Continuous Assessment of Historic Structures – A State of the Art of applied Research and Practice in Belgium

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1. Abstract

With approximately 10 000 listed and protected monuments, the Belgian Building Heritage is exceptionally rich. The preservation of this unique patrimony requires fundamental effort. The Koning Boudewijn Stichting (Rosiers et al., 1998) estimated the total cost necessary to maintain or improve the building heritage to such an extent that it would only require regular maintenance for a reference period of 50 years, to be 2.25 billion EURO. This paper gives an overview of the state of the art in (applied) research and practice. Besides a global overview, more detailed information concerns the research activities developed at the KULeuven with respect to the preservation of historic structures. The topics treated are situated all over in the process of conservation: monitoring, design and analysis models, assessment tools and consolidation and strengthening methods. As a large number of monuments and buildings are made out of brick/stone masonry it is not surprising that a lot of research effort goes to the masonry material behaviour. Seen the use of wood as a building material for historic structures, strengthening of wooden structures is also addressed in this paper. Sometimes even a reinforced concrete structure is considered an historic building. Due to the decay seen, several techniques for strengthening and repair have been developed. These will be presented shortly too.

2. Introduction

2.1 Main players in the field of historic structures

In Belgium, education is mainly concentrated at the universities:

- RUG (Rijks Universiteit Gent) and KULeuven (Katholieke Universiteit Leuven) with the Lemaire Centre for Conservation of Historical Towns and Buildings at the Flemish part
- UCL (Université Catholique Liège) and ULB (université Libre the Belgique) at the Walloon part.

Research is mainly done at the universities. It is concentrated around:

- doctoral research,
- master thesis of last years' students
- research funded by governmental grants.

Additionally research is done at the BBRI (Belgium Building Research Institute). Seen the increasing importance and market share of restoration works, research in that area gains field.

From the government side (Flemish part), our built heritage is preserved by organisations such as Monumenten en Landschappen (AML) (Monuments and Landscape), Erfgoed Vlaanderen (Flanders Heritage). For the French community, similar organisations are active. In daily practice, the monuments are inspected on a regular basis by the Vlaamse Monumenten Wacht (Flanders Monument Watch (MOWAV)) who carry out small repairs to prevent large costs caused by dereliction.

Besides this governmental organisations, several other organisations fill out the basic players in the field of our built heritage, such as ISCARSSAH, ICOMOS- Flanders and Brussels (International Scientific Committee for Analysis and Restoration of Structures of architectural Heritage) and WTA-Belgium-Netherlands (International Scientific and Technical advisory group on Conservation and Rehabilitation). At the same time, these international organisations ensure that information and experience is mutually exchanged with the rest of the world.

The number of architects and engineering offices specialised in this growing market section is limited. The main contractors that carry out restoration projects, consolidation or strengthening works are: Building NV, Denys NV, De Neef Engineering NV, Group Monument NV, Vandekerckhove NV, Verstraete en Vanhecke NV. For most of them, restoration works are only a part of the projects they are working on.

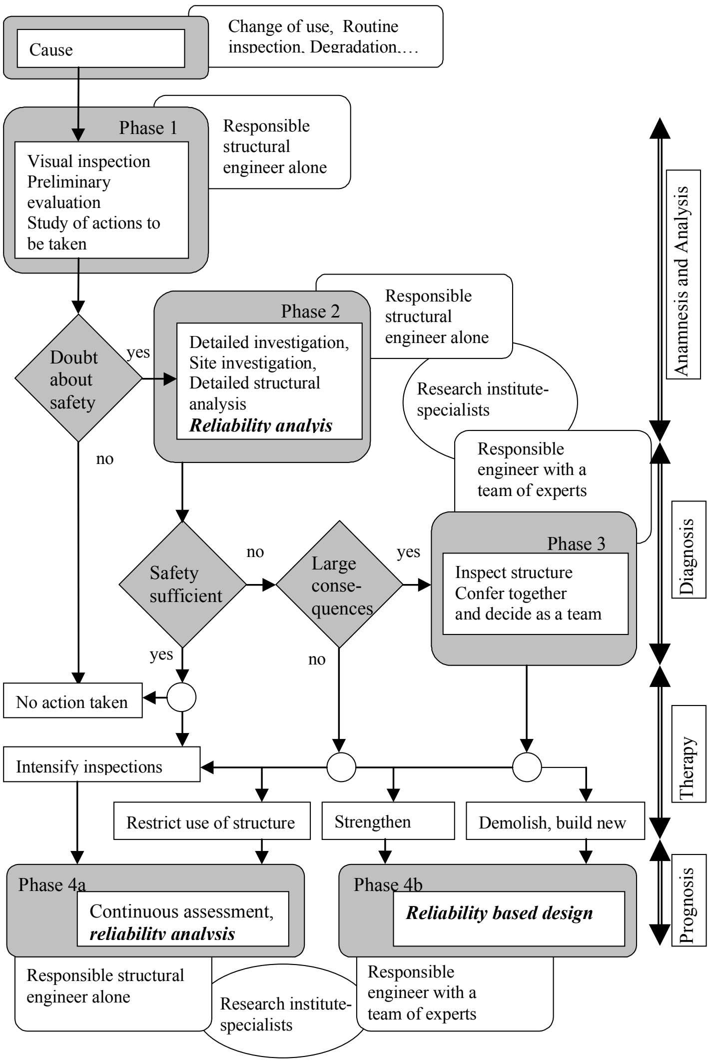

Figure 2.1: *Global framework for the assessment of existing buildings [Schueremans, 2001; adopted from Diamantidis, 1999,2001]*

2.2 The preservation process

The preservation process of historical monuments is generally based on a sequence of anamnesis and analysis(1), diagnosis(2), therapy(3), control(4) and prognosis (Croci, 1998; ICOMOS, 2001; Lemaire and Van Balen, 1988; Van Balen, 1997), **Figure 2.1**. In each of these steps, extensive research and practice have been developed in Belgium the last decades. To give an overview of the state of the art of the research in Belgium, this framework will be used. In all parts of this framework, work has been done or research is going on, as well as on the framework itself.

3. Anamnesis, Analysis and Control

In the fases of anamnesis, analysis and control, all possible information on the historic structure available should be gathered that is relevant for the structure at hand. As it concerns historic buildings, the minimum destruction theorem applies (Charter of Krakow,2002). Monitoring techniques, simple, complex or combinations of both, can deliver a lot of information, and often are a far less destructive option.

