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Vibration Based Damage Identification of Masonry Structures

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ABSTRACT: In the process of preservation of ancient masonry structures, damage evaluation and monitoring procedures are particularly attractive, due to the modern context of minimum repair and observational methods, with iterative and step-by-step approaches. High-priority research issues related to damage assessment and monitoring are global non-contact inspection techniques, sensor technology, data management, diagnostics (decision making and simulation), dynamic (modal) analysis, self-diagnosing / self-healing materials, and prediction of early degradation. On these concerns, the present paper aims to assess damage in masonry structures at an early stage. Replicates of historical constructions were built in virgin state. Afterwards, progressive damage was applied and modal identification analysis was performed at each damage stage, aiming at finding adequate correspondence between dynamic behavior and internal crack growth. Accelerations and dynamic strains were recorded in many points of the replicates. Comparisons between different techniques based on vibrations measurements are made to evaluate different damage identification methods.

1 INTRODUCTION

It is known for a long time that service loads, environmental and accidental actions may cause damage to the structural systems. In this issue the long life maintenance plays an important roll. Regular inspections and condition assessment of engineering structures allow programmed repair works and economic management of the infrastructures, with significant attenuation on the costs. Relating these aspects to the historical constructions area, maintenance is even more essential because of their cultural importance of these constructions, the safety of visitors, potential seismic risk and the accumulation of physical, chemical and mechanical damage through the time.

It what concerns the modifications of the dynamic structural response, changes in element dimensions, in the boundary conditions, in the mass and the degradation of the mechanical properties of the materials, including the damage process, or the simultaneously occurrence of all these phenomena, affects the dynamic behaviour of the structures, i.e. changes the resonant frequencies, mode shapes, damping coefficients and the quantities derived from the basic modal parameters, see Doebling et al. (1996). If the environmental influence (temperature, moisture, etc) is evaluated and separated from the dynamic response of the structure, see Peeters (2000), the damage occurrence can be globally detected. After detection, next task is to localize the damage and its extension with more detail. Finally, its consequences for the construction should be evaluated.

As far as concerned to masonry constructions, there are few references in literature dedicated to damage identification based on vibration signatures.

2 DAMAGE IDENTIFICATION PROCESS

The present paper tries to deal with the problem of damage identification by using Global and Local damage identification techniques, which is indeed the first possible general classification for the identification methods.

Regarding that classification, is possible to have two categories of methods: (a) the vibration based damage identification methods, currently defined as Global methods, because they do not give sufficiently accurate information about the extent of the damage, but they can alert its presence and define the precise location of it (Chang et al. 2003); and (b) the methods based on visual inspections trough experimental tests of acoustic or ultrasonic methods, magnetic field methods, radiograph, eddy-current methods and thermal field methods (Doherty 1987), also called as Local methods. The last ones need the preceding global approach (Global methods) to detect and localize the damage, and then, if the possible location of damage is accessible in the structure, they can describe the damage in an accurate way.

From another point of view, to study more carefully the damage identification problem, Worden and Dulieu-Barton (2004) underline the importance to use exact taxonomy for the precise definition of what constitutes a fault, a damage and a defect in a structure. The authors proposed the following definitions:

- **Fault** is a state when the structure can no longer operate satisfactorily, caused by an unacceptable reduction in the quality for user requirements;
- **Damage** is when the structure is no longer operating in its ideal condition, but can still function satisfactorily;
- **Defect** is inherent in the material and statistically all materials have some unknown amount of defects. This means that the structure can operate in its ideal condition even if the materials contain defects.

The definition above allows a hierarchical relationship: defects can leads to damage and damage leads to fault. This relationship can be used to establish a state when the presence of several damages scenarios means that the structures can no longer operating in a satisfactory manner.

In the literature of vibration based damage identification methods it is common by assume that damage is directly related to a decrease of stiffness and not to any change of the mass. The next step of the methodology for damage identification is to define a classification for the methods and actions used in the process of monitoring and accessing the damage. The first historic classification was presented by Rytter (1993) who establish four levels of damage assessment (classical definition):

- **Detection** (Level 1): the method gives a qualitative indication that damage might be present in the structure;
- **Localization** (Level 2): the method gives information about the probable position of the damage;
- **Assessment** (Level 3): the method gives an estimate of extent of the damage;
- **Prediction** (Level 4): the method offers information about the safety of the structure, estimating the residual operating life.

