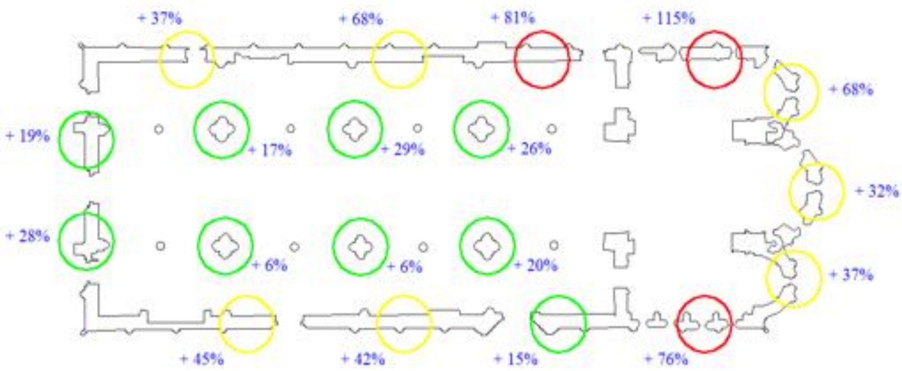


Figure 16. Increments of the stress at the base of the walls due to the inclination of the vertical elements.

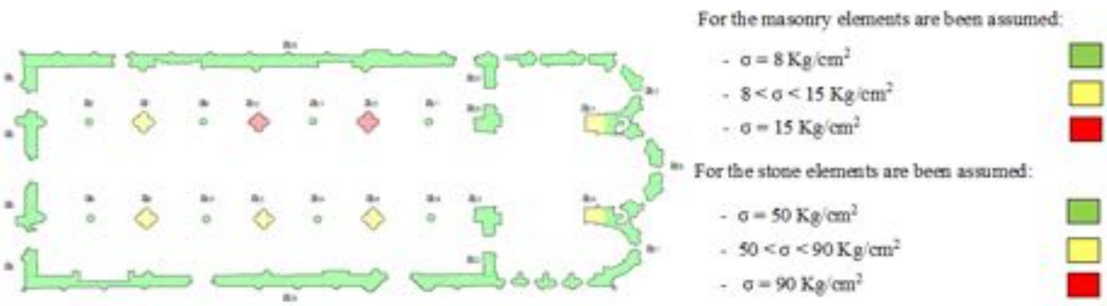


Figure 17. Level of stress at the base of the vertical elements including the effects of the inclinations.

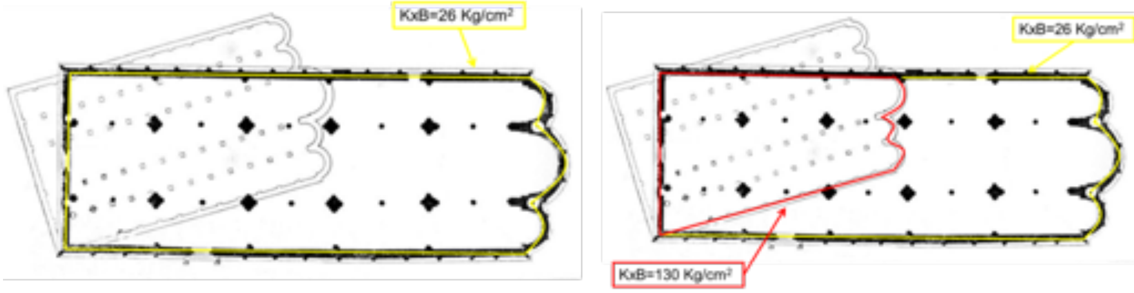


Figure 18- (a) Uniform distribution of Winkler's constant (W1) and (b) Non Uniform distribution of Winkler's constant (W2).

