New Technologies for Safeguarding cultural Heritage– 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 text provides a global overview of the state of the art in (applied) research and practice. However, the text focuses on new techniques for the diagnosis of damage and the monitoring and control of the quality of restoration (non-destructive testing), the development of new building materials and revolutionary techniques for reinforcing existing concrete and masonry structures.

To complete the overview of the research activities, a probabilistic approach for the evaluation of masonry is presented.

The main point of research activities in the field of restoration concerns masonry structures. But gradually concrete structures will be considered being part of cultural heritage. Degraded wooden parts are frequently present in valuable historic buildings and hence attention is paid to the restoration of both materials.

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.

3. Using non-destructive testing to support restoration

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). A variaty of monitoring techniques, simple, complex or combinations of both, can deliver a lot of information, and often are a far less destructive option.

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 Overview of available techniques

3.1.1 Radiography

The screening of elements with gamma radiation reveals hidden discontinuities like reinforcement, holes, anchors or cracks. Accessibility on both sides is a necessary condition. Only the most powerful equipment is usable for masonry or concrete because of the attenuation of the gamma rays. This requires severe safety regulations. As such the technique is mainly valid for controlled circumstances in the laboratory.

3.1.2 Infrared thermography

A crack is a local discontinuity that hinders the conduction of heat. By heating the wall locally, a thermal camera is able to bring into vision these discontinuities. The method gives good results in case of large cracks close to the surface. Therefore, the method could work in case of rendering or stucco that is coming loose.

3.1.3 (Ultra) sonic research

This NDT-technique uses sonic waves from the audible spectrum (sonic) of the higher frequency range (ultrasonic). A longitudinal sonic wave is send through the material. Since the wave reflects on all kind of heterogeneities the analysis of the reflected waves provides a confusing image. Therefore most of the time the transition speed is recorded. The speed of the sound wave depends upon the materials' properties. Since internal loss of coherence forces the sound to follow a longer way or to pass through a layer of air, the transition time increases. Figure

1 shows a wall that consists of two prefabricated concrete parts that are filled up with concrete. The responsible man on site had a suspicion that the filling up of the prefabricated wall was inadequately done and requested the Reyntjens laboratory to investigate the wall. Fig. 2 shows the transition time as measured on the wall. The light zones show a transition time of about 60 to 90 µsec. The darker the greyscale, the higher the transition time and the worse the filling of the zone between both faces. These zones are injected with epoxy resin to ensure perfect contact between the faces and the poured concrete.

Fig. 1: The investigated wall consists of two prefabricated faces filled up with poured concrete. The raster shows the measruing points.

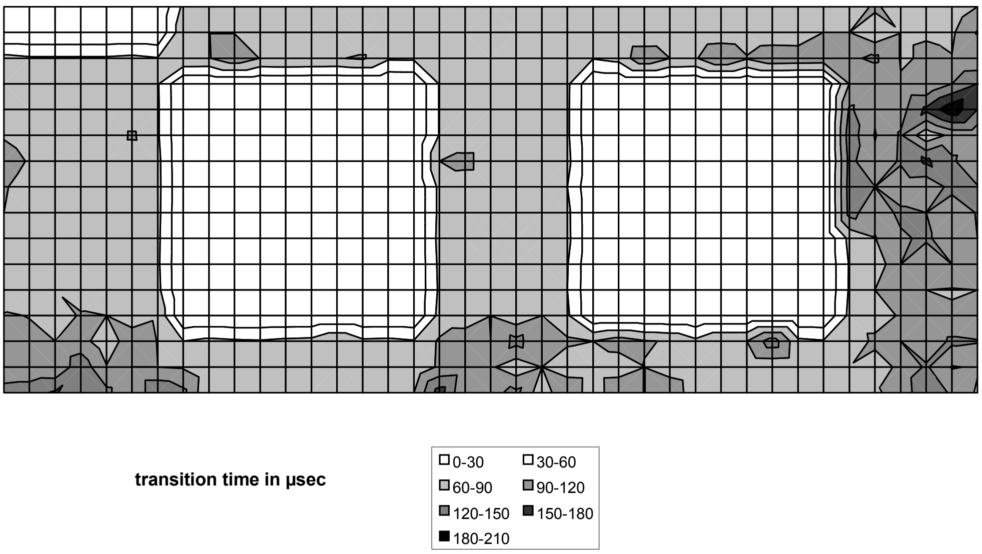

Fig. 2: The map of the transition time displays the zones that were inadequately filled up.

