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STRUCTURAL HEALTH MONITORING AND DIAGNOSTIC INVESTIGATIONS OF THE SCROVEGNI CHAPEL, ITALY

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Abstract. *The Scrovegni Chapel represents without doubt a masterpiece in the history of painting in Italy and Europe in the 14th century and it is considered the most complete series of frescos executed by Giotto in his mature age. Given the crucial importance of the building from a cultural point of view, in 1995 a systematic research campaign started, including the execution of studies on the structural health state of the Chapel. The final aim is to guarantee optimal preservation conditions on the occasion, and in direct continuation, of the restoration of the Giotto's frescoes performed in 2001-2002. The investigation plan, based on non-destructive techniques, includes punctual tests, periodically repeated, and continuous monitoring, direct measurements and indirect identifications (back-analysis) of relevant structural parameters. Although the structural layout of the chapel is apparently simple, the protection of the monument is strongly connected to the fact that its historic and artistic value cannot be separated from the structure itself and the effects of strengthening interventions carried out in the last 150 years need to be carefully evaluated. In this framework a structural health monitoring system has been recently installed by the authors. A network of static and dynamic sensors controls the relevant parameters related to the structural safety of the monument and the protection of the artistic content. The paper describes the diagnostic investigations carried out, including ambient vibration tests, crack pattern survey and identification of possible on-going degradation phenomena. Then the installed monitoring equipment is presented focusing on the algorithms developed and implemented into a processing software to perform the online automatic analysis of static data and the identification of modal parameters. Relevant features extracted from monitoring data are then used as inputs for the application of damage detection algorithms and the numerical calibration of a finite element model of the structure.*

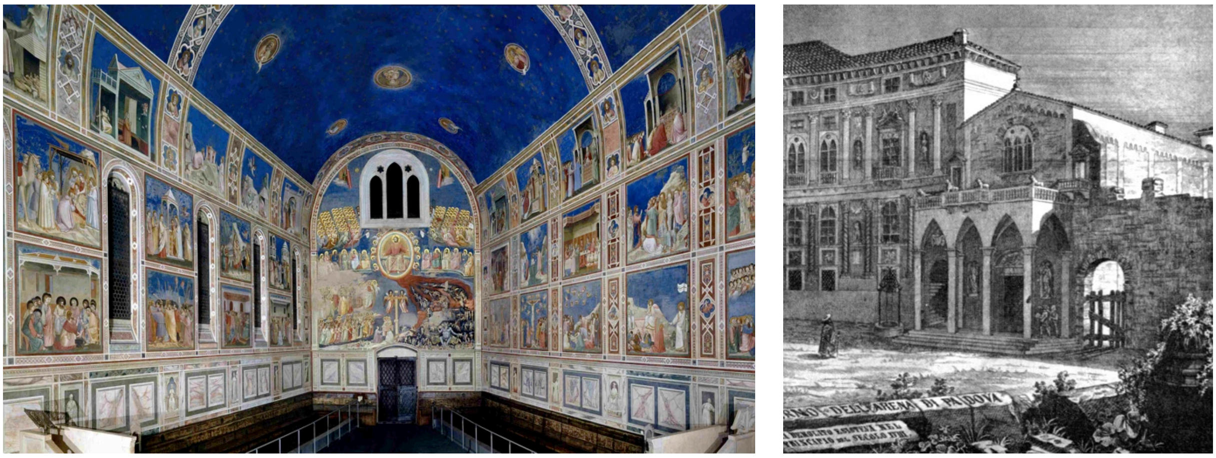
1 INTRODUCTION

1.1 Historical background

The Scrovegni Chapel, dedicated to St. Mary of the Charity and frescoed by Giotto between 1303 and 1305, is located in the hearth of the historical city center of Padua and it is one of the most important masterpieces of Italy (Figure 1a). In 1300 Enrico Scrovegni of Padova purchased a piece of land from Dalesmanini family. The property included an oval area where a Roman Arena was originally present and he decided to build in this perimeter a family palace with a private chapel. Giotto's Last Judgment covers the entire wall above the chapel's entrance. Opposite it, on the chancel arch above the altar, there is an unusual scene of God in Heaven. The longitudinals walls are arranged in three tiers of narrative frescoes, each with four two-meter-square scenes, representing the Nativity, the Passion of Jesus, the Resurrection, and the Pentecost [1] [2].

The building was subjected to several transformation and interventions over centuries. During the 16th c. mainly modifications were introduced on the palace. The last heirs, the Gradenigo family, occupied the arena since 18th c. and by the time the lack of maintenance was evident showing several damages on the buildings. In 1817 the portico of the chapel collapsed and was demolished. Even after this event the family took no interest and instead of looking for bills for urgent repairs, the palace was demolished in 1827 (Figure 1b). Without the protection of the palace, the north wall of the chapel began to deteriorate, allowing rainwater to seep through and causing serious damage to the frescos inside.

Since then several damages and deteriorations are progressively reported: cracks on the triumphal arch, propped in 1871, cracks in the barrel vault, walls, break of iron ties, etc. In 1901 a long series of works repair began. In 1937 the foundations at the south-east corner of the chapel were strengthen and in 1957 huge interventions were performed on the facade, with insertion of iron ties in the wall thickness. Finally in 1963 the original timber structure of the roof was substituted with steel trusses and the iron ties of the main vault replaced.



a) b)

Figure 1: a) Interior view of the chapel with the Giotto's frescos; b) Drawing of 1842 referring to a scene from 1817, before the demolition of the Scrovegni palace

1.2 Geometrical and structural description

The general floor plan has a rectangular shape of 10.40 m by 20.89 m composed by a nave, a square chancel of about 4 m and a polygonal apse (Figure 2). The perimeter walls of the nave (about 12 m high) are the lowest volume of the building. The height increases gradually up to 13,5 m in the chancel and vestry, until reaching 15 m in the small octagonal tower of the apse. A crypt extends beneath the whole nave, having a height of about 2.66 m from the crypt floor level to the sides of the vaults, and a maximum height of 4.15 m from the crypt floor to the top vault.

The building maintains the homogeneity of materials originally used, even if several interventions were executed during its history. Brick masonry is the principal constitutive material used for the side walls, the pillars, the barrel vaults over the nave and crypt, the cross vault of the vestry and over the apse ceiling vaults. The side walls of the nave chapel are 0.67 m thick, increasing their thickness up to 0.88 m to contain five pillars in the north and south façade respectively. The external brickwork was originally plastered. The reddish-brown color clay bricks of 25x12 x2,5 cm used for its construction were placed according to the Flemish type. The mortar joints between the brick courses of a pinkish-white color are about 2-2,5 cm height.