Table 3.1 lists a number of monitoring techniques that deliver information about the quality of the building (masonry). The tests, their application area, a small description and references are listed (Schueremans and Van Gemert, 2000; Schaerlaekens et al. 1999).

Table 3.1: *Judging the quality of (masonry) historic building*

Technique	D/SD/ND ID/IL	Principle, application, reference
Historic research	ND IS+IL	Information about the geometry of the structure, used materials, loads, strengthening, structural events,…(Van de Vijver, 2001)
Visual inspection	ND IS	Is being used in all cases. This still is the cheapest and often also the most efficient, non-destructive test method. Use of additional guidance, e.g.: Damage Atlas and expert system (Van Balen,1998)
Foto-grammetry	ND IS	Evolution of large cracks en relative displacements. Is often used for measuring and documenting of damage of structural elements and materials (Santana, 1999)
Electric resistivity	ND IS	Qualitative interpretation of the global condition of masonry (cavities, layering of material,…) Very valuable to check the effectiveness of executed consolidation injection (Venderickx, 1999; Van Rickstal, 2000)
Radiography	ND IS	By radiation of the element by gamma-rays discontinuities that are located deep in the masonry (reinforcement, cavities, trusses,…) can be identified and located. Both sides of the element have to be admissible. Only very powerful apparatus can be used for masonry. Safety precautions have to be taken into consideration (Silman et al., 1993; Wenzel et al., 1993)
Infra-red thermo-graphy	ND IS	Identification of the layering of the structure (e.g.: hidden behind stucco), traces of hidden cavities and discontinuities (Silman et al., 1993; Wenzel et al., 1993)
Magnetic methods	ND IS	Locating of iron elements in thick masonry walls (e.g.: reinforcement bars, connection clamps,…) (Silman et al., 1993; Wenzel et al., 1993)
Radar	ND IS	Receiving of transmitted or reflected electric energy allows to identify different layers, hidden cavities, old foundations, … (Silman et al., 1993; Wenzel et al., 1993)
Mechanical pulse velocity	ND IS	By the impact, waves of 0.3-5.0 kHz are sent into the material. The wave velocity is a measure for the density and integrity of the material (Silman et al., 1993; Wenzel et al., 1993).
Ultra sonic	ND IS	Only useful for homogeneous materials, like natural stones. In case of heterogeneous materials (masonry) the penetration depth is too small.
Vibration tests	ND IS	Relative stiffness, control of possible progressive damage of the structure in time
Endoscopy	ND/SD IS	Check out of the inner structure of the masonry. Use in drilling holes. Can be combined with photographs or video images (Thomasen et al., 1993).
Flat jack	(S)D IS	Quantitative determination of the stress-strain relation of masonry (SD) and possibly also compressive strength (D) (Schaerlaekens et al., 1999)
Proof loading	ND IS	Check of the resistance of the structure for the expected loading. Is ND when the loading remains in the elastic area

Monitoring	IS	Permanent (automatic) data-acquisition of parameters that are of importance for the structural behaviour, such as: high accurate levelling devices (HLS), invar-wire measurements,…
Legend: D:**D**estructive; SD:**S**emi-**D**estructive; ND:**N**on-**D**estructive IS:**In** **S**itu; IL: **I**n **L**abo. Techniques used in Belgium are underlined		

In Belgium, research focuses on several monitoring techniques. The state of the art on some of these techniques is further outlined. Different test techniques are available to gather information about the quality of the masonry. Seen the increased emphasis on non-destructive test methods, focus is on these techniques.

3.1 Geo-electrical measurements

Two subsequent doctoral research programs have developed this technique into a practical applicable instrument. The first doctoral research (Janssens, 1993) calibrated the methodology for different configurations of potential and current electrodes. The subsequent research (Venderickx, 2000) focused on the influence of geometrical boundaries and the influence of physical parameters (humidity and salts). Practical applications (Church of Saint Mary, Brugge (B)) confirm that this test method is a valid way to obtain a qualitative image of the integrity of the masonry. It can be used not only to gather information on the initial state of the masorny. More often it is used to judge the quality of an executed grout injection (Schueremans et al., 2002; Van Rickstal et al., 2002). In practice, it did prove to be a convenient way to judge the executed consolidation by means of grout injection.

3.2 Load-cells

This monitoring technique is used to control the effect of new elements that are added to the structure. At the St. Jacobs Church at Leuven (B) the force was measured during installation of new trusses in the nave replacing a flying buttress (Smars, 2002), during the removal of the critical flying buttress and during post-tensioning of the trusses, **Figure 3.1**. The latter was done in combination with a continuous measurement of the distance between the walls in the nave that supports the vault.

***Figure 3.1:** load cell in truss and removal of flying-buttress*

3.3 High accurate levelling devices (HLS)

This monitoring technique based on the accurate measurement of the water level, has been used several times to obtain high accurate information on the relative movement of different points of an historic structure (Saint Jacobs Church, Leuven (B), 's Hertogenmolens water mills, Aarschot, (B)). This semi-automatic method can be used for a (mid)-long term period. The method has an accuracy of 0.01 mm. It has been used to measure the vertical movements of the foundation of the 's Hertogenmolens water mills at Aarschot (B), that is founded in the river Demer, **Figure 3.2**.

Based on these measurements (over a period of 6 months), it was seen that the main settlements were caused by temperature variations and the water level of the River Demer (Schueremans et al., 1999).

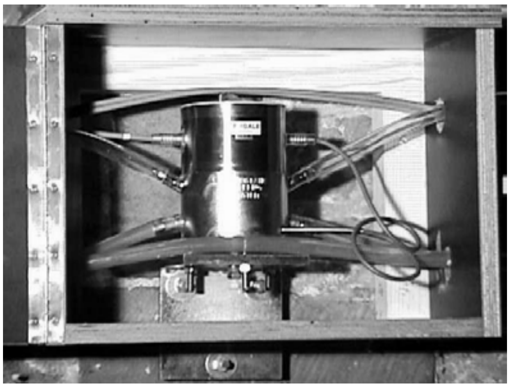

Figure 3.2: *HLS measurements, 's Hertogenmolens Watermills at Aarschot (B)*

3.4 Convergence measurements using invar-wire

Convergence measurements (using invar wire) are used for an accurate measurement of the distance between two materialized fixed points on a structure and the evolution of the distance in time. The accuracy that can be reached in practice is about 0.05 mm. Recently it is used in several practical applications, such as in the Church of Saint Mary at Tongeren, to check the stability of the pillars during aercheological excavation in the different naves of the church up to a depth of 4.0 m (Ignoul et al. 2002), **Figure 3.3**.