The investigated structure needs to be accessible from both sides. Furthermore, the wave attenuates quite fast. Acoustic tomography is an enhanced version of the same technique. By combining a variety of measuring points, a picture of the transition time of the complete cross surface of the wallet is obtained. Figure 3 shows an image of a masonry wallet that was measured before loading (a), after loading and cracking (b) and after repair by means of grout injection (c). The internal cracks caused by overloading the wallet, bring about a fanciful picture. After repair the picture is almost as uniform as I used to be before cracking.

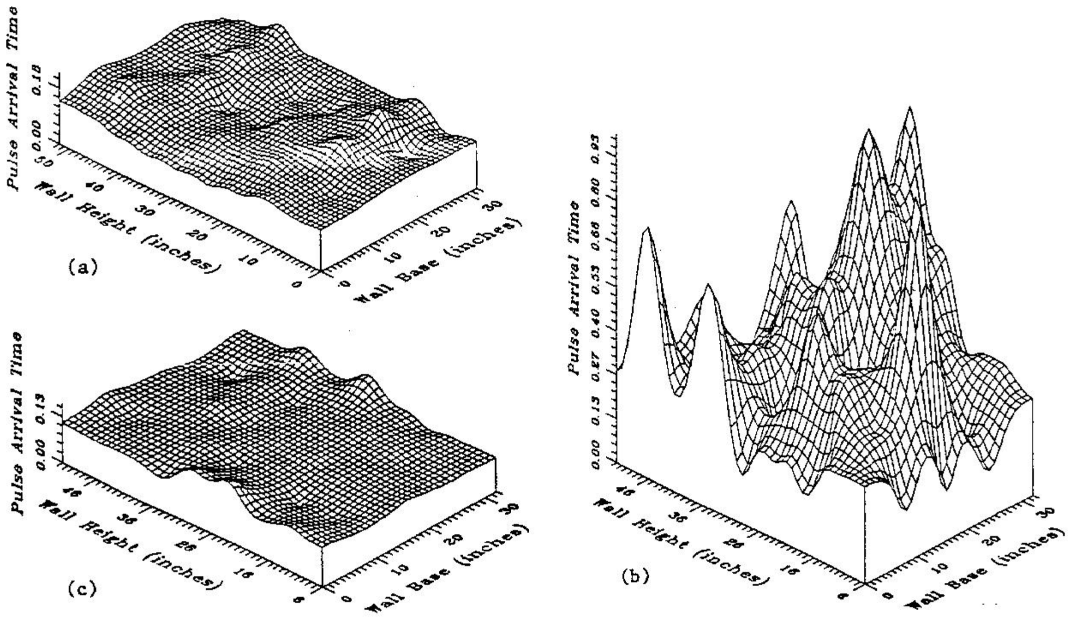

Fig. 3: Using a suitable combination algorithm, (ultra) sonic measurements can detect and locate the internal crack pattern. The technique proves to be a good control method for the reparation.

3.1.4 Soil penetration radar

This technique is entering the field of non-destructive testing of buildings. The method as such has been taken from soil investigation. The method is developed in order to detect borders or transitions between different layers. This way the technique can be adapted to the needs of non-destructive testing of masonry structures. The principle of the method is relatively simple. An antenna sends a radar wave into the material and the reflected signal is analysed. Internal cracks or transitions between different materials reflect the radar wave. Knowing the speed of the waves, the depth of the transition can be calculated. By moving the transmitter, a surface can be scanned. The processed signals are called a profile. The shape and the position of the reflections inform the researcher about the inner state of the structure.