Each presented level is connected in a hierarchical way, because to pass for the following level it is necessary to know the previous one. It is also stressed that the term damage identification is the conjunction of one ore more presented levels.

More recently, Worden and Dulieu-Barton (2004) proposed a classification with one intermediate level, reminding the major approach on Structural Health Monitoring of the complete damage survey. They present the following levels:

- **Detection** (Level 1): the method gives a qualitative indication that damage might be present in the structure;
- **Localization** (Level 2): the method gives information about the probable position of the damage;
- **Classification** (new Level 3): the method gives information about the type of damage;
- **Assessment** (new Level 4, the classical Level 3): the method gives an estimate of the extent of the damage;
- **Prediction** (new Level 5, the classical Level 4): the method offers information about the safety of the structure, estimating the residual operating life.

In author's opinion, the introduction of the third level is vital for effective identification of Level 5 (classical Level 4) and possibly for Level 4 (classical Level 3), since information about the characteristics of damage is necessary to predict the residual operating life time of the structure. Also, all the first four levels need structural observation while the last one can be estimated with numerical analysis.

The Global vibration methods can be divided by Linear or Nonlinear depending on each type of behavior is assumed after the damage occurrence, e.g. if during the crack breathing it is assumed that the response is linear, then the method is classified as Linear. In this last classification, the damage can be only associated with changes in boundary conditions, material properties (loss of stiffness) or changes in geometry. On the contrary, the Nonlinear methods take into account the changing stiffness according with the oscillating amplitudes for the simulation of the crack breathing, i.e. when the crack is closed there is a restoration of the original stiffness, see Fig. 1. The Linear methods are often founded in literature. They can also be divided as Model Based or Non-model Based methods, depending if they use or not numerical models for the damage identification.

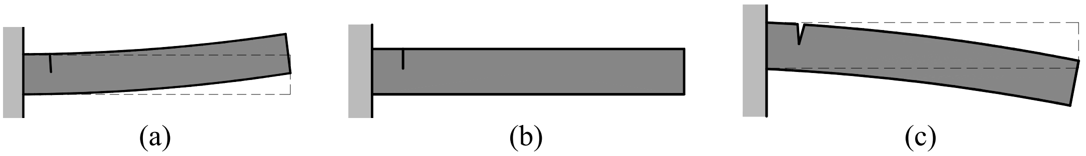

(a) (b) (c)

Figure 1 : Crack breathing of a cantilever beam: (a) crack closed with initial stiffness; (b) transitory stage; and (c) crack open with minimum stiffness.

Related to the last issue, in the present work it is assumed that the modal identification can be accurately performed with linear operational modal analyses at very low ambient excitation level. Cracks breathing effects will not occur or they will be small. So it will be valid to use Linear identification methods.

3 VIBRATION BASED DAMAGE IDENTIFICATION METHODS

There is not yet one methodology which gives accurate damage identification through all the presented levels of damage assessment and for all type of structural systems. So it is still a challenge for the next decades (Farrar and Doebling 1998). The presentation of all proposed methods will be an exhaustive task and in literature there exist already works during the last decades which summarize the principal developments in this field (Doebling et al. 1996, Salawu 1997, Hemez and Doebling 2001, Chang et al. 2003).

4 APPLICATION TO MASONRY CONSTRUCTIONS

As previously mentioned, there are few references in literature where damage identification based on dynamic response is applied to masonry structures. The first attempt at the University of Minho to establish a relation between the damage progress and the dynamic response of a masonry building was done on a real scale rubble stone masonry structure (see Fig. 2), built in the "Laboratório Nacional de Engenharia Civil" (LNEC), at Lisbon. This structure was tested in the LNEC shake table, under the EU RP within the 5th EU framework program, ECOLEADER – Enhancing Seismic Resistance and Durability of Natural Stone Masonry.

