Towards Computer–Aided Maintenance of Structures

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1. Abstract

Presented researches on historical structures cover a spectrum from non–destructive survey to structural interventions and from theoretical study to practical implementation. All research procedures are assisted by computer calculations and modelling. Hence brought together they can be seen as a step in development of a unified computer-aided maintenance of structures (CAMS) approach.

2. Introduction

Restoration and rehabilitation of historical structures took place centuries before the collapse of Civic Tower of Pavia in 1989 and installing a large digital monitoring system in Santa Maria del Fiore Cathedral in Florence in 1987. But since that time a combined use of experimental methods and numerical techniques has been understood as a tool of identification of estimates of structural properties and material parameters [1–3]. Especially good examples of such a methodology can be found in Italy.

Similar needs emerge in Poland, where mechanics of historical constructions with monitoring of deformations, modelling and assessment has been since the last decade recognized as a new challenge.

Presented examples of the researches cover various fields of maintenance of historical structures. We shall discuss main structural risks and follow the examples to show how they build a common framework of computer–aided maintenance of structures (CAMS), although it has not been fulfilled in a single project yet.

3. Main structural risks

For the purpose of our discussion we may classify various reasons of structural failure as “structure related”, “element related” and “material related”.

Material and element related reasons are sources of damage accumulation within material of the structure. These are mainly material creep (intrinsic property), ageing because of chemical and weathering corrosion, fatigue due to thermal and water table cycles or microseismic and traffic loads and also man induced material incompatibilities while grouting and after flat jack tests.

Element related reasons result from structural interventions like adding frames of steel reinforced concrete, new or replaced tie rods, restoration or reinforcement of vaults, subsoil cementing or underpinning of pillars and walls. These interventions change boundary conditions of the particular and usually of neighbouring elements as well.

Failure reasons related to a structure are also of boundary condition type rather then material one. These are load changes due to seismic events (seismic zone migration towards north-west) and very strong winds (much stronger then in medieval ages) or changes of a structure support due to landslides, subsoil creep, biodegradation of soil and ground water table changes.

Looking across Europe it can be stated, that some failure reasons dominate in one region (e.g. seismicity) while being rare or absent in the others. From this point of view in

Poland dominate structural related reasons like soil creep induced by ground water table changes and biodegradation of organic compounds of the soil, landslides, structural interventions and paraseismic loads related to rock bursts or heavy traffic.

Next section presents examples of the researches inspired by such reasons.

4. Examples of computer–aided researches on historical structures in Poland

Examples were chosen to cover a broad spectrum of research from non–destructive survey to structural interventions and from theoretical study to practical implementation.

To illustrate a framework of CAMS let us discuss a process of rehabilitation of a historical structure shown in Figure 1 [4].

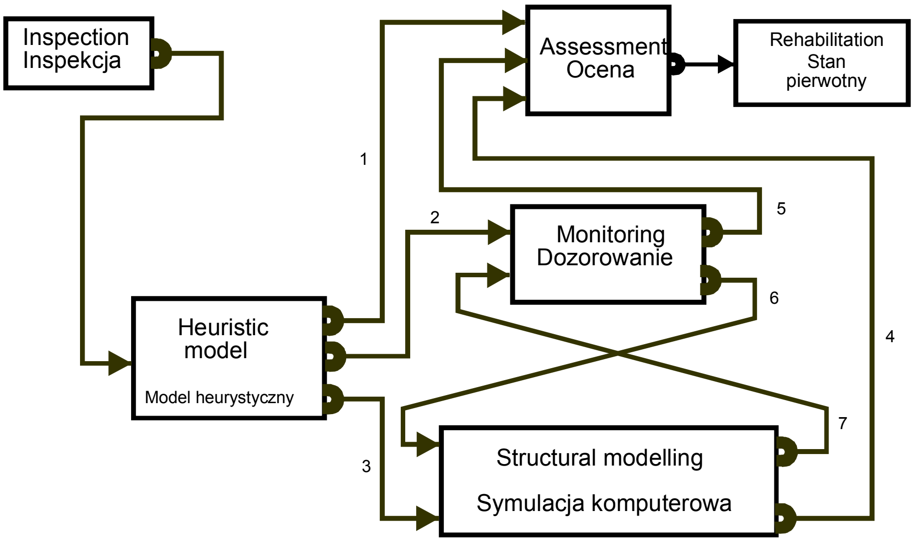


Fig. 1 Process of rehabilitation of a historical structure

A crucial point is an assessment of the structure to which one can come in several ways. Following are examples of path "1" (computer–aided survey and geometrical modelling), "3" and "4" (computer–aided structural modelling and restoration), "2" and "5" (computer–aided monitoring and assessment), "2", "6" and "4" (computer–aided monitoring and structural modelling) and a combination of "2", "3", "6", "7" and "4" (computer–aided damage monitoring system).