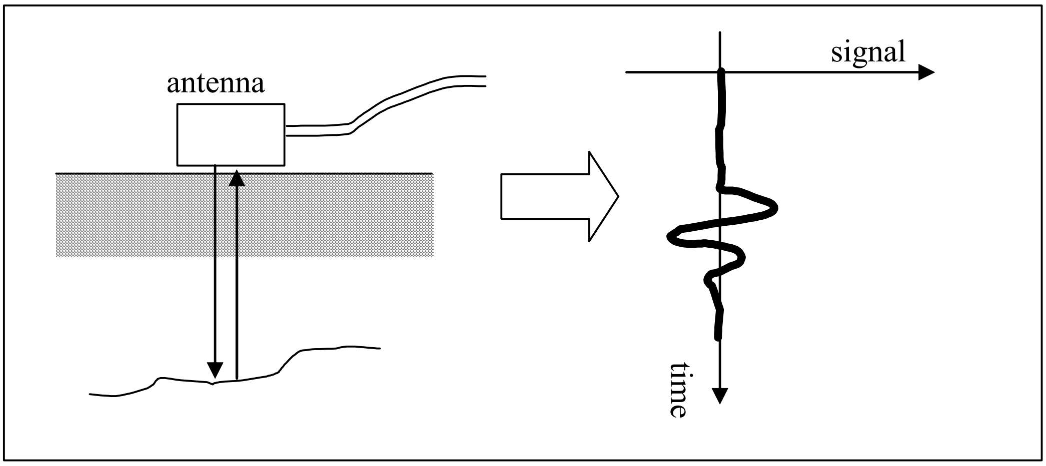

Fig. 4: Principle of the radar method

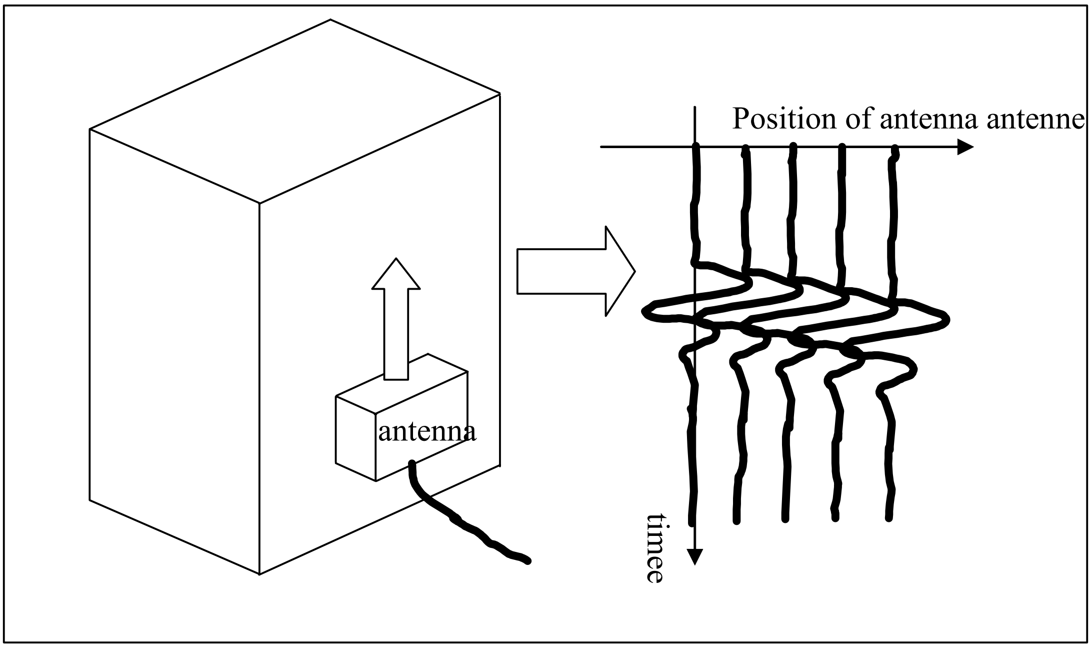

Fig. 5: Profiling a surface using the radar method

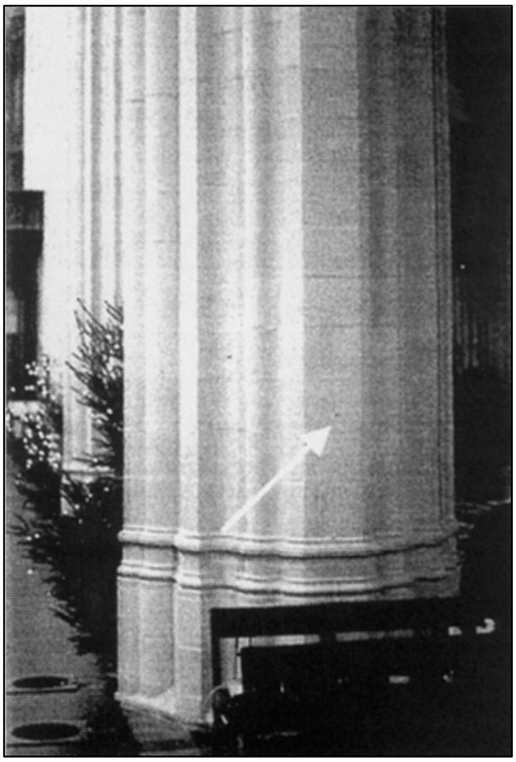

Fig. 6: Column and location where the radar method was carried out

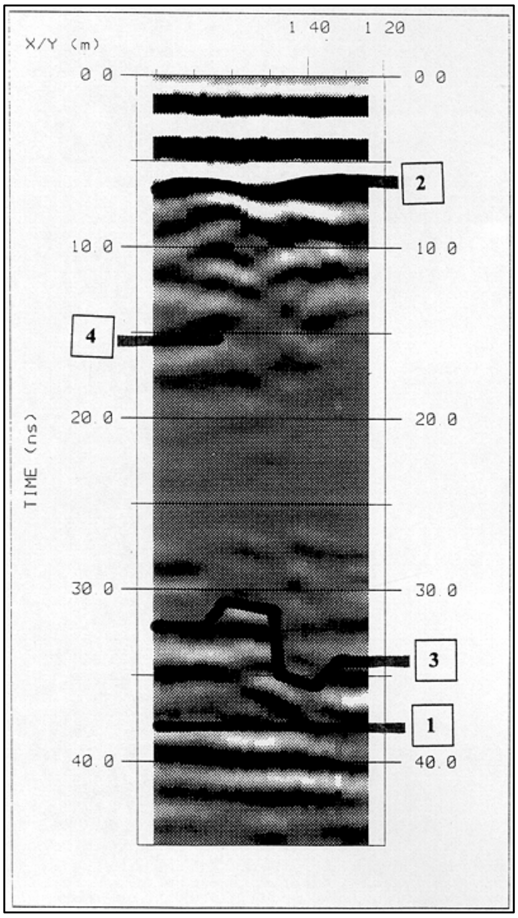

Fig. 7: Profile of the measured part

This profile shows a way to estimate the width of the cracks. Reflection 4 is larger than reflection 2 and hence we conclude that the crack represented by reflection 4 is larger than the crack represented by reflection 2. The exact width however can not be judged. Similar to the acoustic tomography, the method can be enhanced to obtain a surface scan.

3.2 Geo-electrical measurements

3.2.1 Introduction

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 soluble salts).

In 2001 the technique was successfully applied for determining the restoration strategy of a part of the tower of the Church of Our Lady in Brugge (Belgium). This year, the technique is used to visualise internal defects in the rampart of ‘s Hertogenbosch in Holland.

3.2.2 Principle

The method is, again, adapted from a geophysical research method. Two current probes induce an electrical current in the material, the potential difference is measured by the potential probes. Depending on the geometry of the investigated structure a different probe configuration can be used (fig. 8). The potential difference between both measuring probes is influenced by the coherence of the material (Fig. 9).