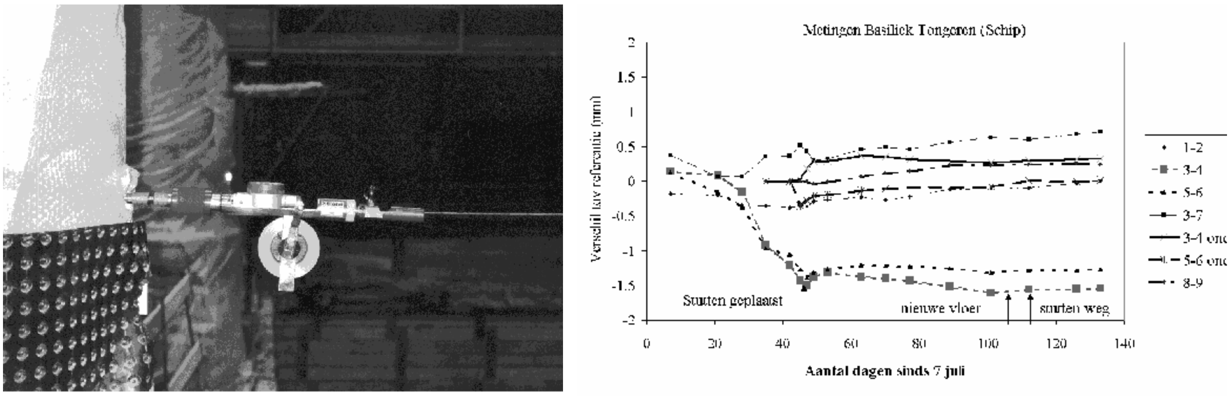

Figure 3.3: *Invar wire measurements at the Church of Saint Mary at Tongeren (B)*

3.5 Damage atlas and expert system

Visual inspection remains one of the most powerful methods to detect deterioration of different causes. Based on a European project, knowledge and typology of different types of deterioration processes of masonry has been collected, inventarised and illustrated with case studies. These can be used as a reference guide during visual inspection (Van Balen, 1998). The aim of the project is to improve knowledge of the effects that environmental factors have on damage to Europe's Cultural heritage and to guarantee better treatment and protection of this heritage by placing an expert system including a damage atlas at the disposal of those professionals involved in analysing ancient buildings.

3.6 Fotogrammetry and VIRTERF

At this moment many architects involved in conservation still work in the traditional way. They use hand-measured (tapes, plumb-bobs, levels...) or instrument based (theodolite, total station, photogrammetry) survey methods. This information is usually transferred to 2D paper drawings: plans, sections and facades. The main drawback of this approach is that all information is distributed in different types of documents (2D drawings, texts, photographs...). This makes it often very difficult for policy makers, engineers or other persons involved in one particular phase of the process, to get a complete and unambiguous overview of the available information. In addition, it is very difficult to use this material for exchange with other architects or researchers (for comparative studies...) or for distribution to the public (publications in periodicals, tourist information...).

As many architects are shifting towards computer-aided design for new buildings, they also try to apply these programs to renovation or conservation projects. However, the number of tools available to accomplish the task of 'getting the existing building in the CAD program' is limited, and mainly directed to 'translate' traditional methods to CAD (automatic import of full station co-ordinates, error-adjustment of triangulation...). Based on a limited number of actually measured points, 2D plans and sections or a 3D model can be constructed. This typically results in a very 'simplified' representation of the building, which is absolutely not in line with the high requirements for conservation purposes.

Since september 1999 a project was funded by the Flemish Community via the STWW program of IWT. The official title of this research project is *"Three dimensional digital information system for the documentation, representation and conservation of our architectural heritage."* The abbreviation VIRTERF refers to Virtual Heritage (in dutch) (Kris Nuyts, 2001; htttp://www.virterf.asro.kuleuven.ac.be).

This project aims at developing a technology that, using recent developments in computer vision and reverse engineering, enables the operator to build up an accurate three dimensional model - without too much annoying work - starting from photos of the objects and measured reference co-ordinates. This model can in a later phase be used as a core for a multimedial database, to represent designs for interventions, or for distribution to the wider public.

3.7 Simple monitoring techniques, groups of monitoring techniques

Research not only focuses on complex monitoring techniques, but also on the quality of the information that can be gathered from simple tools such as tell-tales or crack opening sensor. These can be handled with ease, and are far less expensive. Experience on their applicability and reliability is built form the numerous case studies in which they are used.

Moreover, information is looked for on what monitoring technique offers what information and which (group of) techniques are required to obtain the required information (Schaerlaekens et al., 1999). Procedures on how the different monitoring techniques are used, what information these deliver and how to combine techniques is subject of a technical committee, organised by the BBRI, that will result in printed guidelines very soon “Procedures for the restoration of outer walls”.

3.8 Flat jack

The use of flat-Jack as a non-destructive testing methods has been extensively researched (Schaerlaekens et al., 1999). When a good calibration procedure is followed, this technique provides reliable quantitative information on the in site stress-strain relationship of the masonry. Using a double flat-jack test-setup, the compressive strength of the masonry can be determined.

3.9 Test methods for wood - Resistograph

The focus is on the measurement of the resistance of the wood using a fine needle that is drilled into the wood, with constant velocity, **Figure 3.4**. The force required to maintain the pre set velocity, is a measure for the quality of the wood. A similar technique exists in using a constant drilling force and measuring the velocity of the needle penetrating the wood (Ignoul et al., 2001).

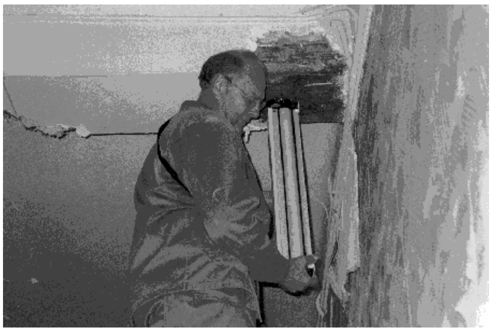

Figure 3.4: *Resistograph*

4. Analysis and Diagnosis

To answer the question, how far is the structure from failure, or what are the reasons for the observed damage, more than standard design techniques are required. When an assessment is performed, the limit state functions are needed. EC1 requires that for each relevant limit state verification, a design model shall be set up. In several cases the border between the safe and unsafe region can be expressed analytically, in other cases a numerical model or finite element model will be necessary. These models should be an appropriate description of the structure, the constitutive materials from which it is made and the relevant environment or boundary conditions.