4.1 Computer–aided survey and geometrical modelling

Assessment based on engineering experience of an expert is represented by path "1". But even in this simple case computer aided experimental investigation during inspection stage can be done and proof to be very helpful.

This computerized methods are mainly sonic and radar tests which detect material inhomogeneities and crack distribution within structural elements. This is feasible thanks to numerical modelling of wave propagation phenomena within a heterogeneous body.

An interesting example of such a research by the original method of semitomography (ultrasonic layer inspection) was presented in [5].

The research was done in Krzyżowa near Wrocław where there is situated XIX century Historical Complex, previously property of Helmut von Moltke.

In columns of the stable serious damages due to the deep corrosion of embedded steel rods were observed (Fig.2, 3). The aim of the research was to find crack distribution and orientation to assess the safety of the structure being restored and raised by one storey.

Fig. 2 Cracked column [5].

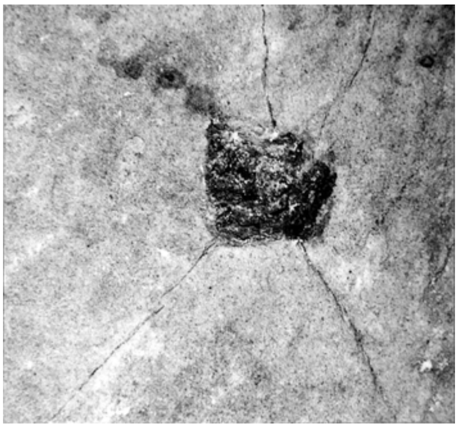


Fig. 3 Corroded steel rod [5].

Measurements of the ultrasonic wave propagation time in various horizontal cross-sections of the columns were interpreted according to the model developed by the authors. The key idea is shown schematically in Figure 4 were assumption was made that the signal coming from transmitter to receiver in the case of crack existence follows curvilinear pass which can be satisfactorily approximated by an arc of the circle passing through the crack tip and transmitter/receiver localisation points. Then performing the measurements in several horizontal cross-sections and elaborate the data on a computer there was produced CAD model of each surveyed pillar (Fig. 5).

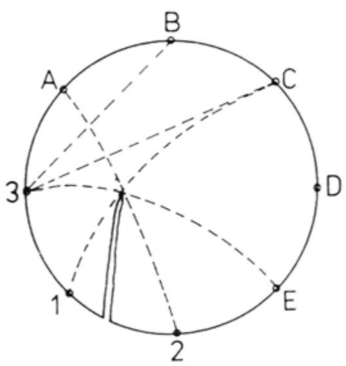


Fig. 4 The idea of determining the crack tip position when its beginning is visible on the surface. If the straight line connecting transmitter and receiver crosses the crack then the wave follows the nearest possible circular path [5].

This geometrical modelling helped to assess that the cracks run from the one to another holes in which corroded rods are embedded and confirmed that the high pressure exerted by swelling rust was the origin of fractures.