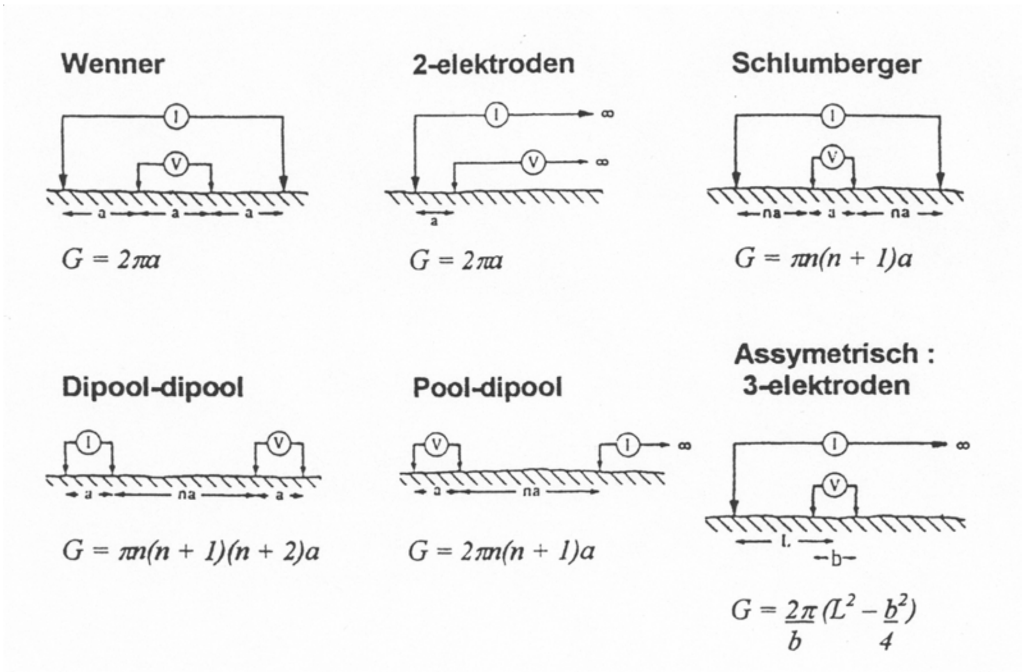

Fig. 8: Possible electrode configurations for the geo-electrical measurements

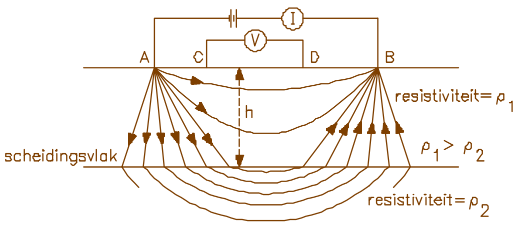

Fig. 9: Both layers influence the potential values and the current

3.2.3 Case study: church of Our Lady in Brugge

The tower of the church of our lady in Brugge has been restored at the occasion of the cultural festival Brugge, cultural capital of Europe 2002. The Reyntjens Laboratory was requested to perform an non destructive testing of the oldest part of the tower. These data helped to fix the restoration strategy of that part of the tower. The equipment was adapted to the on site situation. A hinge was built in the measuring device to measure the corners and a spring system makes sure a constant contact pressure.

The complete surface, being 300 square meters, was measured and the data are converted into a resistivity map.

The resistivity map of the east façade shows a homogeneous image, whereas the southwest façade has a lot of zones with high resistivity and with a big resistivity gradient indicating heterogeneous material inside. Fig. 11 displays the completed unfolded resistivity map of the investigated part of the tower. The damage is clearly located at the West, Southwest and South orientation of the façade.