4.1 Constitutive models for masonry

For the **analytical models**, the accent is on masonry in compression. Because a vertical load will never act perfectly central, the effect of excentrical loading is dealed with in detail. Besides non-tension materials (NTM), f_t =0, the influence of a limited tensile strength is accounted for as well as the effect of plastic behavior, that is often encountered in practice when lime mortars have been used (Schueremans, 2001).

Columns and walls act in compression by developing vertical compressive stresses according to the vertical forces that are applied. Arches, vaults and cupolas withstand vertical loading by developing compressive stresses along their shape (Beckmann, 1994). In that, the same models can be adopted, when the position of the thrust line is known. Indeed, in practice most arches are built with stones or bricks, with or without mortar joints. Therefor, the material behaviour is similar. The safe theorem for an arch reads (Der Kooherian, 1952; Heyman, 1966): „if a thrust line can be found which is in equilibrium with the external loads and which lies wholly within the masonry, then the structure is safe“. Extensive research has been conducted in this area by Pierre Smars (Smars, 2000). His doctoral research led to a user-friendly software application „*Calipous*“ that calculateds thrust lines in arches, based on the NTM material model concept as well as safety facors.

For masonry shear walls and walls subjected to lateral loading, elementary design (analytical) models are available in EC6. From experimental research however, it is seen that the material behavior is more complex (Vermeltfoort et al., 1993; Van der Pluijm, 1999). Therefor, more complex numerical models become a valid alternative.

The **finite element** methodology that is used for masonry mainly is based on the behavior of quasi-brittle materials. In most cases, these models are (closely) related to the constitutive models used for concrete or rock material. Both distinct element methods (DEM, such as: Udec (Roberti and Spina, 2001)) as well as Finite Element Methods are used (FEM). For the latter, two commercial software packages are mainly used in Belgium:

Atena2D (Cervenka Consulting, 2001) and *Diana 7.2* (Diana, 1998) which is developed at the TUDelft (Nl). Most of the codes are developed for research purposes (*Mason*: Lee et al., 1996; *Strumas*: Sicilia et al., 2000). A state of the art report of available FEM en DEM codes was made up in 1997 (Schaerlaekens and Schueremans, 1997) (*Abaqus*, *Adina*, *Algor*, *Ansys*, *Cosmos*, *Marc*, *Msc-Nastran*, *Microfield*, *Samcef*, *Systus*).

Masonry is a material that exhibits distinct directional properties due to the mortar joints which act as planes of weakness. In general, the approach towards its numerical representation can focus on the micro-modelling of the individual components, or the macro-modeling of masonry as a composite. Depending on the level of accuracy, the simplicity desired and the application field, it is possible to use the following strategies (Lourenço, 1996; TC MMM N9, 2000 [TC MMM-N9: RILEM Technical Committee, Mechanical Modelling of Masonry]):

detailed micro-modeling: units and mortar joints are represented by continuum elements whereas the unit-brick interface is represented by discontinuous elements,

simplified micro-modeling (meso-model): expanded units are represented by continuum elements whereas the behavior of the mortar joints and unit-mortar interface is lumped in discontinuous elements. These interface elements represent the preferential crack locations where tensile and shear cracking occur,

macro-modeling: units, mortar and unit-mortar interface are smeared out in the continuum.

Macro-models, **Figure 4.1**, are applicable when the structure is composed of solid walls with sufficiently large dimensions so that the stresses across or along a macro-length will be essentially uniform. Clearly, macro modelling is more practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation. This type of modelling is most valuable when a compromise between accuracy and efficiency is needed (TCMM N9,2000).

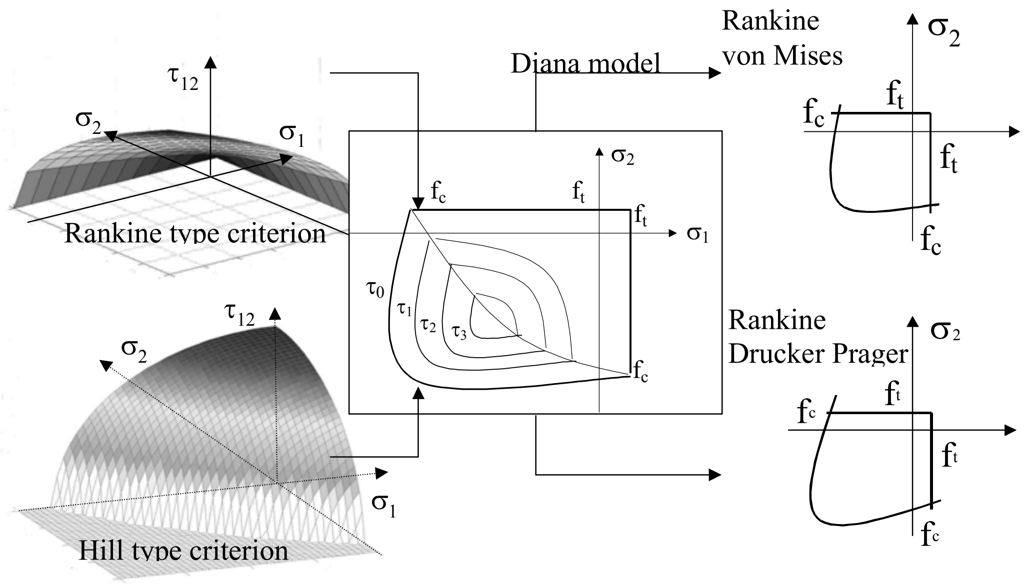

***Figure 4.1**: Rankine and Hill-type yield surfaces for masonry composite material implemented in Diana (Diana, 1999)*

4.2 Evaluation methods - different levels to assess a structures' safety

Nowadays, powerful methods are available for the calculation of structural safety values. These permit to calculate the global probability of failure of complex structures, relying on deterministic techniques – see above - able to determine the stability state for a prescribed set of parameters. The Joint Committee of Structural Safety, defines four levels at which the structural safety can be assessed (JCSS 1982, Melchers, 1999), **Table 4.1**. Level IV adds economical data to the level I, II or III methods to obtain maximum benefits and minimum costs. The other three levels were adopted in the European Standard Eurocode 1 (EC1, 1991). Level III methods are the most accurate. Level I and level II methods are simplified approaches introduced for computational reasons. Ideally, they should be calibrated using a level III method.