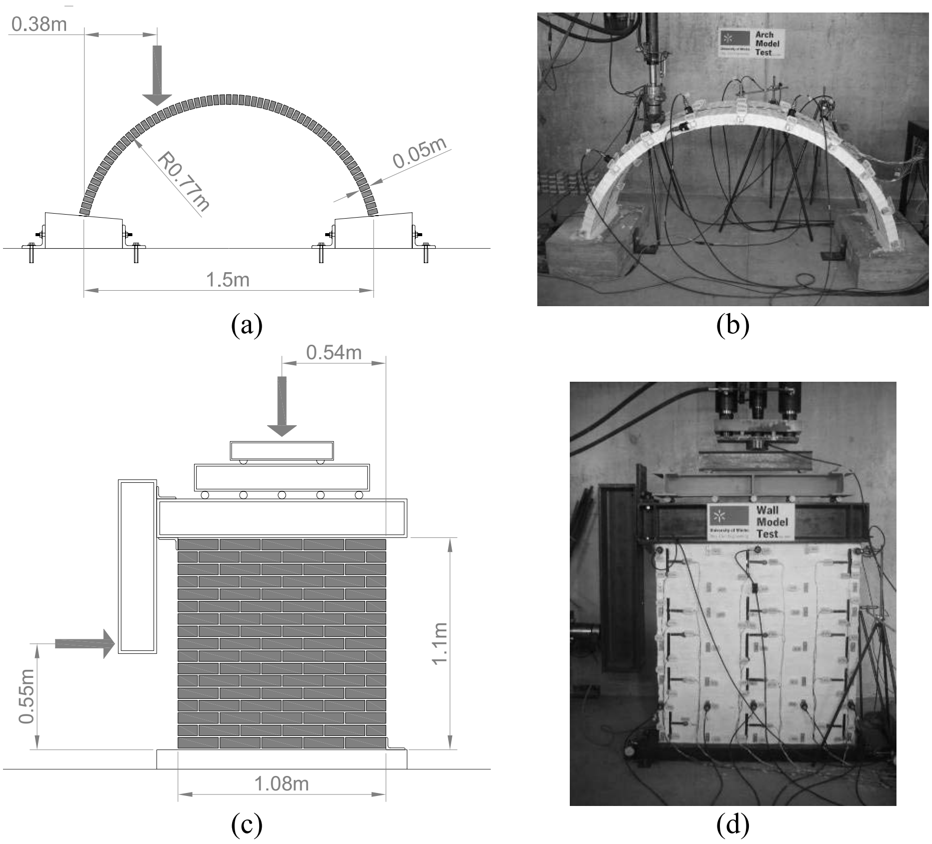
In the works of ECOLEADER Project several and progressive damage scenarios were induced in the shaking tests. At each scenario, a modal identification was performed with operational modal analysis techniques for further comparison between each damage scenario and the virgin stage of the structure. The results of this study are presented elsewhere (Ramos et al., 2005). The natural frequencies decreased significantly during the several damage scenarios, but the relation between the dynamic response and the crack pattern was difficult to analyse. Furthermore it was decided to study simpler models and two masonry replicates were constructed in the Laboratory of University of Minho, which form the main focus of the present paper.

(a) (b)

Figure 2 : Masonry mock-up: (a) general view; and (b) final crack pattern.

5 TESTS OF THE MASONRY REPLICATES IN THE LABORATORY

The two replicates of ancient masonry arches and walls were built with clay bricks and poor mortar joints, see Fig. 3. Progressive and controlled damage was applied by static loads. On each model it was intended to reach multiple damage levels (several cracks). Between each stage, modal identification analysis using output-only (ambient or natural vibration) techniques was done, where the ambient temperature and humidity were also recorded, to evaluate the environmental effects on the dynamic response of the specimens.