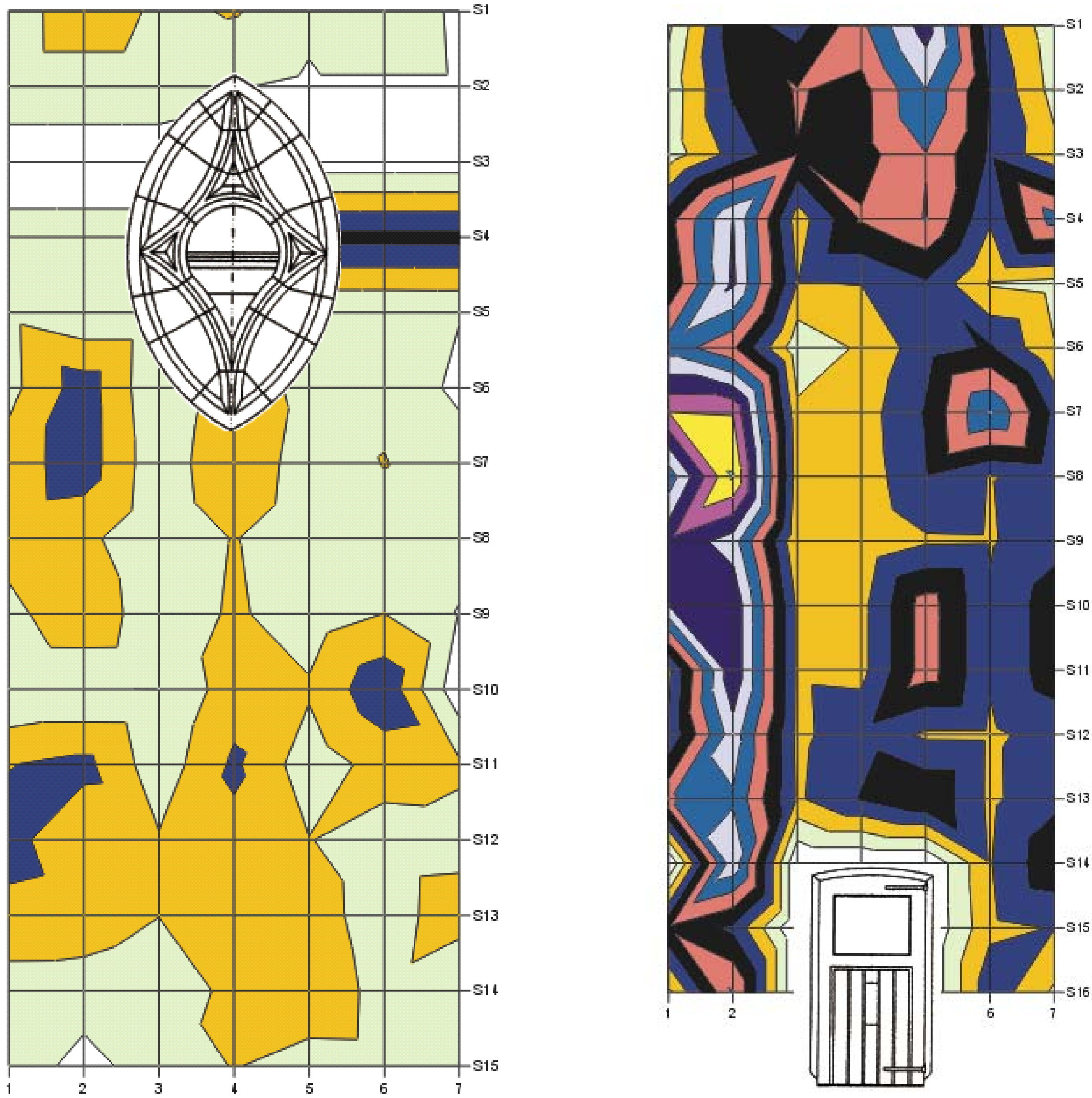

Fig. 9: Resistivity map of the eastern façade (left side) and South-western façade

Coring enabled to calibrate the resistivity maps: the heterogenity was surprisingly not caused by big internal holes or loose material, but by relatively fine cracks parallel to surface. The restoration actions were:

- Drilling a dense pattern of injection holes
- Inserting a stainless steel bar in each hole
- Injecting the holes with a cementitious grout
- The stainless steel bars anchor the different layers