The horizontal structure of the main body consists of two masonry vaults and the roofing. The brick barrel vault over the nave is a typical stilted semicircular arch structure, about 0.24 m thick, with a span of 180 degrees and a radius of 4m. The vault over the crypt is a flat arch of solid brickwork, 0.27 m thick.

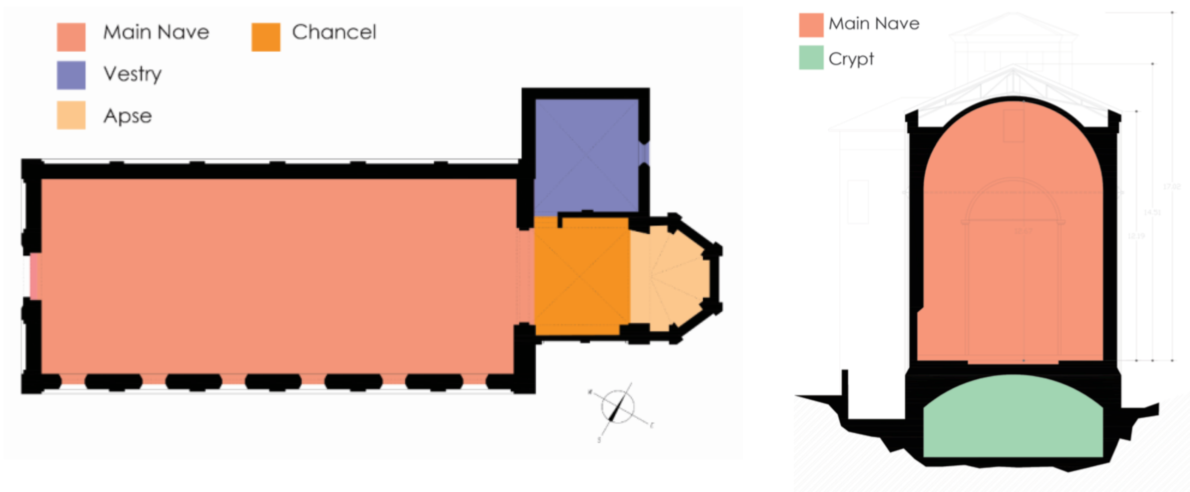


Figure 2 - Floor plan and section of the chapel

1.3 Past strengthening interventions

Unfortunately nothing is known about the work that took place before 1817, when the portico of the Chapel collapsed. The main structural interventions performed on the chapel date back to the 20th c. (Figure 3). In the period 1936-1946 some consolidation works on the foundations were carried out; the crypt vault was strengthened through the insertion of three tie beams besides the side walls; during the Second World War in the crypt 8 equidistant buttresses were built, at right angles to the side walls, up to the height of the ceiling vaulting in order to prevent possible collapse due to bombing.

During the early Sixties the original wooden truss beams of the roof were replaced with eight steel trusses. The weight of the roof was taken by the side walls where a RC beam was constructed. Five tie-rods of the nave were replaced and anchored through external steel plates on the side walls. The ceiling vaults of the vestry and loggia were strengthening by constructing reinforced concrete sections and the original roofing over the loggia was replaced by concrete V beams and tie rods. The original floor over the vestry vaulting was probably strengthening at the same time, during the 1960 intervention, applying the same technique.