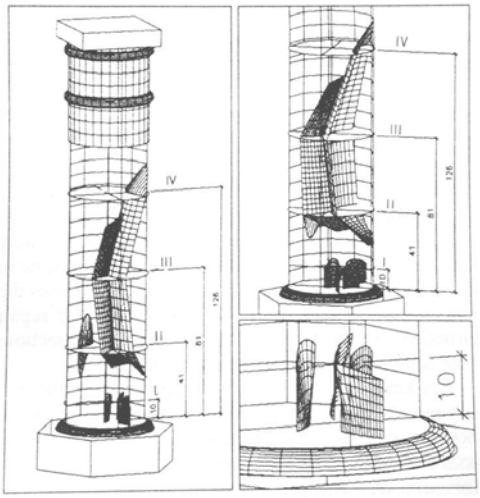


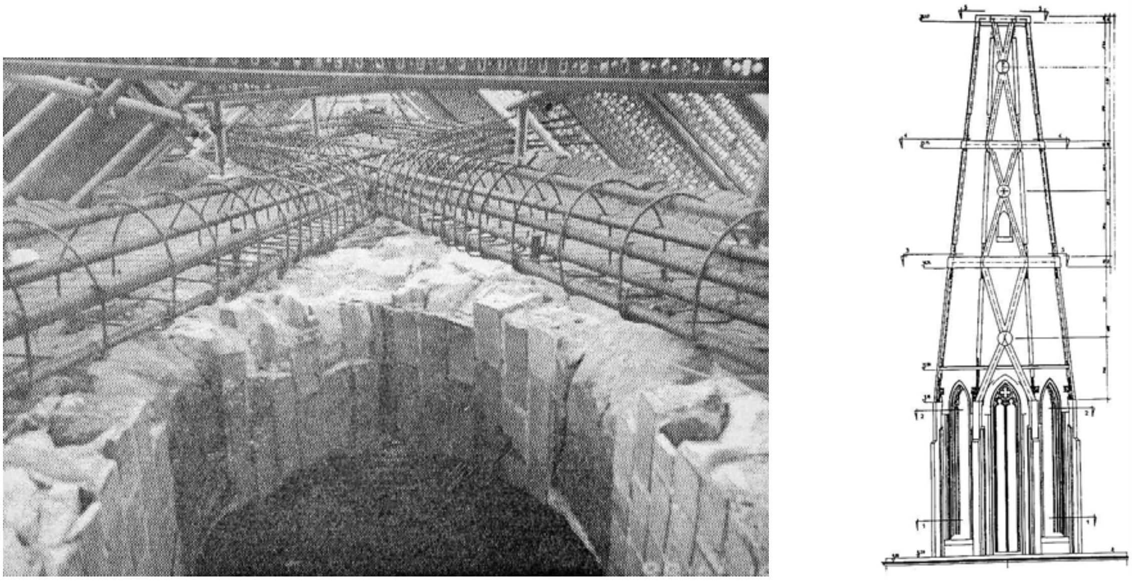
Fig. 5 Axonometric view of cracks in column 6 [5].

4.2 Computer–aided structural modelling and restoration

The church of Our Lady in Chojna near Szczecin was built in XIII–XIV century and so was its tower which collapsed in 1843. New, almost 100 m high, neogothic tower has already been repaired several times. It was decided in 1992 after the survey including laboratory testing of material samples to build an outer skeleton of reinforced concrete to consolidate original cracked structure of the upper part of the tower [6] to preserve it in its actual state.

The strengthening structure is a 3D frame with 20 cm thick plate base. Static behaviour of the structure was modelled by elastic FEM elements with 156 triangular plate elements for the base plate [7] and taking into account directions of principal stresses.

A local view of the construction of the strengthening and the shape of the reinforced concrete frame are shown in Figure 6.



a) b)

Fig. 6 Construction stage and designed 3D frame [7].

4.3 Computer–aided monitoring and assessment

Computer–aided maintenance of the structure with monitoring of deformations during the structural intervention is an example of Malbork Castle.

Malbork castle is the biggest teutonic castle in Europe and was the capital of the teutonic knights state in Poland after Grand Master moved here his residence from Venice in 1306.

The castle is situated on a sandy hill while its western wall is founded on oak piles at the footing of a slope in the vicinity of Nogat river.

Structural problems had begun in XVI century starting from narrow cracks and despite of several interventions the problem continued after the 2nd World War with increased differential subsidence, cracks in walls and vaults. The last restoration works started about ten years ago [8]. The idea of the designed support is presented in Figure 7.

During the construction works temporal computer–aided monitoring system was installed. There was monitored subsidence of the castle, load change in buttresses, forces in temporarily mounted tie rods and in roof trusses as well as relative displacements between east and west walls of the castle. Hence quasi–continuous assessment was performed during underpinning, clamping and the check out period afterwards.