(a) (b)

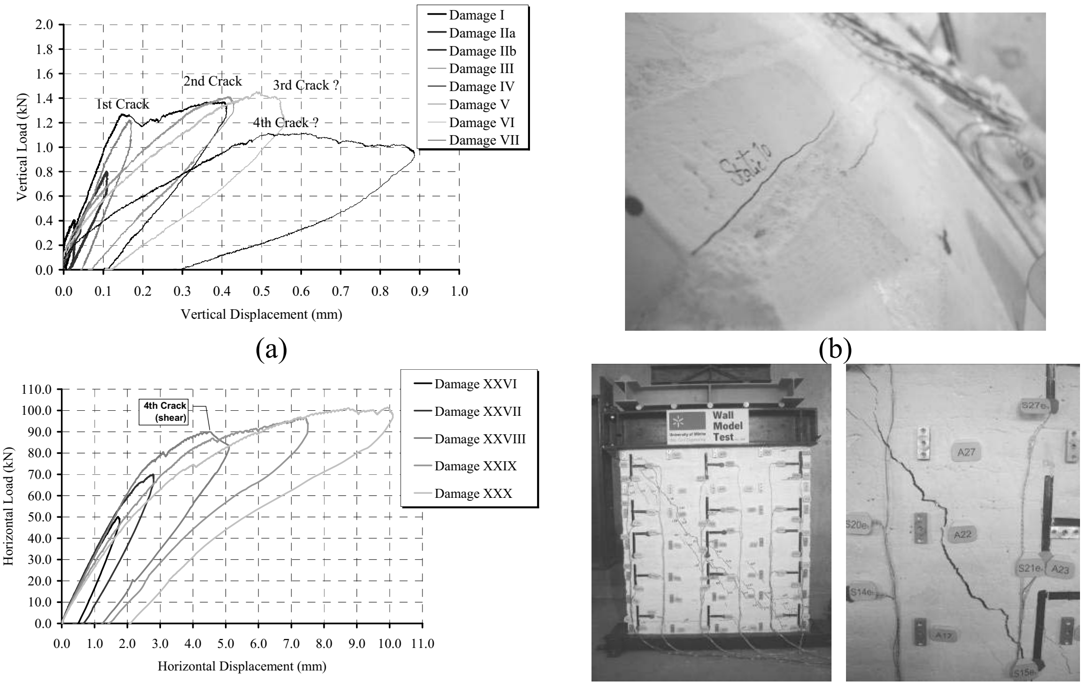
(c) (d)

Figure 3 : Masonry replicates: (a) and (b) an arch model; and (c) and (d) a wall model.

The modal identification tests at each load stage/damage scenario were performed by two different excitation conditions: natural ambient noise present in the laboratory and random excitation in space and time, induced by an impact hammer (2.5 kg of mass). The produced impact forces were about 5% of the mass of the models.

5.1 Test Planning and Analysis Procedures

For each model several damage scenarios were induced by static loads on the specimens, see Fig. 3. Fig. 4 shows the response of the models during the subsequent static tests and some crack patterns in the specimens. Following each stage it was possible to observe the decreasing of the stiffness of the models. The maximum crack openings were 0.05 and 1.2 mm for the arch and wall models, respectively. Between each stage, at unloading, it was difficult to visually observe the cracks.



(a) (b)

(c) (d)

Figure 4 : Damage scenarios: (a) static test of the arch; (b) one crack of the arch with 0.05 mm width; (c) static test of the wall; (b) one crack of the wall with 1.20 mm width.

On each model, both accelerations and strains were recorded. The acceleration response of the arch was measured in twenty-two points, equally distributed along the two longitudinal edges of the vault and in the arch plane directions. The response of the wall was measured in a regular net of thirty-five points and in the out of plane direction. The strains in both models were measured with quarter bridge configurations and they were disposed in a way to measure the curvature mode shapes. The mesh of sensors was kept rather close to have better resolution in the higher mode shapes. Thus, the maximum distance between sensors was 20 cm, approximately 1/8 of their maximum dimension.

The acquisition system was composed by 8 uniaxial piezoelectric accelerometers, with a bandwidth ranging from 0.15 to 1000 Hz (5%), a dynamic range ±0.5 g and a sensitivity of 10 V/g, several strain gauges of 120 Ω resistance, connected to a data acquisition system with 16 bit A/D converter, provided with anti-aliasing filters in the amplification cards for both strains and accelerations.

In the analysis of each model, the modal parameter estimation was done with Stochastic Subspace Identification (SSI) techniques. These techniques are suited for systems under natural (ambient or operational) conditions, and they are based on the assumption that the excitations are reasonably random in time and in the physical space of the structure (Ewins 2000, Brincker et al. 2000).