In the anamnesis and analysis phase, an objective way to assess the safety of the structure is essential. The present raises the need for a reliability based assessment framework for existing masonry structures (Diamantidis, 1999, 2001), **Figure 2.1**.

***Table 4.1**: Different levels for the calculation of structural safety values (EC1, 1991; JCSS, 1982)*

Level	Definition
Level III	Level III methods such as Monte Carlo (**MC**) sampling and Numerical Integration (**NI**) are considered most accurate. They compute the exact probability of failure of the whole structural system, or structural elements, using the exact probability density function of all random variables.
Level II	Level II methods such as **FORM** and **SORM** compute the probability of failure by means of an idealization of the limit state function where the probability density functions of all random variables are approximated by equivalent normal distribution functions.
Level I	Level I methods verify whether or not the reliability of the structure is sufficient instead of computing the probability of failure explicitly. In practice this is often carried out by means of partial safety factors.
References: Eurocode EC1, Annex A; Joint Committee of Structural Safety 1982	

Reliability-based assessment deals with estimating the actual reliability level for a certain reference period based on all the information that can possibly be gathered from the existing structure. It is in the detailed analysis phase, that reliability based assessment fits into the framework. It is meant as an objective manner to assess the safety of the existing building, taking into account all kinds of uncertainties inherent to the structures' state. In that it is an objective tool in the decision process. The objective in the prognosis phase is similar (reliability based design). It is meant as a tool to compare possible restoration options, to identify critical parameters and to derive an optimal solution, again accounting for all kinds of (future) uncertainties, such as future loading.

Extensive research has been conducted in this area (Schueremans, 2001; Waarts, 2000) that leads to practical applicable tools to calculate the failure probability of a structural system. More applied research is going on for this moment. Current research focuses on the development of the probabilistic procedure to increase efficiency and to increase the applicability towards less-specialised engineers (Schueremans, "Use of *Splines* and *Neural Networks* in structural reliability – new issues in the applicability of probabilistic methods for construction technology", ongoing research 2002). Complementary research is conducted by S. Ignoul, "Structural safety of historical masonry", that focuses on the influence of time dependent behaviour on the modelling of masonry and the risk analysis (Ignoul, ongoing research 2002). Target is to build design models and see how these models can be calibrated with long term data gathered from data-acquisition (forces, deformations, etc.) in situ.

4.3 Material properties

A large number of monuments and buildings are made out of brick/stone masonry. A lot of research effort goes to the material behaviour of the components and composite material.

Parallel to the evolution in design methods (from level 0: elastic methods tot level III probabilistic methods), numerical models tend to be more representative for the real material behaviour, but only if the extra experimental information needed as input is available. Often more parameters are required, which puts an increased emphasis on experimental research.

In addition, the number of test samples should be increased in order to estimate the probability distribution functions that are representative for the uncertainty on the material properties. When a probabilistic evaluation method is used, the material properties are defined as random variables. This is done to examine the effect of the material property uncertainty on the failure probability of the whole structure. Using masonry, additional uncertainties are traced when compared to steel or wood. Masonry is a composite material. It is built from bricks and mortar following a certain (ir)regular framework. Relatively large test samples are needed to retrieve the material properties of the composite material. Moreover, evaluation deals with existing structures, not with design of a new masonry structure, adding a major difficulty in gathering consistent information. Of course, the theorem of minimum destruction applies (Krakow, 2000).