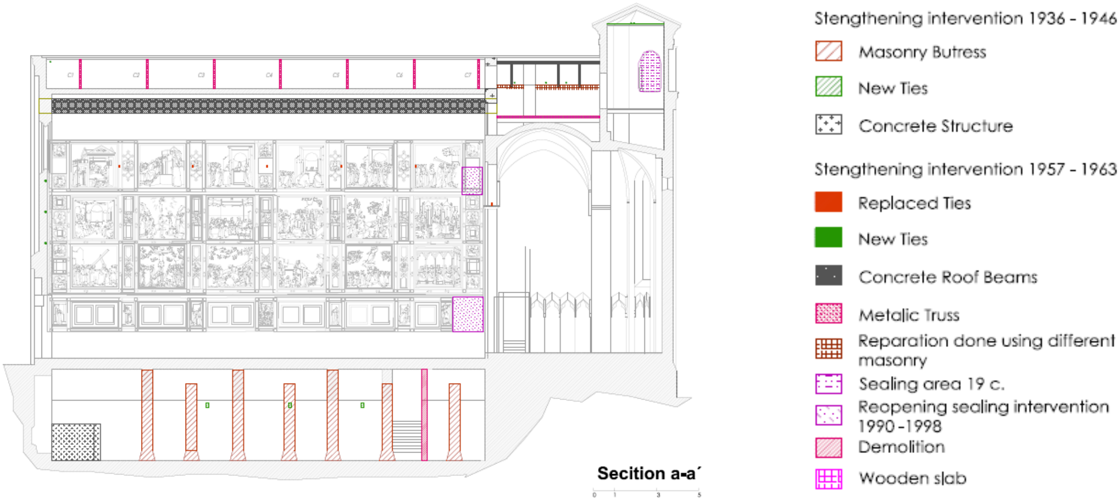


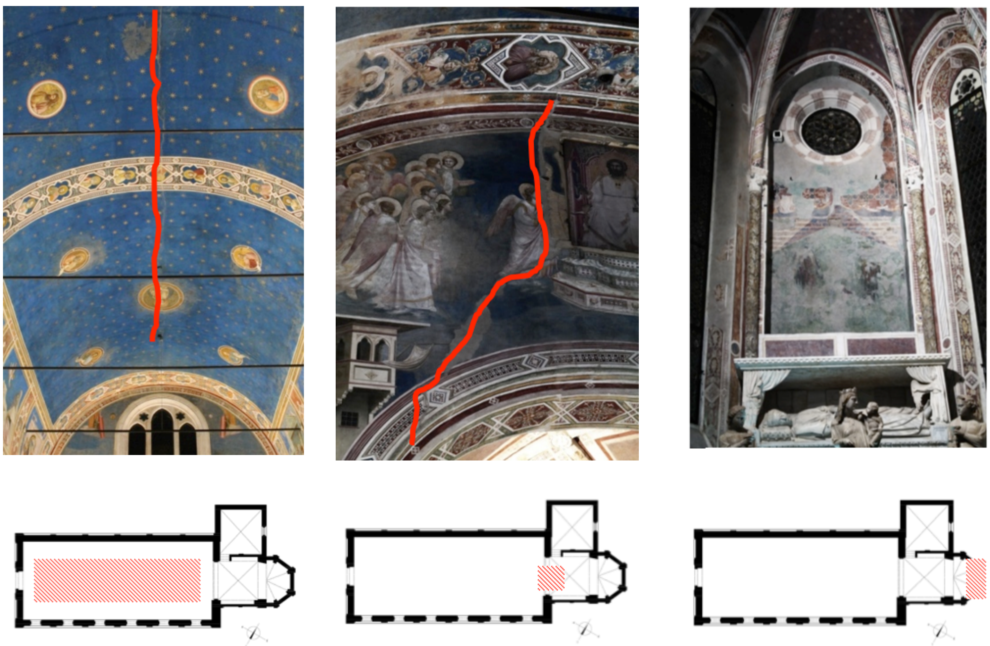
Figure 3: Strengthening interventions performed in the 20th c. on the chapel

2 ON SITE INSPECTIONS

2.1 Damage survey

In order to define the current state of the building and design the optimum layout of the monitoring system detailed visual inspections were carried out to correct and refine the available geometrical surveys and perform a precise survey of the structural, physical and chemical deterioration factors affecting the chapel.

Most of the interior cracks surveyed within this work were already reported during the 19th century. The geometrical survey of 1871 showed several cracks still present at that time in the south wall, in the triumphal arch, in the main façade (below the window) and on the vault.



a) b) c)

Figure 4: Damage survey: cracks on the intrados of the frescoed vault of the main nave (a) and on the triumphal arch (b); damages due to salt crystallization on the wall of the apse (c)

Without any doubt, the most critical crack is placed on the main triumphal arch mentioned in several reports and subjected to subsequent reparations that included a partial reconstruction of the upper part of the wall (Figure 4b).

Three main longitudinal cracks are visible along the development of the nave barrel vault: two at the thirds of the vault on the extrados and one at the top on the intrados (Figure 4a), showing a clear three-hinges behavior of the arch. These cracks were probably induced by the structural configuration of the previous roof and the geometry of the vault. Moreover horizontal cracks at the impost of the vault were observed at the end of the 19th Century, probably due to the ineffectiveness of the ties that counteract the thrust of the vault.

Comparing the current condition to previous reports, it is possible to observe that the chancel was severely damage with vertical cracks and repaired afterwards. Today is only possible to recognize some detached area, without any evidence of serious stability risk.

Rising damp has severely affected the frescos and also contributed to cause damage on the masonry surface. Salts crystallization were manifested in different areas due to different mechanism of deterioration: efflorescence, spoiling, spalling and splitting (Figure 4c). Even if several structural problems were solved in the middle of the 19^{th} century, the cracked areas of lunette and triumphal arch were still subjected to serious detachments at the end of the 90s, clearly caused by water infiltration from the roof. The roof was repaired in 1999 to solve the water infiltration problems. However, still now soluble salts are detected in the façade as efflorescence, what reveals the presence of moisture at different location of the walls.

At the base of the exterior walls the mechanism of deterioration is manifested mostly due to spoling, splitting and biological attacks, related to the groundwater absorption and the atmospheric dry/wet deposition that lead to fluctuations of the moisture content.

2.2 Ambient vibration tests

Before the installation of the Structural Health Monitoring (SHM) system, dynamic identification tests were performed on the main nave of the chapel. The objective is to understand the dynamic response of the structure subjected to ambient vibrations and to extract the fundamental modal parameters (natural frequencies, damping ratios and mode shapes), later used to calibrate numerical models. It was decided to use 5 single-axial acceleration transducers, which later were kept in the same positions for continuous dynamic monitoring. Two accelerometers were placed along the two orthogonal horizontal directions at the NW corner between the façade and the longitudinal wall (A4, A5); one in the middle of the nave, on the NW wall (A6); at the same section of the vault two other sensors were installed perpendicular to the vault, one in the haunch (A7) and the last at the key (A8) (Figure 5).

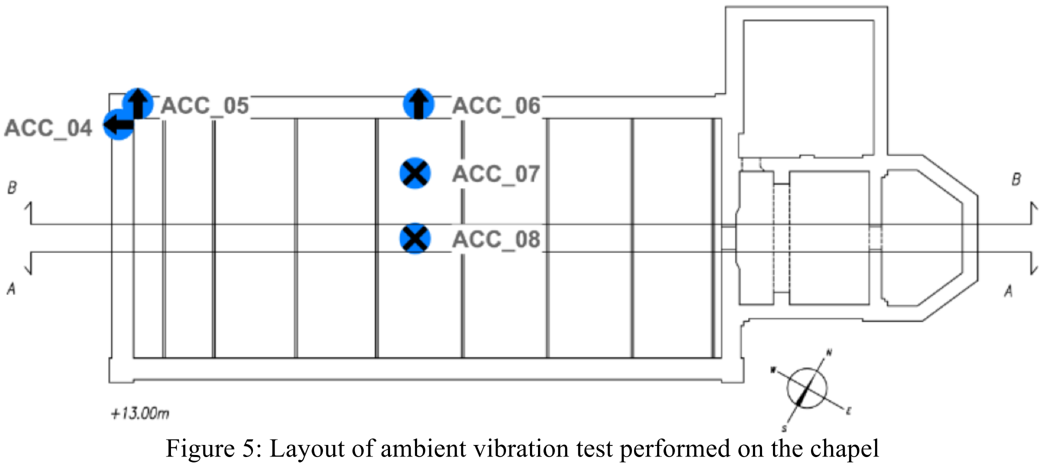


Figure 5: Layout of ambient vibration test performed on the chapel

Once fixed the transducers to the structure in the selected positions, tests consisted in acquiring data in 5 different registrations over a predetermined period, at a specific sampling rate. A typical acquisition consisted in a record length of 131'072 samples, resulting in an acquisition time of approximately 20 minutes at a sampling frequency of 100 Hz. For the identification of the modal parameters (natural frequencies and corresponding mode shapes), output only identification techniques were used (Operational Modal Analysis).