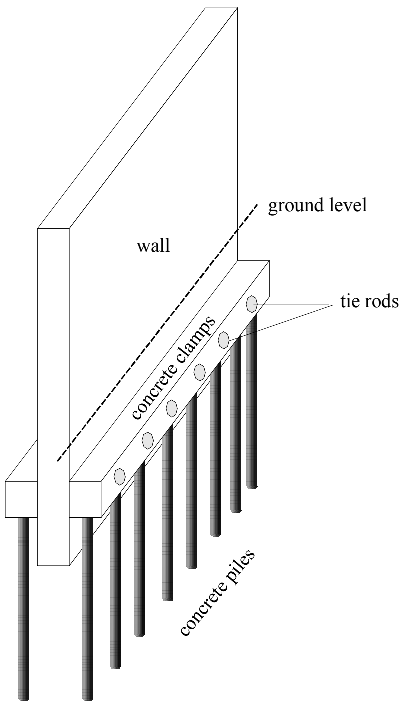


Fig. 7 Concrete clamp designed to support western part of Malbork Castle

4.4 Computer–aided monitoring and structural modelling

A study of the influence of paraseismic loads on historical structures and numerical modelling of dynamic structural response is in many cases a useful diagnostic tool. An example of such a research is the dynamic structural modelling of Barbican in Cracow.

This well preserved XV century historical monument, formerly the main entrance to the capital of Poland, today is at the risk of vibrations from traffic, especially of a tram communication origin. To assess its structural safety in short and long terms it was decided to perform dynamic load spectra measurements [9].

Modelling was done by FEM with elastic 3D 20-nodal elements (with over 20 000 of elements). There was studied a dynamic response to external loads (as measured in 1982) and modal frequencies of the model [10]. These modal frequencies of orders 1 to 6 are shown in Figure 8 where the last two frequencies belong to the main part of the structure.

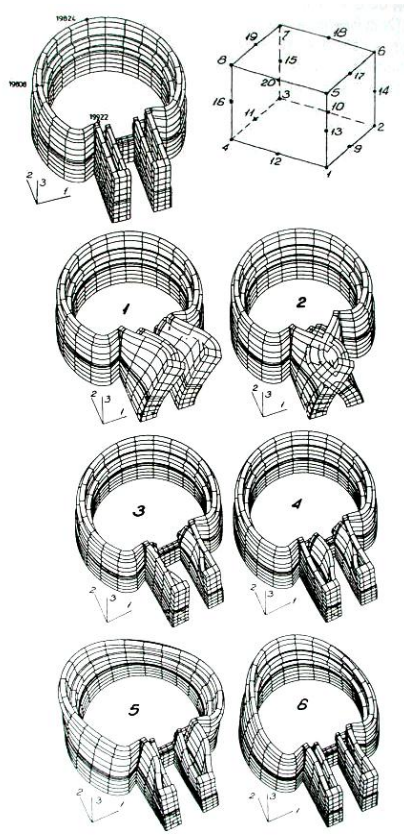


Fig. 8 Numerical model and modal frequencies of Cracow Barbican [10]

4.5 Computer–aided damage monitoring system

The concept of DAmage MONitoring (DAMON) system follows the ideas expressed in [1–3] and is an attempt to combine together structural modelling and monitoring into a feed back system (path “6” and “7” in Fig. 1) to assess structure health and predict possible cracks development thus allowing to maintain the structure in an adequate way in advance [11]. All components of the system were developed at a laboratory level.

As the idea was inspired by a restoration of XIV century St. John’s church in Gdańsk monitoring system including sensors and their configuration as well as 3D FEM model with over 200 000 elements (Figure 9) are designed to be applied to this case [12,16].

The key point was to find numerically effective method which can be used to model existing and emerging discontinuities (cracks), subsoil plasticity and stiffness degradation of the structure due to material softening.

For this purpose there was chosen Virtual Distortion Method (VDM) [13] which allows to carry analysis without a need of remeshing and stiffness matrix reformation in the analysis process. Damage and cracks development are simulated by fictitious field of virtual distortions. The actual nonlinear structural behaviour is composed of the linear response and nonlinear one caused by the virtual distortions which are calculated with use of a priori computed influence vectors describing relations between locally induced unit distortions (e.g. crack openings, ground subsidence) and global stress/strain fields.

Applying the VDM concept of brittle-plastic progressive damage analysis [13] one can postulate that local stresses σ as well as deformations ε for the *modified* structure (with non-linear material properties $\mathbf{C}^*$ shown in Fig. 10) and for the *distorted* structure (with original linear properties **C** and with introduced virtual distortions ε^o) are identical:

$$\sigma = \mathbf{C}^*\varepsilon = \mathbf{C}\,(\varepsilon - \varepsilon^o) \quad (1)$$

where ε can be decomposed:

$$\varepsilon = \varepsilon^L + \mathbf{D}\,\varepsilon^o \quad (2)$$

and where:

ε^L - strains caused by external load, ε - global strains caused by external load as well as virtual distortions, **D -** the influence matrix which denotes strains caused by unit virtual distortions and **C** is the constitutive matrix