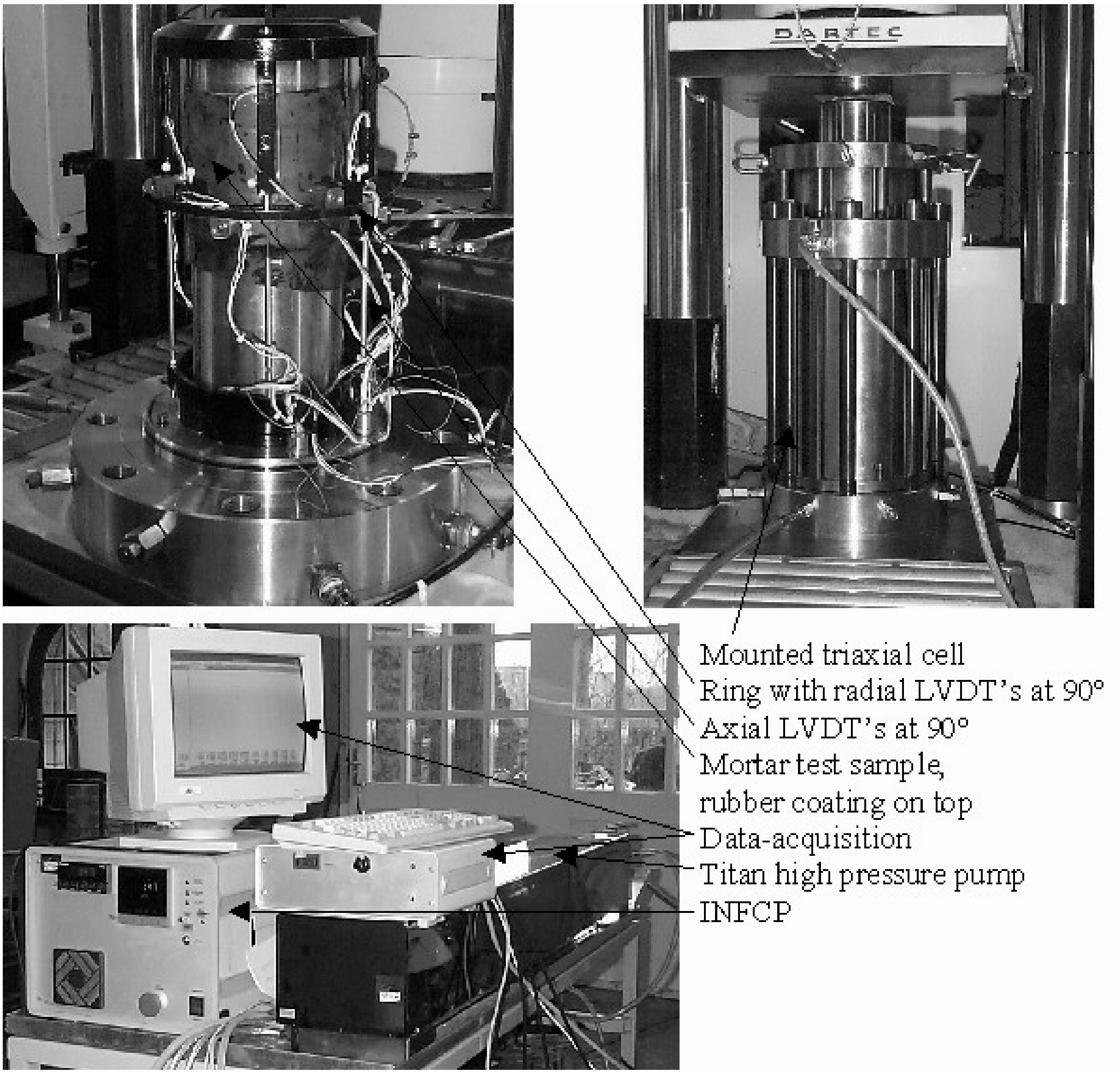

Figure 4.2: *Triaxial cell – research of material behaviour subjected to a lateral confining pressure*

As for the **mortar**, research is conducted in the field of:

- the material behaviour of historical (lime) mortars (Hayen et al. 2001), the relationship between their fysical and chemical properties and the carbonation processes (Van Balen, 1981; Hayen, 1999). The research concerns both mortar for jointing and pointing.
- the material behavior in multi-axial stress state (Hayen, 1999; Schueremans et al., 2001). For that research purpose, the Laboratorium Reyntjens (KULeuven) acquired a triaxial cell, capable of testing large test samples at low confining pressures, **Figure 4.2**. The confining pressure on the test samples simulates the stress-state induced by the brick-mortar interaction. From this research it is seen that:
  - the classic brittle behaviour shifts towards a plastic-flow when the confining pressure increases with increasing confining pressure,
  - a compressive strength increase with even for small confining pressure

- material failure ranges from shear failure to pore collapse (a change in pore structure is evidenced) ,
- there are no significant differences in material behaviour between pure lime mortar, cement mortar and hybrid mortar
- a biaxial yield criterion is established.

As part of repair and strengthening technique, the rheological, physico-chemical and mechanical properties of lime based **multi-blend grouts** are studied (Toumbakari et al., 1999). Many historical buildings are built with multi-leaf masonry walls. The consolidation and strengthening of these multi (three)-leaf masonry is the subject of a doctoral research that will be finalised at the fall of this year (Toumbakari et al., 2000; Toumbakari, 2002). The research focuses on the use multi-blend grouts (lime, cement, puzzolanes) to increase the chemical and physical compatibility with the original material (joints and infill material). The stability, fluidity, and mechanical properties of several compositions are compared to achieve optimal rheological properties and compatibility with the masonry to be injected.

As for the **masonry**, an answer to the following questions covers the main research activities in Belgium:

- what is the variability of the composite masonry (distribution type and parameters (Schueremans, 2001)),
- can the material properties of masonry be estimated from the components brick and mortar using existing test methods and numerical relationships (Schueremans, 2001; Hayen, 2000; Schaerlaekens and Schueremans, 1999),
- are these test methods adequate to gather this information in site from an existing building ?

Based on experimental research filled out with numerical relationships and literature values, reliable probability distributions and parameters can be retrieved for the most common material properties, required to feed the numerical models (Schueremans, 2001).

5. Therapy

5.1 Grout injection

For consolidation, strengthening and repair of masonry, different techniques are available, amongst which the technique of grout-injection. The influencing parameters such as mechanical properties, stability of grout, bleeding, penetrability and fluidity have been studied in detail (Van Rickstal, 2000). Main achievements of this research are:

- the importance of technological options on the effectiveness of the consolidation is given (use of separate mixing installation in addition to the collector, a three way valve with return pipe and constant pressure at the inlet)
- a new method is developed for testing the stability of grouts and its evolution in time
- development of a reproducible masonry sample that creates conditions that are very near to reality of masonry, to check the injectability of different grouts and their water retaining properties
- different blocking mechanisms were observed from experiments
- a model has been built that enables the simulation of the grout inside the masonry. This model is based on three pillars: the study of literature about grout penetration inside the

masonry, the theory about the rheology of dispersion and about flow of fluids through porous materials and finally an experimental program. Numerical methods are used for the mathematical description of the flow of Newtonian and Bingham fluids inside channels. Main results obtained of parameter study are:

- decreasing the critical shear stress of the grout is recommended instead of increasing the injection pressure,
- sealing a leakage has to be done as soon as possible
- the injection hole should preferable be in contact with a major crack

5.2 External reinforcement of reinforced concrete structures

Of course, masonry is not the only material encountered in restoration practice.

Reinforced concrete structures may suffer from degradation for example caused by chloride attack (Poupeleer, 2001; Schueremans et al., 1999). Research on strengthening techniques focus on external strengthening of reinforced concrete structures using steel plates or carbon fibre reinforced plastics (CFRP). Recently, three Ph. D. researches have been finished concerning externally bonded steel or non metallic (FRP-laminates) to strengthen concrete structures (Matthys, 2000; Ahmed, 2000; Brosens, 2000).

This research responds to an increasing demand from practice. Externally bonded steel plates are used in Belgium since 1970. Nowadays, externally bonded CFRP-laminates are used more often. Parallel to practice, the need for more fundamental research became clear. With these researches, a thorough basis is available to support practical applications guidelines and practice.

Main achievements of this research are (Ahmed, 2000; Brosens, 2001; Matthys, 2000):

- use of non-metallic materials (use of fiber reinforced plastics)
- fire resistance
- extensive experimental research supporting the design models,
- different failure modes are addressed (bending, shear failure, premature delamination, plate end shear failure, …)
- design of the cross-sectional area is based on the combination of bending and shear
- design of the anchorage zone, mechanical anchorage,
- clear distinction between the application area of steel plates and CFRP-laminates

Figure 5.1: *External reinforcements using steel plates and CFRP (Library, Leuven, (B))*

Ongoing research focuses on the improvement of fire resistance (RUG), ductility design models for mechanical anchorage at the end zones (KUL) on the one hand and on guidelines and certification on the other side (WTA referat 5 beton, Arbeitsgruppe 5.18, KUL).