The signal-processing phase consisted in the elaboration of the measured data using dedicated software for OMA: SVS ARTeMIS Extractor 4.0, 2007 [3]. It was decided to use different frequency-domain modal parameter extraction techniques and compare the results: FDD (Frequency Domain Decomposition) and EFDD (Enhanced Frequency Domain Decomposition) [4]. Both methods are based on the evaluation of the spectral matrix (i.e. the matrix of cross-spectral densities) in the frequency domain:

$$\boldsymbol{G}(f) = E[\boldsymbol{A}(f)\boldsymbol{A}^H(f)] \tag{1}$$

where the vector A(f) collects the acceleration responses in the frequency domain, superscript H denotes complex conjugate transpose matrix and E denotes expected value. The diagonal terms of the matrix G(f) are the (real valued) auto-spectral densities (ASD) while the other terms are the (complex) cross-spectral densities (CSD). The ASDs and CSDs were estimated from the recorded time-histories using the Welch's averaged periodogram method.

Peaks in the frequency domain related to structural frequencies were selected through the peak peaking method and the corresponding mode shapes defined (Figure 6).

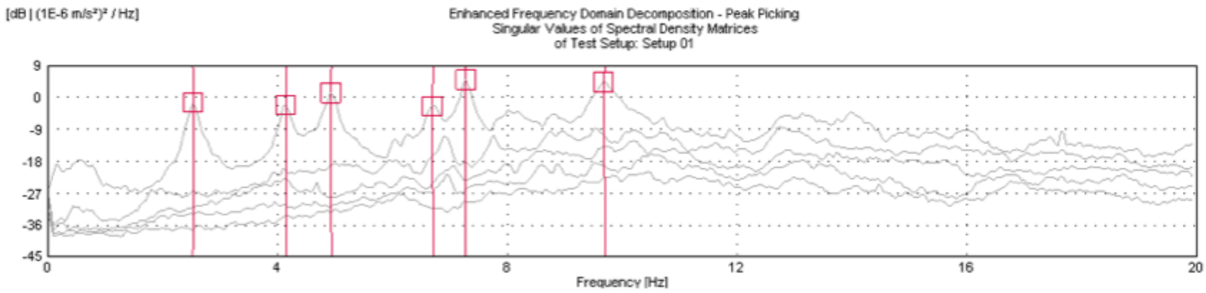


Figure 6: Singular values decomposition of the spectral density matrices: peaks related to structural frequencies are identified on the first singular value through the peak peaking method

Since the number of sensors used in the test is limited it was decided to exploit all the records, comparing the outcomes derived from different OMA algorithms. Once the modal identification phase was completed, the two sets of mode shapes resulting from the application of FDD and EFDD were compared by using the well-known Modal Assurance Criterion (MAC) [5]. The MAC is probably the most commonly used procedure to correlate two sets of mode shape vectors and is defined as follows:

$$MAC(\Phi_{A,k}, \Phi_{B,j}) = \frac{(\Phi_{A,k}^T \Phi_{B,j})^2}{(\Phi_{A,k}^T \Phi_{A,k})(\Phi_{B,j}^T \Phi_{B,j})} \tag{2}$$

where $\Phi_{A,k}$ is the k-th mode of data set A and $\Phi_{B,j}$ the j-th mode of the data set B. The MAC is a coefficient analogous to the correlation coefficient in statistics and ranges from 0 to 1; a value of 1 implies perfect correlation of the two mode shape vectors while a value close to 0 indicates uncorrelated (orthogonal) vectors. In general, a MAC value greater than 0.80 is considered a good match while a MAC value less than 0.40 is considered a poor match. The MAC was also later on used to correlate the results of FE models and OMA.

Table 1 reports the six main natural frequencies and corresponding damping ratios of the chapel, identified through ambient vibration tests. The comparison between different OMA techniques (FDD and EFDD) is also reported in terms of percentage errors of the frequency variations and MAC coefficients calculated on the mode shapes extracted with the two methods. It is possible to state that both techniques prove to be reliable and provided consistent results.

Mode no.	f_{FDD} [Hz]	f_{EFDD} [Hz]	ξ [%]	Error [%]	MAC $(\Phi_{FDD}, \Phi_{EFDD})$
1	2.539	2.535	2.356	0.16	0.99
2	4.15	4.147	2.268	0.07	0.98
3	4.932	4.939	2.087	0.14	0.96
4	6.738	6.715	1.338	0.34	0.99
5	7.227	7.241	1.549	0.19	0.98
6	9.668	9.666	1.973	0.02	0.95

Table 1: Results of dynamic identification tests in terms of natural frequencies and damping. A comparison between different OMA techniques is also reported as percentage error of frequency variations and MAC coefficients between mode shapes

Figure 7 shows the mode shapes related to the structural frequencies of the chapel identified through ambient vibration tests.

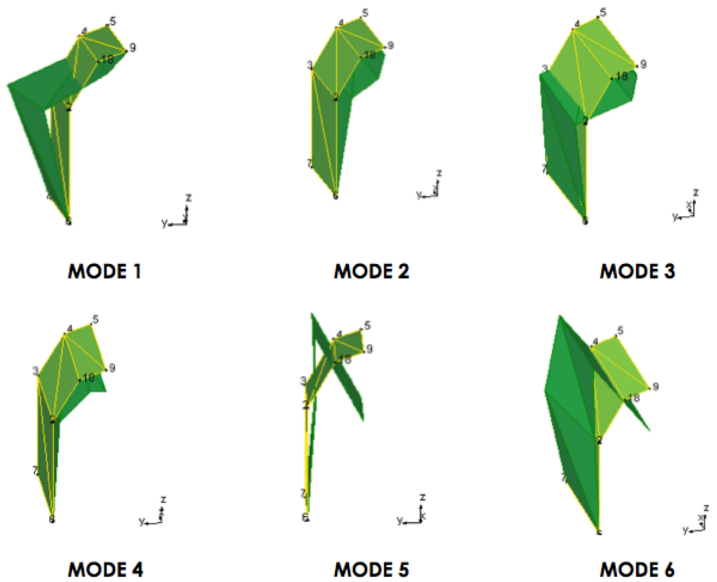


Figure 7: Mode shapes of the chapel identified through ambient vibration tests

3 STRUCTURAL HEALTH MONITORING

Once the on site investigations were concluded, a static and dynamic monitoring system was installed on the Chapel in August 2013 to assess continuously its structural health state. It acquires vibration characteristics, evaluates the opening or reclosing of the main cracks and controls the inclination of the lateral main walls. The system gives interesting information on the progression or stability of the assessed damage pattern. These readings are constantly related to environmental parameters (temperature and relative humidity). The evaluation of the measured quantities, and in particular their changes over time, gives a strong indication in assessing the structural behaviour of the building.