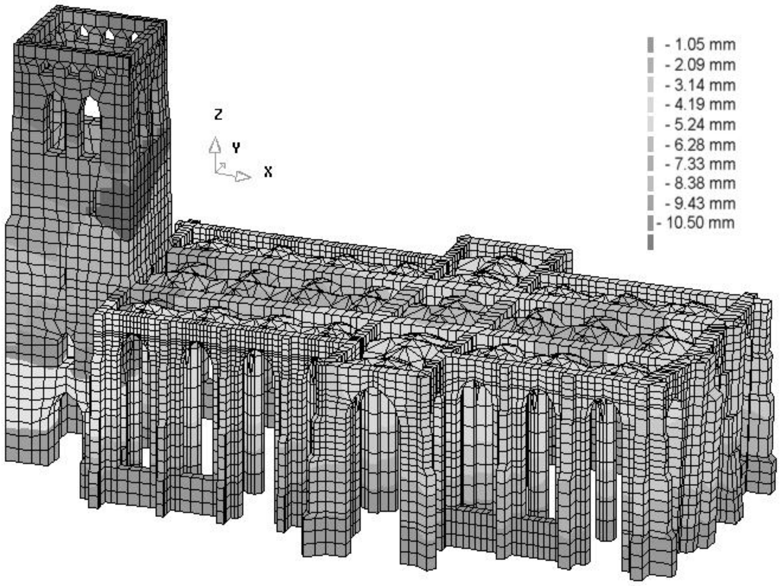


Fig. 9 FEM model of St. John's church with calculated vertical displacements under dead load.

For brick masonry structure of the church there were assumed [14] Nadai's brittle plastic surface and uniaxial material behaviour shown in Figure 10 where σ_c is a critical tensile stress and σ_p is a plastic yield stress in compression.

a) Stress limits in2D Model *b) One-Dimensional Stress-Strain Characteristics*

Fig. 10 Assumed material characteristics ($\sigma 1$,$\sigma 2$ - principal stresses)

Note that the virtual distortions ε^o (analogously to the deformation state ε) are determined by 3 independent components ε^o_{11}, ε^o_{22},, ε^o_{12} for each 2D finite element. Composing the actual influence matrix **D** gradually, from vectors describing structural deformations caused by unit local virtual distortions $\varepsilon^o_{11}=1$, $\varepsilon^o_{22}=1$, $\varepsilon^o_{12}=1$ in each overloaded finite element detected in the loading process the following requirements satisfying local brittle or plastic behaviour has to be postulated due to particular case of the stress state:

- for the fracture case (tension) - for the plastic case (compression)

$$\sigma_n = 0 \qquad\qquad \sigma_n = \sigma^p$$
$$\sigma_{nt} = 0 \quad (3) \qquad\qquad \sigma_{nt} = 0 \quad (4)$$
$$\sigma_t = E\,\varepsilon_t \qquad\qquad d\varepsilon^o\,\sigma = 0$$

where E denotes the Young's modulus and t, n denote directions, respectively, along the crack and normal. Condition $(4)^3$ describes orthogonality of plastic distortions increment to the plastic surface.

Expressing local stresses as superposition of linear solution σ^L and influence of virtual distortions (cf. Eqs.1, 2):

$$\sigma = C\,[\varepsilon^L + (D - I)\,\varepsilon^o] \qquad (5)$$

and substituting (5) to (3) and (4) we can get a system of linear equations determining virtual distortions simulating cracks (in over-tensioned areas, Eqs.3) and plastic deformations (in over-compressed areas, Eqs.4)

In this way, solving the system of linear equations (with the size equal to the number of observed damaged finite elements times three) the piece-wise-linear brittle-plastic response can be determined. If no new damaged element is detected, the analysis can be finished. Otherwise, the new, overloaded elements must be included into the damaged area and the simulation process (determining virtual distortions) has to be repeated.

To illustrate potential of the VDM for modelling progressive damage in historical structures there were done several simulations (in 2D) of reconfiguration of monitoring system or its extension according to possible modelling results. These studies are summarized in [15].

5. Conclusions

Researches on historical structures follow ways depending on the monument itself. They are inspired by the local needs and often full computer-aided maintenance of the structure is not justified. On the other hand various elements of full CAMS framework which have already been studied and applied suggest that CAMS philosophy might be dominating approach in near future. This philosophy allows modular development of CAMS systems within each case study while maintaining its inner compatibility during the whole project live.