5.3 Strengthening of wooden structures

Similar techniques can be used for wooden structures (Desmidt, 1990; Horckmans, 1988; Ignoul et al., 2001; Schueremans et al., 2001). Strengthening of wooden structures became common practice in Belgium, Figure 5.2. Main strengthening techniques used are:

- replacement of wooden beam end by an epoxy mortar/wooden prosthesis,
- strengthening of wooden beams for increased loads (shear, bending), with internal or external reinforcement plates or bars from metallic or non-metallic material (wood, FRP) or with additional external reinforcing structures

Figure 5.2: *Reinforcement of wooden beam (Quartier Des Célestines, 1998)*

Guidelines for design and practice are published recently (Ignoul et al., 2001).

6. Conclusions

An rough overview of the different parties involved in the preservation of historical structures is given. The state of the art in Belgium in (applied) research and practice is presented by means of the different steps in the preservation process. Often used monitoring techniques are listed and recent developments presented. In the analysis phase, the constitutive models are addressed. Some typical topics are highlighted on the material behaviour and material properties required in these models. The different levels at which a safety assessment can be performed are presented, as well as a state of the art the probabilistic evaluation methods available. The last chapter treats the different consolidation and strengthening techniques. No only masonry is addressed, but also wood and concrete.

7. References

[1] Ahmed O., „Strengthening of RC beams by means of externally bonded CFRP laminates – improved model for plate and shear“, Ph. D. Thesis, KULeuven, 1999.

[2] Beckmann, P., “Structural aspects of building conservation”, Mc Graw-Hill, International Series in Civil Engineering, 286 pages, 1994.

[3] Brosens K., “Anchorage of externally bonded steel plates and CFRP laminates for the strengthening of concrete elements”, Ph. D. Thesis, KULeuven, Department of Civil Engineering, 2001.

[4] Cervenka Consulting, “Atena Computer Program for Nonlinear Finite Element Analysis of Reinforced Concrete Structures - Program Documentation -Part I: Theory”, 2001.

[5] Charter of Krakow, “Principles for conservation and restoration of building heritage”, Krakow, 2000.

[6] Croci G., “The conservation and Structural restoration of architectural Heritage”, Computational Mechanics Publications Southampton, 251 pages 1998.

[7] Der Kooherian A., “Limit analysis of voussoir (segmental)and concrete arches”, Journal of the American Concrete institute, Vol.24, No.4, pp. 317-328, 1952.

[8] Desmidt I., “Structurele restauratie van hout. Het vervangen van een balkkop door een epoxymortel prothese - Deel III”, Thesis, KULeuven, Department of Civil Engineering, 1990.

[9] Diamantidis D., “Assessment of Existing Structures”, Joint Committee of Structural Safety JCSS, Rilem Publications S.A.R.L., The publishing Company of Rilem, 159 pages, 2001.

[10] Diamantidis D., “Koordination und Entwicklung eines probabilistischen Sicherheidskonzepts für neue und bestehende Tragwerke”, T2881, Fraunhofer IRB Verlag, 1999.

[11] Diana, “Diana 7.2 - Reference Manual”, *Diana* Release 7.2, TNO Building and Construction Research, Delft, The Netherlands, 1999.

[12] EC1, “Eurocode 1: Basis of design and actions on structures - Basis of design”, CEN, ENV 1991-1, 1994.

[13] Hayen R., “Triaxial interaction of natural stones, bricks and mortar joints in historic masonry. Experimental and analytical approach”, Master Thesis, KULeuven, 1999.

[14] Hayen R., Schueremans L., Van Balen K. and Van Gemert D., “Triaxial behavior of historic masonry”, The Fifth International Symposium on Computer Methods in Structural Masonry, 18-20 April, Rome, pp.151-160, 2001[a].

[15] Heyman J., “The stone skeleton”, International Journal of Solids Structures, Vol. 2, pp. 249-279, 1966.

[16] Horckmans J., “Structurele restauratie van hout. Het vervangen van een balkkop door een expoxymortel prothese - Deel I”, Thesis, KULeuven, Department of Civil Engineering, 1988.

[17] Icomos, “Recommendations for the analysis, conservation and structural restoration of architectural heritage”, ICOMOS, International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage, Draft Version n°11, September, 2001.

[18] Ignoul S., Maertens J., Loosen W., “Standzekerheidsanalyse van historische gebouwen: Eenvoudig, nauwkeurig en betrouwbaar meten van horizontale bewegingen met het convergentiemeetapparaat, ICOMOS, studiedag, Gent, 2002.

[19] Ignoul S., Schueremans L. and Van Gemert D., “Houtherstelling”, Handboek Onderhoud, Renovatie en Restauratie, Hoofdstuk II, Kluwer Editorial, in press, 2001.

[20] Janssens H., “Geo-electrische controle van consolidatie-injecties in historisch metselwerk”, Ph. D., KULeuven, 1993.

[21] JCSS, “General principles on reliability for structural design”, Joint Committee of Structural Safety, 1982.

[22] Lee J.S., Pande G.N., Middleton J. and Kralj B. , “Numerical modelling of brick masonry panels subject to lateral loadings”, Computers & Structures, Vol. 61, pp. 735-745, 1996.

[23] Lemaire R.M. and Van Balen K., "Stable-Unstable: structural consolidation of ancient buildings", Center for the conservation of historic towns and buildings, KULeuven, Leuven University Press, 344 pages, 1988.

[24] Lourenço P.B., "Computational Strategies for Masonry Structures", Doctoral thesis, TU Delft, Netherlands, 206 pages, 1996.

[25] Matthys S., „Constructief gedrag en ontwerp van betonconstructies versterkt met uitwendig gelijmde vezelcomposietwaqpening", Ph. D. Thesis, RUG, Ghent, 2000.

[26] Melchers R.E., "Structural Reliability, Analysis and Prediction", Ellis Horwood Series in Civil Engineering, 1999.

[27] Poupeleer Anne-Séverine, "Analyse van de diffusie van chloride-ionen in gewapend betonnen structuren ter beoordeling van de corrosie problematiek van de wapeningen", ongoing doctoral research, 2001.

[28] Roberti G.M. and Spina O., "Discrete element analysis on the Sardinian 'Nuaraghe'", STRUMAS V, International Symposium on Computer Methods in Structural Masonry, Rome, April, 2001.