3.1 Equipment and layout

The monitoring system installed is composed by: (i) static sensors to control the damage and crack pattern of the structure and (ii) accelerometers to measure ambient vibrations and capture possible seismic events (Figure 8).

The static system includes devices to measure displacements of the surveyed cracks and inclinations of the lateral walls. It is composed by 12 static channels: 7 displacements transducers installed on representative cracks on the vault and 1 on triumphal arch; 2 inclinometers to control the overturning of the two lateral walls; 2 integrated sensors of temperature and relative humidity to control both internal and external environmental conditions. Data from the static system are registered every 2 hours.

The dynamic monitoring system is composed by 8 high sensitivity piezoelectric accelerometers connected to the acquisition unit. 3 reference sensors are fixed at the base of the structure to record the ground acceleration both in operational conditions and during seismic events. The other acceleration sensors are placed in the same positions of ambient vibration tests. High-density (100 samples per second) dynamic information is continuously recorded every 12 hours.

The continuous dynamic monitoring has several connected purposes: (i) characterize the dynamic response from ambient vibrations along with its dependence with environmental parameters; (ii) capture the dynamic response in the occasion of possible seismic events; (iii) calibrate reference Finite Element models based on the daily extraction of modal parameters from recorded vibrations.

The system is equipped with an internet router for remote data transmission.

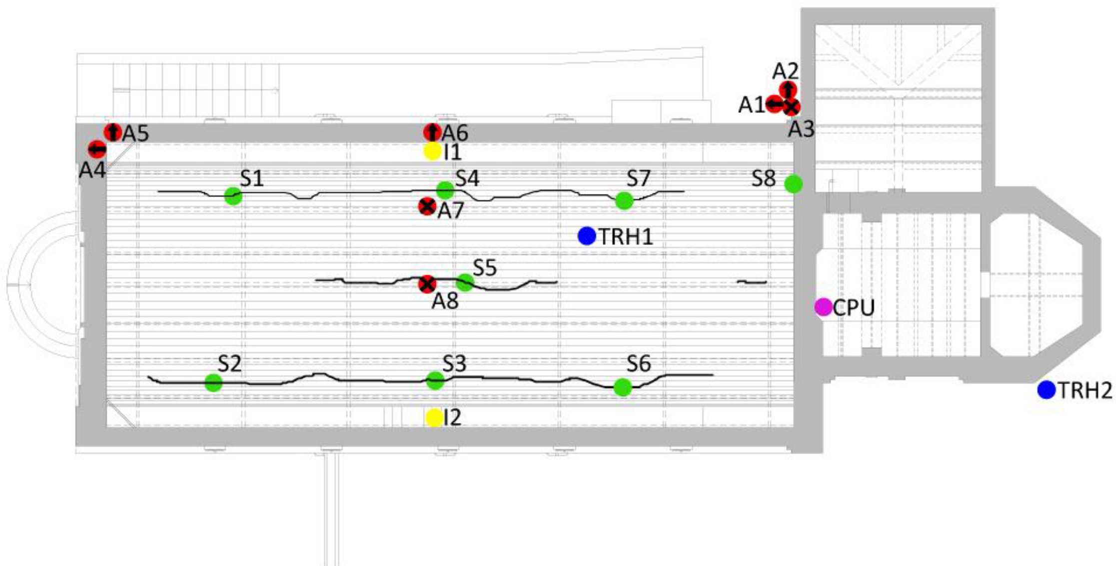


Figure 8: Layout of the monitoring system: S1 to S8 are displacement transducers, I1 and I2 inclinometers, TRH1 and TRH2 temperature and relative humidity sensors, A1 to A8 accelerometers, CPU the acquisition unit.

With regard to the dynamic measurements, two strategies have been set: "long" acquisition, (corresponding to 131'072 points), on regular intervals to allow subsequent identification by means of structural vibration in different environmental conditions (seasonal cycle), and "short" acquisition which is done automatically when the vibrations exceed the trigger (significant event).

3.2 Automatic data analysis

The installed monitoring system stores a huge amount of static and dynamic data every day and thus significant effort is devoted to the analysis of recorded data. For this reasons, it has been implemented automatic procedures for both static and dynamic data processing in Matlab environment.

The automatic procedure applied to static data elaborates a standard .txt file acquired by the static system and create automatically a series of graphs, representing the variation over time of the monitored parameters (displacements and inclination) and correlating them with temperature variations. The algorithm is also equipped by an early warning system that automatically send a message if a sensor exceed a predefined threshold.

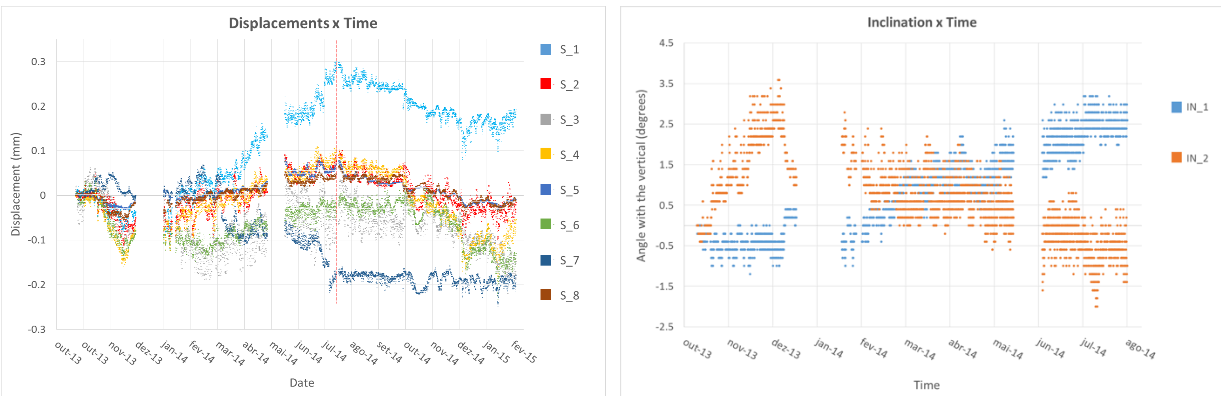
The automatic procedure applied to dynamic data elaborates the acquisition files and automatically estimate modal parameters from measured vibrations. Usually this process involves a large amount of user interaction, especially when lots of data need to be processed in a short amount of time. The developed algorithm, based on a Matlab toolbox (MACEC 3.2, 2011) [6], implements several frequency-domain OMA techniques in order to extract automatically model parameters (frequency and damping ratio development over time, MAC indexes variation between the starting reference identification and the daily identification).