For the damage identification process a selected group of damage detection methods presented in literature, see Doebling et al. (1996) and Maeck (2003), will be used to validate their performance for Levels 1 and 2. The selected methods will be the Damage Index Method and the Direct Stiffness calculation applied to shell alike structures.

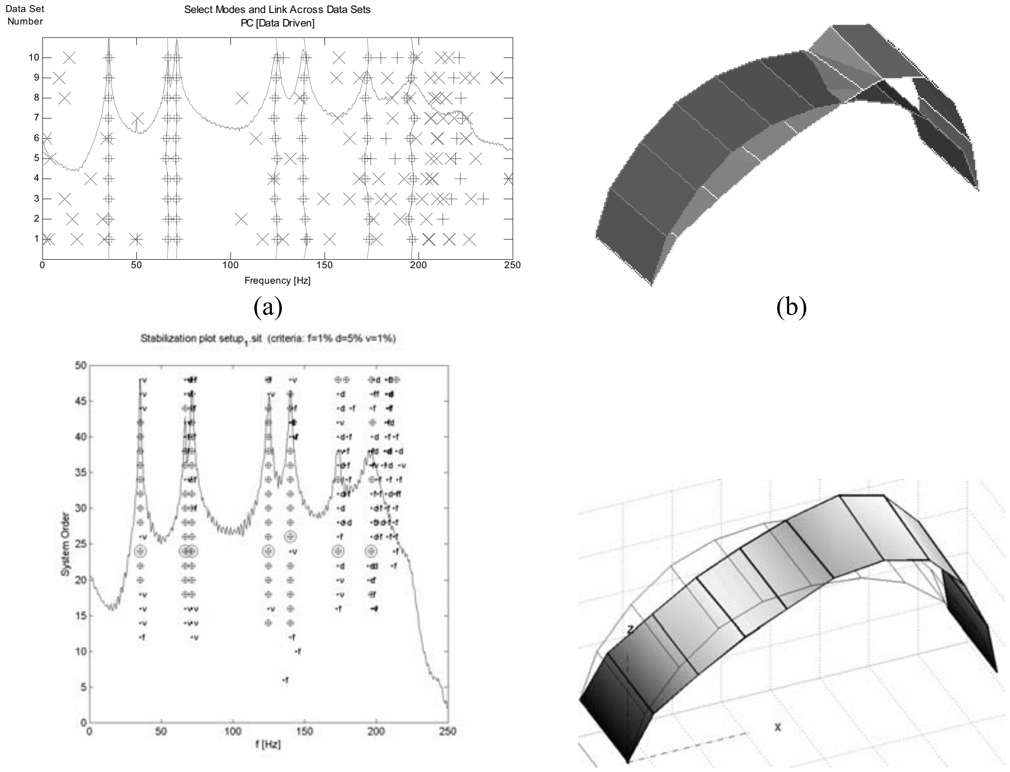
In a second and more detailed phase, model updating techniques following the work of Teughels (2003) will be performed. This belongs to another group of damage assessment methods, where a finite element model is calibrated for every damage stage by minimizing the differences between calculated and measured modal parameters.

5.2 Preliminary Results

At the moment only some data from the entire test campaign was analyzed. The results between two different Stochastic Subspace Identification (SSI) techniques of the arch reference tests in the undamaged condition will be compared, and the evaluation of the frequencies values between the several damage scenarios for both specimens will be reported.

5.2.1 Comparison between Different SSI Techniques

The SSI techniques selected were the Principal Component method available in ARTeMIS Extractor software (SVS, 2004) and the SSI/Ref method implemented in the MACEC tool from Catholic University of Leuven (Peeters and Roeck 1999). The results were accurate and are satisfactory for both analyses. Seven mode shapes were easily estimated with ambient and randomly distributed impact tests. Fig. 5 shows the stabilization diagrams and the 1st mode shape configuration for both analyses.



(a) (b)

(c) (d)

Figure 5 : Different SSI methods: (a) and (b) using ARTeMIS; and (c) and (d) using MACEC.

Table 1 : Results comparison between different SSI analyses.