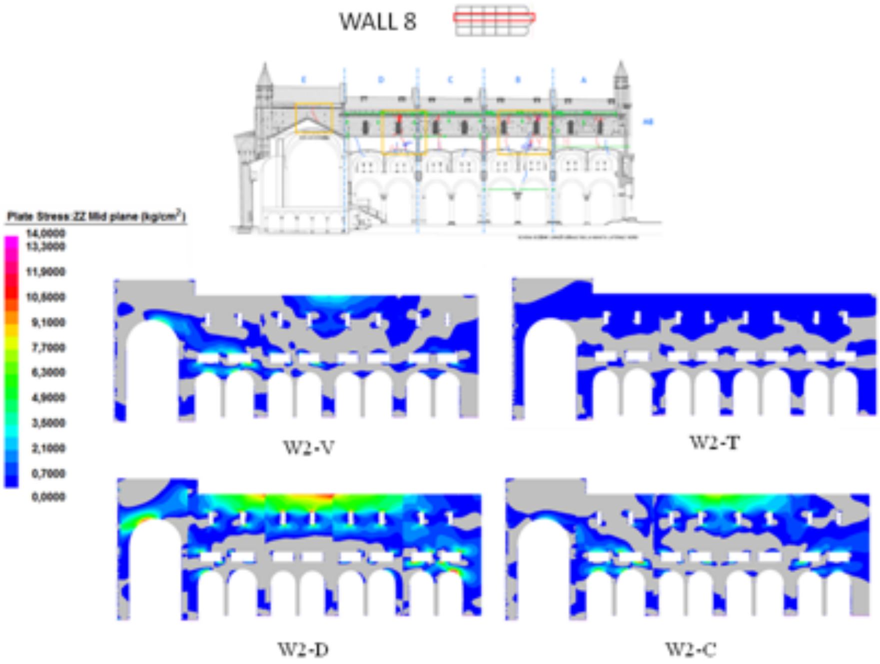


Figure 19. Stress of the wall 8 obtained from the W2 model with the different load cases and compared with the observed cracking patterns.

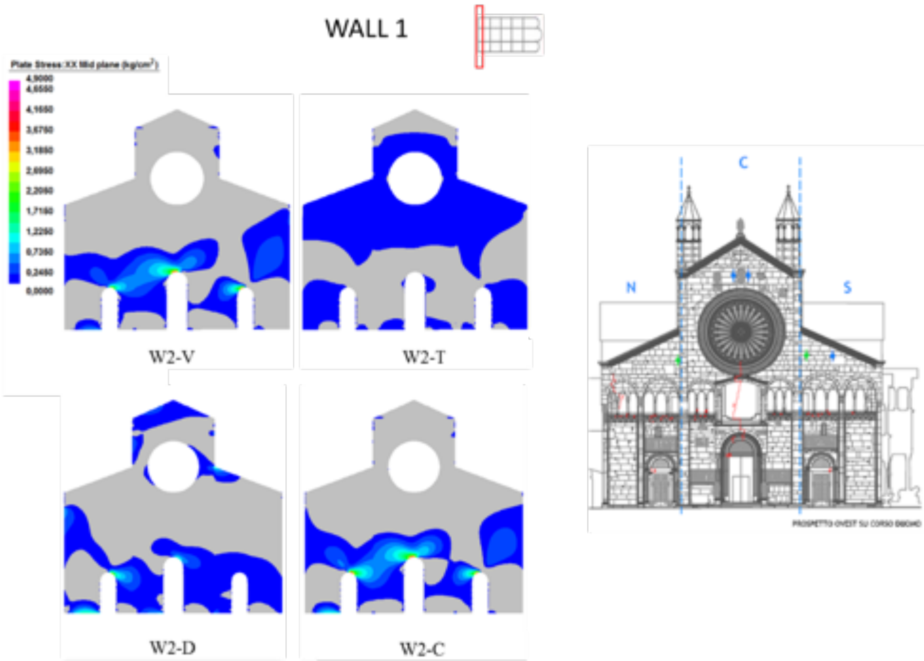


Figure 20. Stress of the wall 1 obtained from the W2 model with the different load cases and compared with the observed cracking patterns.