3.3 Monitoring results

Both static and dynamic data are transmitted from the acquisition unit to the central server of the University of Padova and processed on arrivals by the automated algorithms. In this section the development of static (Figure 9a) and dynamic (Figure 9b) measurements are reported and correlated with the variations of the environmental parameters.

Based on the initial dynamic identification, the variations of the fundamental natural frequencies, mode shapes and damping ratios of the Chapel, especially of the vault, are constantly extracted from the measured vibrations. The frequency development over time (Figure 10) gives a strong indication on the dynamic characteristics of the structure and it is directly related to the environmental parameters. The evolution of the 11 possible natural frequencies are investigate in the period from 22/10/2013 to 02/10/2014.

Unfortunately, a thunder hit the Chapel in August 2014, 09. As a consequence, accelerometers 4 and 5 were severe damaged and was not possible to obtained the values of some natural frequencies anymore.



a) b)

Figure 9: Variation of the crack opening (a) and of the two sidewalls inclination (b) during the monitoring period

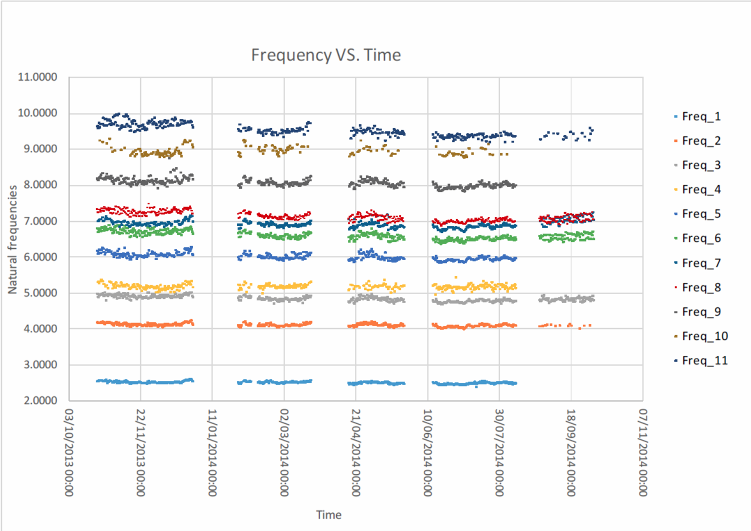


Figure 10: Natural frequencies variation during the monitoring period

3.4 Modeling of environmental effects and amage detection

Analysing the structural behaviour of the monitored cracks or the frequencies trend it is possible to confirm a strong dependence of the these results from environmental parameters, whose control and quantification become essential before any attempt to identify the presence of damage. In fact once the environmental effects are filtered out from recorded data, it is possible to accurately decompose the measurements into their reversible and irreversible components, the latter being associated to active deteriorating processes. Different methods can be applied to remove the effects of environmental or operational factors on the extracted parameters and thus increase the structural reliability.

Within the present research regression analysis and black box models are tested and applied, exploiting a large number of observations to establish relations between the recorded parameters (e.g. crack opening) and the factors that may influence them. Statistical models can be exploited, in an initial phase, to understand the influence of each predictor (input of the model) on the dependent variable (output of the model) and then, to predict future values of the response when only predictors are known. In this case ARX models [7] that comprehends an Auto-Regressive output and an eXogeneous input part are used. This is ideal for representing monitored parameters when they depend (linearly) on the rate of change or trend in temperature as well as the present temperature. The multivariable ARX model with n inputs x and one output y is presented by:

$$\hat{y}_k + a_1 y_{k-1} + \cdots + a_{na} y_{k-na} = b_1 x_k^{env} + b_2 x_{k-nk-1}^{env} + \cdots + b_{nb} x_{k-nk-nb+1}^{env} + e_k \qquad (3)$$

where a_i and b_i are coefficients for the autoregressive and exogenous part, respectively, na is the autoregressive order, nb the exogenous order, nk is the number of delays from input to output, and $e_k = y_k - \hat{y}_k$ is the unknown residual that can be assumed Gaussian. y_k and $\hat{y}_k$ are the actual (real) and the estimated (model) responses respectively.

Preliminarily a correlation analysis is performed with the objective of identifying the time series of environmental parameters x_k presenting higher correlation coefficients with the time series containing the measured output y_k (i.e. crack opening).

The correlation coefficient r_{xy}, which represents the normalized measure of the strength of linear relationship between the two variables, is given by:

$$\hat{r}_{xy} = \frac{\mathrm{cov}(x_k, y_k)}{\sigma_x \sigma_y} \qquad (4)$$

The value of the correlation coefficient varies between -1 and +1: the closer to unity, the more the two variables are correlated.

The parameters of the model, equal to na+nb, were calculated using a least-squares procedure, minimizing the residuals e_k. y_k is the measured output and $\hat{y}_k$ is the output predicted by the model at the same time step. Once the best ARX model is obtained from the first half of the time history of monitoring (estimation phase), new measured environmental parameters (fresh data), collected during the second half (validation period), are used to simulate the response of the studied crack.

From the comparison between the simulated measures behaviour and its recorded counterparts (Figure 11), changes caused by structural damage can be distinguished from those caused by varying environmental conditions. The standard deviations can be used to establish confidence intervals around the predicted values. For instance, if $\hat{y}$ is the predicted output and $\hat{\sigma}_y$ the estimated standard deviation on a new observation, the $(100-\alpha)\%$ confidence interval on $\hat{y}$ is given by:

$$\left[\hat{y} - t_{\alpha/2,\nu}\hat{\sigma}_y \quad , \quad \hat{y} - t_{\alpha/2,\nu}\hat{\sigma}_y\right] \tag{5}$$

where the value $t_{\alpha/2,\nu}$ is found from a statistical table of the t-Student distribution and for a large number of data (as in this case) and $\alpha = 0{,}05\%$ (leading to 95% confidence intervals), we have $t_{\alpha/2,\nu} = 1{,}96$. The confidence intervals defined can be used as an objective criterion to detect damage.