It should be pointed out that presented overview of the historical structure research shows an existing need of application of permanent computer-aided monitoring, computer-aided data transmission and computer-aided assessment systems as they are now lacking elements of CAMS in Poland.

6. Literature

[1] G.M. Carlomagno, C.A. Brebbia, (Eds.), *Computer and experiments in stress analysis*, Springer-Verlag, Berlin, 1989.

[2] Nappi, *Nondestructive testing and system identification*, in Proc. 2nd Int. Seminar, Structural Analysis of Historical Constructions, Possibilities of numerical and experimental techniques, P. Roca, J.L. González, E. Oñate, P.B. Laurenço (Eds.), CIMNE, Barcelona, Spain,, Nov. 1998, pp. 125-147.

[3] G. Macchi, *General methogology. The combined use of experimental and numerical techniques inside a single study,.* in Proc. Int. Seminar, Strucural Analysis of Historical Constructions, Possibilities of the numerical and experimental techniques,

P. Roca, J.L. González, E. Oñate, P.B. Laurenço (Eds.), CIMNE, Barcelona, Spain,, Nov. 1995, pp. 1-14.

[4] M. Skłodowski, *Experimental methods used in inspection and monitoring of historical structures*, FUDoM 01 Finno–Ugric International Conference of Mechanics with Beda Symposium, Ráckeve, Hungary, May 2001 (abstract).

[5] J. Jasieńko, B. Stawiski, *Analysis of cracking plane geometry in old sandstone columns*, Materials and Strucures, Vol. **34**, May 2001, pp. 248-252.

[6] S. Kowalczyk, M. Płotkowiak, *Problemy zabezpieczenia wieży kościoła NMP w Chojnie*, (in Polish), Inżynieria i Budownictwo, No. 5 (1999), pp. 259-262.

[7] S. Nowaczyk, M. Płotkowiak, *Wzmocnienie żelbetowe wieży kościoła w Chojnie*, Proceedings of RewInż 2000, Vol. 2, pp.171–177, Kraków (in Polish)

[8] *Wzmocnienie fundamentów skrzydła zachodniego zamku krzyżackiego w Malborku*, (in Polish), web site of STABILATOR S.A., http://www.stabilator.com.pl/ratujemy.htm.

[9] R. Ciesielski, M. Pieronek, K. Stypuła, *Kinematic exitation of building vibrationscaused by tramway traffic in the old city of Cracow*, Dynamika Stavebnych Konstrukcji, Čelostatna Československa Konferencia, Smolenice-Bratislava, 1985.

[10] R. Ciesielski, K. Kotłowski, *Dynamic influences on "Barbacan" relictic building in Kraków*, Proceedings of RewInż 1998, Kraków (in Polish).

[11] D. Wiącek, J. Holnicki–Szulc, *Progressive damage analysis in historical buildings – VDM Approach,* pp. 45–52 in Proceedings 5th Int. Conf. on Computational Plasticity, March 17-20, 1997, Barcelona, Spain.

[12] M. Skłodowski, W. Cudny, *Monitoring system for St. John's church in Gdansk*. Vol. of Abstracts, 33rd Solid Mechanics Conference, Zakopane, Poland, Sept. 5-9, 2000, pp. 355-356.

[13] J. Holnicki–Szulc, J.T. Gierliński, *Structural Analysis, Design and Control by the VDM Method*, J. Wileyn & Sons, Chichester, 1995.

[14] W. Cudny, M Skłodowski , D. Wiącek, J. Holnicki–Szulc, *Dmage prediction concept based on monitoring and numerical modelling of a medieval church*, pp. 45-52 in Proc. NATO Advanced Research Workshop on Smart Structures, J. Holnicki-Szulc and J. Rodellar (Eds.), Kluwer Academic Publishers, The Netherlands, 1999.

[15] D. Wiącek, *Monitorowanie, ocena i przewidywanie rozwoju zniszczeń w budynkach historycznych*, PhD Thesis, IFTR (Warsaw, Poland), 2001 (in Polish).

[16] M Skłodowski and D. Wiącek, J. Holnicki–Szulc, W. Cudny, *Research program elaboration and measurement of deformations and subsidence of pillars and walls of St John's church in Gdańsk*, Final Report, Grant No. 7TO7E 01096C/40 of State Committee for Scientific research, IFTR (Warsaw, Poland), 2000 (in Polish).