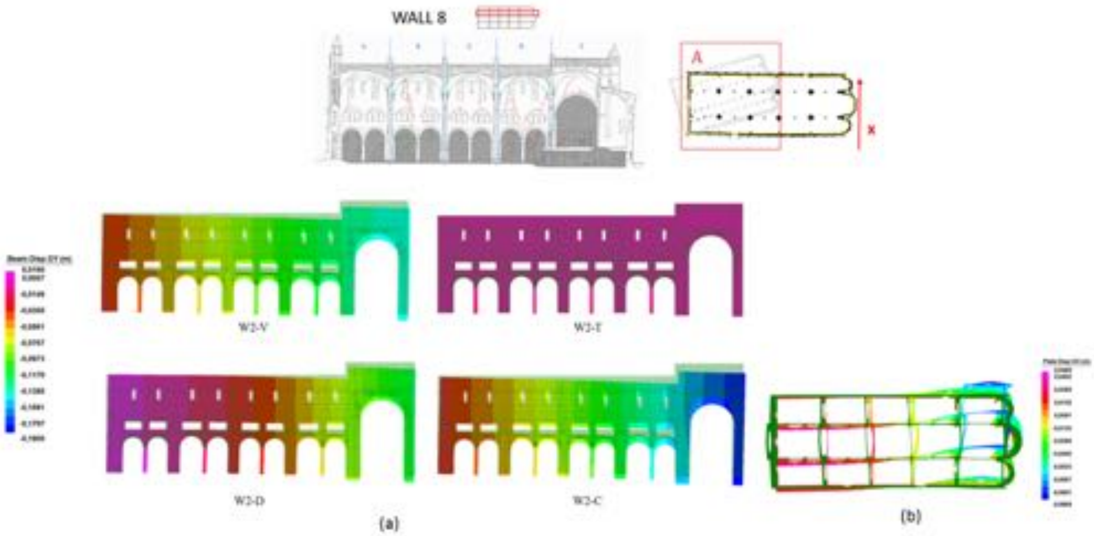


Figure 21. (a) in-plane deformed shape for the wall 8; (b) out-of-plane deformed shape (x direction) for all walls.

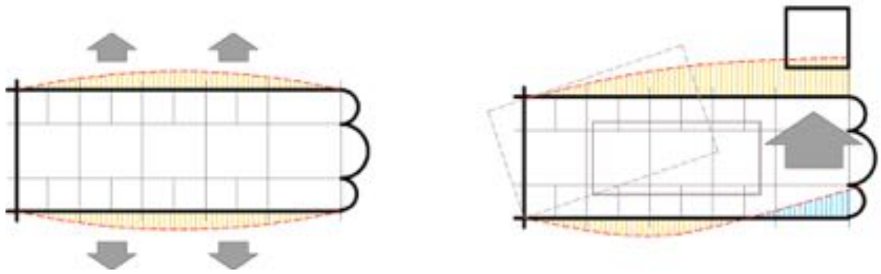


Figure 22- Original sketch of the main global movements of the Cathedral.

Table 1.Summary of the specific models with a specific restrain and a specific load cases provide a specific response developed.

Model and Restrain at the base	Model Response			
	Vertical loads (V)	Thermal stresses (T)	Imposed disp. (D)	Combination (C)
UD-C + F	UD-C + F+ V	UD-C + F+ +T	UD-C + F+ +D	UD-C + F+ +C
UD-C + R	UD-C + R +V	UD-C + R +T	UD-C + R +D	UD-C + R +C
UD-C + W1	UD-C + W1 +V	UD-C + W1 +T	UD-C + W1 +D	UD-C + W1 +C
UD-C W2	UD-C + W2 +V	UD-C + W2	UD-C + W2 +D	UD-C + W2 +C
C-C + F	C-C + F+ V	C-C + F+ +T	C-C + F+ +D	C-C + F+ +C
C-C + R	C-C + R +V	C-C + R +T	C-C + R +D	C-C + R +C
C-C + W1	C-C + W1 +V	C-C + W1 +T	C-C + W1 +D	C-C + W1 +C
C-C W2	C-C + W2 +V	C-C + W2	C-C + W2 +D	C-C + W2 +C