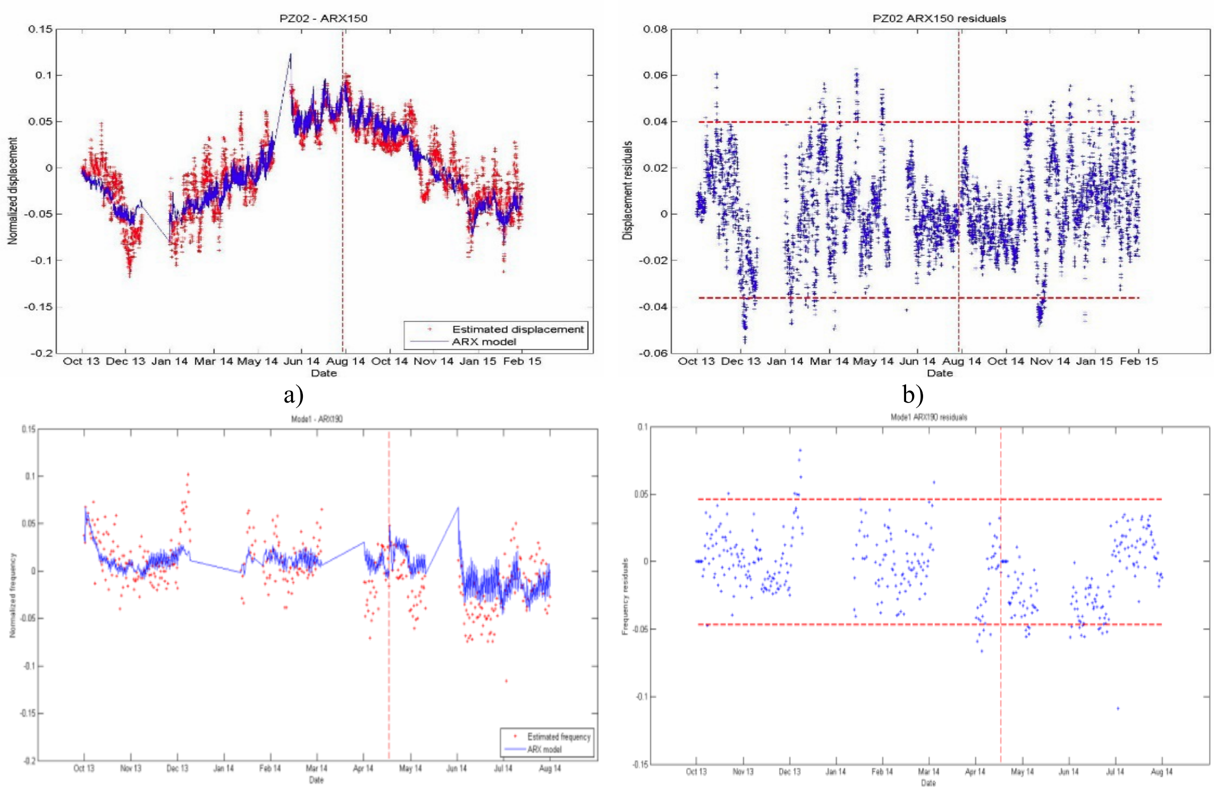
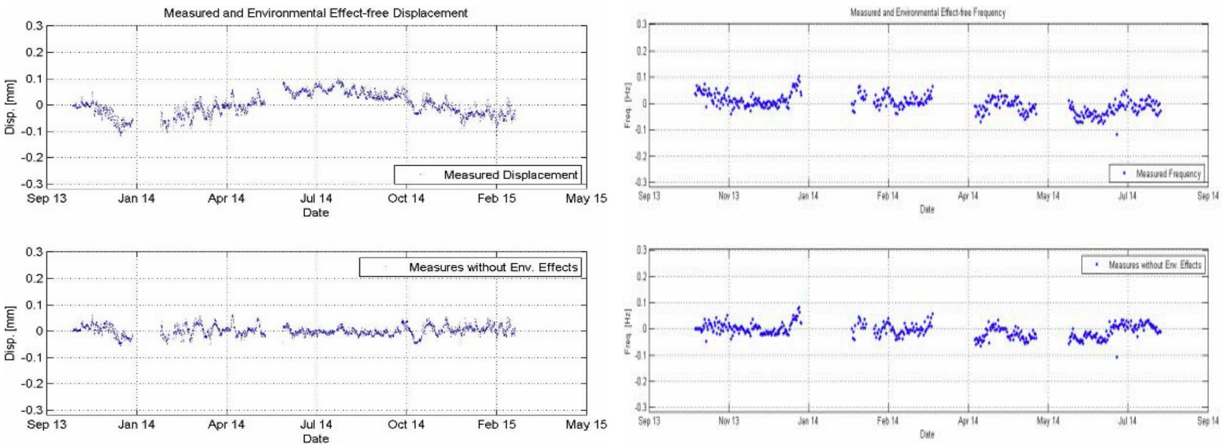


Figure 11: Comparison between measured (red) and simulated outputs of the crack controlled by sensor S2 (a) and first natural frequency variation (c). Residual analysis (blue dots) between measured and predicted values of the same parameters with 95% confidence intervals (b) (d).

Figure 12 shows the temporal evolution of the displacement of a vault crack (a) and of the frequency trend (b) during a period of 18 months before and after the elimination of the environmental effects performed through the described dynamic regression models. It can be observed that the variation of filtered value is reduced to a small range, which proves that the selected ARX model properly describes the factors with greater influence on the output. Any other event, besides temperature, would represent a potential damage.



a) b)

Figure 12: Time evolution of crack displacement (a) and natural frequency variation (b) before and after the elimination of the environmental effects (regression model).

The application of regression analysis and black box models gives the possibility to model and remove the environmental effects from monitoring results. It is possible to state that the controlled crack pattern is stable and that the displacement variations are related only to the seasonal thermal cycles.

Regarding the natural frequency variation it is noted that these parameters are slightly influenced by environmental parameters and poor correlation was calculated with the changes of both internal and external temperature and relative humidity. The applied algorithm form damage detection do not show a variation of frequency related to structural damages.

4 FE MODELING AND CALIBRATION

A detailed FE numerical model of the Scrovegni chapel was implemented in DIANA 9.6 [8] order to evaluate the static and dynamic behaviour of the building. The FE model was calibrated on the basis of the results of the experimental activities, in order to be subsequently used to simulate the response of the structure to different external actions.