[29] Rosiers M., Van Cayseele P. and Van Meerbeek W., "De financiering van de restauratiebehoefte", Brussels, Koning Boudewijn Stichting, 100 pages, 1998.

[30] Schaerlaekens S. and Schueremans L., "IWT-project: Restauratie van buitenmuren - Typologie en procedures, deel 3: standzekerheid", Chapter 3, pp. 3/1-3/141, 1997.

[31] Schaerlaekens S., De Bruyn R., Van Gemert D. and Schueremans L., "Restauratie van buitenmuren: beoordelen van oud metselwerk", WTCB Tijdschrift, Vol. 2, pp. 3-13, 1999.

[32] Schueremans L. and Van Gemert D., "Structureel gedrag. Metselwerk", Kluwer, Handboek Onderhoud, Renovatie en Restauratie, II.2, Afl. 5, pp. 49-98, 2000.

[33] Schueremans L., „Probabilistic evaluation of structural unreinforced masonry", Ph. D. Thesis, KULeuven, 2001.

[34] Schueremans L., Hayen R., Van Gemert D. and Van Balen K., "Triaxial testing of masonry and lime mortars, test setup and first results", 5th Internationales Colloquium, Materials science and Restoration - MSR '99, December 1999[b].

[35] Schueremans L., Ignoul S. and Van Gemert D., "Structureel gedrag. Hout", Handboek Onderhoud, Renovatie en Restauratie, Hoofdstuk II, II.2., pp.1-48, Kluwer Editorial, 2001.

[36] Schueremans L., Van Balen K., Hayen R., Peeters V. and Wittouck R., "The 's Hertogenmolens water mills, monitoring of a historical monument for assessment of structural safety", 5th Internationales Colloquium, Materials Science and Restoration - MSR '99, December 1999.

[37] Schueremans L., Van Gemert D. and Beeldens A., "Accelerated chloride penetration test as a basis for service life prediction model for R/C constructions", Sheffield, pp.1269-1280, June 28-July 2, 1999.

[38] Schueremans L., Van Rickstal F., Van Gemert D. and Venderickx K., "Evaluation of masonry consolidation by geo-electrical difference mapping", RILEM, Materials and Structures, 2002.

[39] Sicilia C., Pande G. and Hughes T., "Numerical modeling of masonry arch bridges", Strumas, International Symposium on Computer Methods in Structural Masonry, Rome, April, 2001.

[40] Silman R. and Ennis, M., “Non-Destructive Evaluation to Document historic Structures”, Zurich, International Association for Bridge and Structural Engineering (IABSE), pp. 195-203, 1993.

[41] Smars P., “Etudes sur la stabilité des arcs et voûtes”, Ph. D. Thesis, KULeuven, Department of Civil Engineering, Faculty of Applied Sciences, Centre Raymond Lemaire pour la Conservation”, 229 pages, 2000.

[42] Smars P., “Study of the St. Jacobs Church at Leuven”, ongoing research, unpublished, 2002.

[43] Thomasen S.E., Sears C.L., “Historic preservation. High and Low tech diagnostic technology”, Zurich, International Association for Bridge and Structural Engineering, pp. 91-98, 1993.

[44] Toumbakari E., Van Gemert D. and Tassios T.P., “Multi-blend cementitious injection grouts for repair and strengthening of masonry structures”, International Congress Creating with concrete, Dundee 6-10 September, Specialist techniques and materials for Concrete Constructions, Ed. Dhir and Henderson, Thomas Telford, pp. 79-91, 1999.

[45] Toumbakari E.E., Vintzileou E., Pisano F. and Van Gemert D., “Experimental investigation of three-leaf masonry walls”, Proc. 1st National Congress on “Mild interventions and protection of historic structures”, Thessaloniki, Greece, 23-25 November 2000.

[46] Toumbakari, E.E., „Development of high-penetrability Lime-Pozzolan-Cement grouts and the study of their effect on the mechanical behaviour of masonry composite walls“, ongoing doctoral research, to be presented, 2002.

[47] Van Balen K., “Karbonatatie van kalkmortel en haar invloed op historische strukturen”, Ph. d. Thesis, Centre for the conservation of historic towns and buildings, KULeuven, 1991.

[48] Van Balen K., “Methodologies for the monitoring of degradation in view of the selection of treatment strategies - expert system for evaluation of deterioration of ancient masonry structures”, Dahlem Conferences, Berlin, 1998.

[49] Van Balen K., Mateus J., Binda L. and Baronio G., “Expert system for the evaluation of the deterioration of ancient brick structures - scientific background for the evaluation of the deterioration of ancient brick structures”, European Community, Energy, Environment and sustainable development, Research report No. 8, Vol. 1, 1997.

[50] Van de Vijver D., “Les relations franco-belges dans l’architecture des Pays-Bas méridionnaux, 1750-1830", Ph. D Thesis, KULeuven, Department of Architecture, Civil Planning and Environmental Organisation, 2000.

[51] Van der Pluijm R., “Out-of-Plane Bending of Masonry, Behaviour and Strength”, Ph. D. Thesis, TUDelft, The Netherlands, 1999.

[52] Van Rickstal F. Van Gemert D., Claes R., “Niet destructief onderzoek als ondersteuning bij restauratie van metselwerk - Electrische resistiviteit, WTA Nederland-Vlaanderen, Scheuren in metselwerk en pleisters, Studiedag, 19 april, 2002.

[53] Van Rickstal F., “Grout injection of masonry, scientific approach and modeling”, Ph. D. Thesis, KULeuven, Department of Civil Engineering, 2000.

[54] Venderickx K., “Evaluatie van geo-electrische metingen op metselwerk”, Ph. D. Thesis, KULeuven, Department of Civil Engineering, 1999.

[55] Vermeltfoort A. Th. and Raijmakers T.M.J., “Deformation controlled tests in masonry shear walls, Part 2", Report TUE/BKO/93.08, Eindhoven, University of Technology, Eindhoven, The Netherlands, 1993.

[56] Waarts P.H., “Structural reliability using finite element analysis”, Ph. D. Thesis, TUDelft, The Netherlands, June 2000.

[57] Wenzel F., Kahle M., “Indirect methods of investigation for evaluating historic masonry”, Zurich, International Association for Bridge and Structural Engineering (IABSE), pp. 75-90, 1993.