Modes	Ambient Excitation (AE)				Impact Excitation (IE)				Ratio IE/AE
	ARTeMIS Hz	MACEC Hz	Error %	MAC	ARTeMIS Hz	MACEC Hz	Error %	MAC	
1	35.33	35.35	0.05	0.97	35.23	35.23	0.01	0.97	1.00
2	66.61	66.67	0.09	0.94	66.56	66.43	0.19	0.95	1.00
3	72.05	72.27	0.31	0.94	71.22	71.24	0.02	0.94	0.99
4	125.25	125.20	0.04	0.78	124.05	124.05	<0.01	0.98	0.99
5	139.73	139.83	0.07	0.97	138.92	138.92	<0.01	0.99	0.99
6	173.65	173.73	0.04	0.95	172.55	172.38	0.10	0.95	0.99
7	193.41	197.09	1.90	0.96	195.95	196.83	0.44	0.95	1.01

Table 1 summarizes the results concerning the frequencies values and the mode shape configuration through the MAC values. It is stressed that the results are highly accurate for frequencies and modal displacements, as the error between the resonant frequency values is less than 2% and the MAC values are greater than 0.94. Another observation is the ratio between the values of forced excitation tests and the ambient excitation. In general, this ratio is inferior to the unit, indicating possible weak nonlinearities in the structure according to the level of excitation. The damping values were depending on the excitation mechanism, but an average value of 0.6% can be observed for all modes and all analyses. Furthermore, the damping will be not used for the damage detection analysis.

5.2.2 Evaluation of Frequencies at Increasing Damage Level

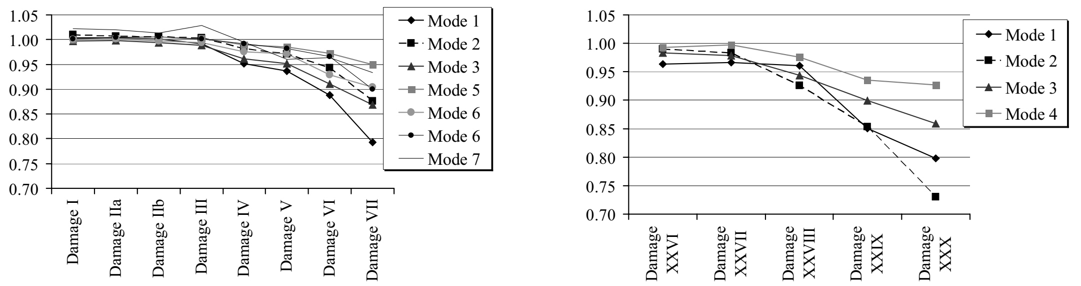
Table 2 and Table 3 present the frequency results for the arch and wall models for the consecutive damage tests, and Fig. 6 presents the relative changes. Observing only the frequency results, it seems that the modal properties of the masonry specimens are sensitive to the damage progress. Fig. 6 shows a sequential decreasing of the frequencies, with residual values in the last scenario between 0.75 and 0.90 compared with the reference values. Concerning the type of structures analyzed, this result seems to be promising, because other tests in literature report about smaller changes of the frequencies values.

Table 2 : Frequency results for the arch model through the different damage scenarios in Hz.

Mode	Reference	I	II	III	IV	V	VI	VII
1	35.44	35.55	35.47	35.13	33.71	33.19	31.46	28.09
2	66.84	67.50	67.23	67.10	65.67	64.88	63.06	58.59
3	72.09	71.84	71.66	71.25	69.33	68.58	65.67	62.62
4	125.63	125.70	125.70	125.99	124.33	123.76	122.10	119.28
5	140.17	140.20	139.71	139.38	136.74	136.17	130.16	126.81
6	173.83	174.10	174.76	173.99	172.48	170.73	167.85	156.41
7	193.30	197.50	195.85	198.75	192.26	185.67	186.22	180.38

Table 3 : Frequency results for the arch model through the different damage scenarios in Hz.