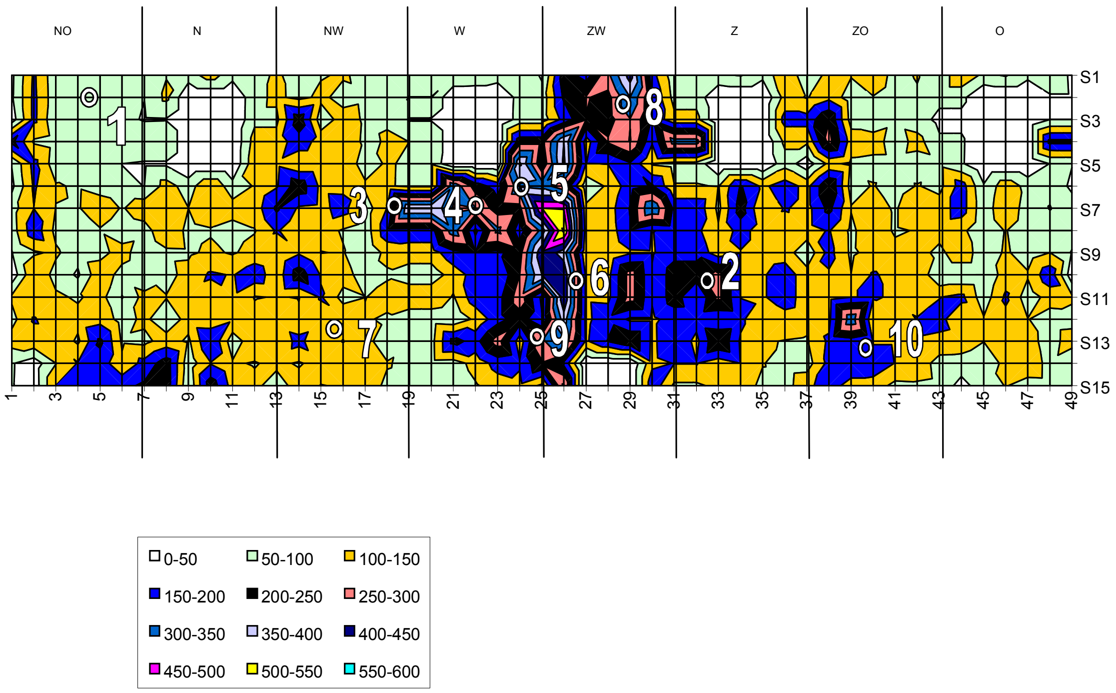

Fig. 10: Unfolded resistivity map of the octagonal part of the tower of the church of Our Lady

After the restoration was finished, a second measuring campaign was done to control the quality of the work. Only the most damaged orientations were measured and the maps were less heterogeneous than before the injection.

3.2.4 Case study: Historic rampart of 's Hertogenbosch

A second large non-destructive study was carried out on the rampart of 's Hertogenbosch in Holland. The city side of the rampart is covered with soil and can not be examined. The Reyntjens laboratory was asked to scan a 300 m zone of the rampart using geo-electrical measurements in order to determine the weak zones of the wall. These zones get a thorough inspection, are cored more intensively and in necessary injected to consolidate them.

Fig. 11: The historic rampart of 's Hertogenbosch is geo-electrically measured.

The measurements are represented on resistivity maps. The left part of the displayed zone (fig. 12) is free from any heterogeneous spots, whereas the right part shows an increased variation in resistivity. This study was only a preliminary study that enables to locate the cores in a more useful way. Unfortunately, the data of the cores are not analysed yet.

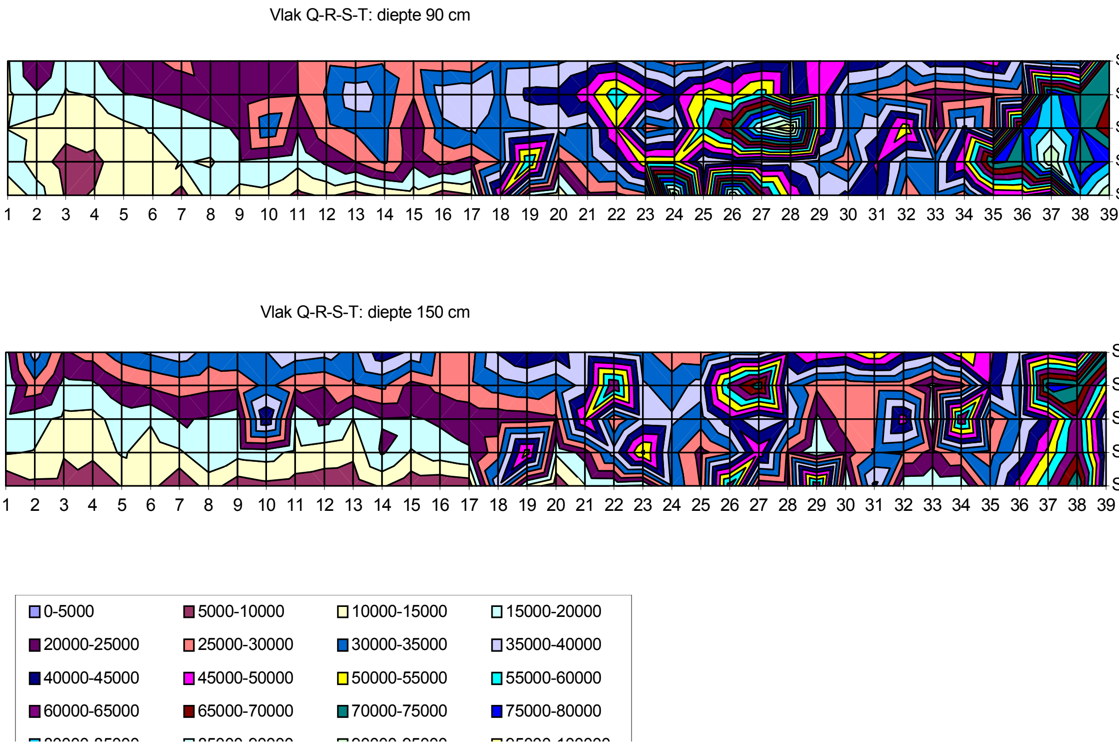

Fig. 12: Resistivity map with a homogeneous left zone and a zone full of heterogeneities on the right side

3.2.5 Benefits and difficulties of the geo-electrical method

The geo-electrical measurements give a good image of the inner condition of a masonry structure. The maps enable to locate the destructive measurements (coring etc…) in a more useful manner. This reduces the number of destructive tests needed to evaluate the masonry and to determine the restoration actions.