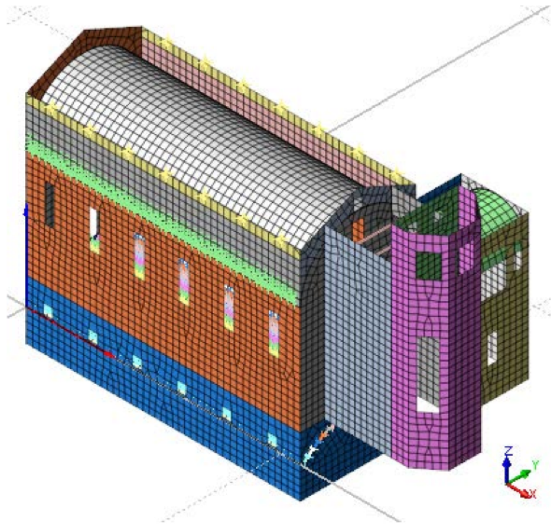


Figure 13: FE model of the Scrovegni chapel

The structure has been modeled with plate elements to schematize walls and vaults and truss elements for iron ties. The weight of the roof and the filling of the vaults are represented in the form of translational masses applied to the nodes (Figure 13).

4.1 Calibration strategy and model updating

The construction and calibration of the FE model was performed as follows:

- Execution of dynamic identification test and extraction of the experimental modal parameters used as reference values
- Construction of the FEM model assigning the most reliable material parameter based on visual inspections and masonry quality identification
- Sensitivity analysis of the elastic parameters that influence more the dynamic response
- Calibration of the parameters
- Quality analysis through MAC comparison of mode shapes

The calibration process is an iterative procedure in which the parameters are changed one by one to achieve an optimal match between experimental and numerical modal parameters.

Model updating results are reported in Table 2 and Figure 14.

Mode no.	f_{EXP} [Hz]	f_{FEM} [Hz]	Error [%]	MAC (Φ_{EXP}, Φ_{FEM})
1	2.539	2.49	1.97	0.81
2	4.15	4.14	0.24	0.56
3	4.932	4.96	0.56	0.65
4	6.738	6.43	4.79	0.72
5	7.227	6.97	3.69	0.90
6	9.668	9.46	2.20	0.63

Table 2: Calibration results of the FE model: comparison between experimental and numerical modal parameters

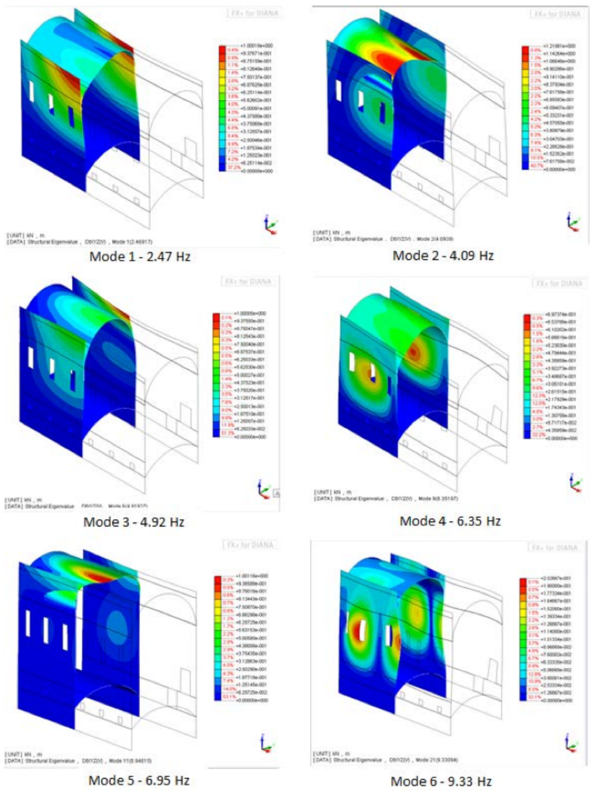


Figure 14: Numerical mode shape of the chapel after the calibration

The model updating leads to excellent results in terms of natural frequency and rather good matching in terms of mode shapes calculated through the MAC coefficient. The absolute frequency errors are less than 5% and on average equal to 2.05%.

5 CONCLUSIONS

A methodology for the study and assessment of an important Cultural Heritage structure based on diagnostic investigations and structural health monitoring is reported in this paper.

The first step was the execution of visual inspections and ambient vibration tests to define the current state of the building and design the optimum layout of the monitoring system, composed by static and dynamic sensors. The aim of monitoring is to control permanently the structural response of the chapel subjected to both operational and exceptional actions (such as earthquakes). It can be used also to assess possible vulnerabilities and avoid the execution of intrusive interventions, unless critical structural problems are detected.

Features automatically extracted from the monitoring data have been statistically analyzed through regression analysis and ARX models. The proposed data driven approach proved to be very effective to remove environmental effects and identify possible damages.

Finally modal parameters extracted from dynamic testing and monitoring were used to calibrate reference FE models of the chapel.

REFERENCES

[1] Fabbri, Colabich, Giorgio**,** *I recenti lavori di restauro alla Cappella degli Scrovegni e le indagi esperite per la sua conservazione*, 1961-63

[2] VV.AA., *La Cappella degli Scrovegni a dieci anni dal resturo*, Atti del convegno svolto il 25 giugno 2012

[3] SVS, ARTeMIS Extractor, Release 4.0, Structural Vibration Solutions A/S, Aalborg East, Denmark

[4] Brincker R., Zhang L., Andersen P. (2000), Modal identification from ambient responses using frequency domain decomposition, in Proceedings of the IMAC 18, International Modal Analysis Conference, San Antonio, USA.

[5] Allemang R.J., Brown D.L. (1982) A correlation coefficient for modal vector analysis, in: Proceedings of the IMAC 1, International Modal Analysis Conference, Orlando, FL, USA, 1982.

[6] MACEC 3.2 Released, a MATLAB Toolbox for Experimental and Operational Modal Analysis, developed by Edwin Reynders, Mattias Schevenels, and Guido De Roeck. Copyright © KU Leuven

[7] Ljung L. (1999) System Identification: Theory for the User, Second edition, Prentice Hall, Upper Saddle River, NJ, USA.

[8] DIANA 9.6 Finite Element Analysis, User's Manual-Release 9, TNO, Netherlands, 2014.