Mode	Reference	XXVI	XXVII	XXVII	XXIX	XXX
1	3.53	3.40	3.41	3.39	3.00	2.81
2	12.65	12.52	12.44	11.72	10.80	9.24
3	18.62	18.31	18.22	17.57	16.74	16.00
4	35.44	35.17	35.34	34.58	33.14	32.84



(a) (b)

Figure 6 : Relative values for the frequencies compared to the virgin state: (a) arch; and (b) wall models

However, the results need to further be analyzed and the other modal quantities will give a better understanding about the damage progress in the structure and the efficiency of the vibrations based methods when applied to masonry structures. Special attention will be paid to the derivative quantities, such as the measured modal curvatures, because they are directly related to the local bending stiffness of the structure. The damage identification task will be also take into account the tridimensional mode shapes and the fact that the masonry structures can, somehow, be well modeled as shell structures with out-of-plane mode shapes.

6 PRELIMINARY CONCLUSIONS AND FUTURE WORKS

In the paper, a new approach for the damage identification process by using Global and Local methods in masonry structures was outlined. Vibration analysis is presented as a potential candidate for Global identification at Levels 1 and 2.

Two experiments on simple masonry structures are set up. The results of the system identification techniques show good accordance between the two SSI techniques. Any method of the two implementations can be satisfactorily used for the estimation of the modal quantities of the several damage scenarios.

The preliminary results from the damage scenarios show that the modal properties of the simple masonry specimens are sensitive to the induced damage. In terms of frequency results, the low frequency values significantly decreases at the progressing damage, more then reported for similar structures in literature. If this observation is confirmed with real case studies, such as buildings, bridges or towers, the vibration based damage identification techniques applied to similar masonry constructions can be a useful tool for the preservation of ancient masonry structures. However, the results of the experimental campaign need to be carefully analyzed.

The next phase of the analysis should be the application of direct methods, such as Damage Index Method or the Direct Stiffness Calculation. In a second phase, model updating techniques will be applied.

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REFERENCES

Chang, P.C.; Flatau, A. and Liu, S.C. 2003. Review Paper: Health Monitoring of Civil Infrastructure, Structural Health Monitoring, Vol. 2 (3), pp. 257-267

Doebling, S.W.; Farrar C.R.; Prime, M.B. and Shevitz D. 1996. Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review, Los Alamos National Laboratory, NM

Doherty, J.E. 1987. Nondestructive Evaluation, Handbook on Experimental Mechanics, A.S. Kobavashi Edt., Society for Experimental Mechanics, Chapter 12

Farrar, C.R. and Doebling, S.W. 1998. Damage Detection and Evaluation II – Field Applications to Large Structures, Modal Analysis and Testing, Júlio Silva and Nuno Maia (Editors), NATO Science Series E, Vol. 363, Kluwer Academic Publishers, London, pp 345-378

Hemez, F.M. and Doebling, S.W. 2001. Review and Assessment of Model Updating for Nonlinear, Transient Dynamics, Mechanical Systems and Signal Processing, 15(1) pp. 45-74

Maeck, J. 2003. Damage Assessment of Civil Engineering Structures by Vibration Monitoring, PhD Thesis, Catholic University of Leuven, Belgium

Peeters, B. 2000. System Identification and Damage Detection in Civil Engineering, PhD Thesis, Catholic University of Leuven, Belgium

Peeters, B. and Roeck, G. De. 1999. Reference-based stochastic subspace identification for output-only modal analysis. Mechanical Systems and Signal Processing, 13(6):855-878

Ramos, L.F.; Lourenço, P.B.; Costa, A.C. 2005. Operational Modal Analysis for Damage Detection of a Masonry Construction, Proc. 1th Int. Operational Modal Analysis Conference, Copenhagen, Denmark, April 24-26, 2005, pp. 495-502

Rytter, A. 1993. Vibration Based Inspections of Civil Engineering Structures, PhD Thesis, Departement of Building Technology and Structural Engineering, university of Aalborg, Denmark

Salawu, O.S. 1997. Detection of Structural Damage through Changes in Frequency: a Review, Engineering Structures, Vol. 19, No. 9, pp. 718-723

SVS. 2004. ARTeMIS Extractor Pro, Release 3.42, Structural Vibration Solutions A/S, Denmark

Teughels, A. 2004. Inverse Modelling of Civil Engineering Structures Based on Operational Modal Data, PhD Thesis, Catholic University of Leuven, Belgium

Worden, K. and Dulieu-Barton, J.M. 2004. An Overview of Intelligent Fault Detection in Systems and Structures, Structural Health Monitoring, Vol. 3(1), pp. 85-98