Some destructive tests remain necessary to calibrate the non-destructive data. Only in this way explanation can be given about the cause of the increased heterogeneity that the resistivity maps reveal.

Methods have been developed that filter the desired information from the rough data. Indeed, the measurements are disturbed to a large extend by the geometry of the structure, the variation of humidity and the presence of soluble salts.

A first step is taken to apply the method for on line control of grout injection.

4. Scientific design of grouts

4.1 Microstructure of blended hydraulic grouts

The microstructural study involves the identification, follow up and, if possible, quantification of the physical and chemical processes that take place within a material. The microstructural evolution of ordinary Portland cement or of OPC blended with pozzolans is well known. The interaction between OPC, pozzolans (natural and/or artificial) and hydrated lime represents, however, a gap in the relevant literature.

Aim of this project has been the study of the type, morphology and evolution of the microstructure and of the hydration products of lime-pozzolan-cement mixtures with time. The parameters of the study were the lime/pozzolan ratio, the silica fume content and the age. In a preliminary research, the cement content was optimised.

The hydration of the produced specimens was stopped at various ages from 28 to 365 days. It is, however, known that cementitious compositions are sensitive to environmental conditions. Thus, a methodology was set up aiming to stop hydration of the samples with an appropriate procedure so as not to affect the unhydrated materials or the products of hydration. The preparation methods included treatment with pure ethanol and ether and, finally, drying at 50 °C under vacuum. Special care was taken to avoid humidity or carbonation during storage. In order to follow the evolution of the microstructure with time, the following techniques were used: isothermal calorimetry, X-ray diffraction, mercury intrusion porosimetry, scanning electron microscopy coupled with energy-dispersive electron probe microanalysis. Prior to secondary electron imaging, the pieces were again crushed and the newly produced fracture surface was covered with platinum coating.

The evolution of the mechanical properties highlights that, in grouts without silica fume, the pozzolanic reaction continues for, at least, 6 months. For grouts with a 10 %-wt silica fume content, the reaction seems to slow down after 90 days. The reasons for this different behaviour are (i) the quicker consumption of calcium hydroxide by the reactive silica fumes and (ii) the difficulty of calcium ions to diffuse through the denser matrix of silica fumes containing grouts. Considering the abundance of portlandite even at the age of 180 days, the second reason seems the controlling factor for the pozzolanic reaction. The pore volume of both types of grouts is, initially, concentrated at the range of 1-2 μm and at the micropores' range. As the reaction proceeds, a clear refinement of the pore structure occurs, whereas the porosity above 0.4μm becomes negligible. The main hydration products are C-S-H. The more important crystalline species are well-shaped hexagonal portlandite plates. Ettringite has been detected in one of the specimens. Furthermore, calcium carboaluminates develop in non silica fumes containing grouts. Their presence highlights the reaction occuring between calcium aluminates and carbonates, the latter being the product of the carbonation of portlandite. The fact that calcium carboaluminates have not been detected in the silica fume-containing grouts is a further evidence of the difficulty with which diffusion occurs within their matrix. The pozzolanic reaction was highlighted through the morphological changes occurring at the edges or the surface of the portlandite crystals, on which amorphous reticular C-S-H develops.

4.2 Effect of mixing procedure on rheology and injectability of grouts

Grout design involves the study of the behaviour of a suspension in the fresh and in the hardened state. The required performances at the fresh state are: high penetrability, stability and limited or no bleeding. In order to achieve high penetrability, the use of finely ground materials is necessary. Nevertheless, penetrability does not depend only on the maximum diameter of the particles contained in the grout. Indeed, fine materials in suspension coagulate very easily due to inter-particle interactions. The use of superplasticizers permits the development of repulsive forces due to the adsorption of the polymers on the surface of the grains. However, their action does not appear sufficient when the grout contains very fine materials such as silica fume and lime (calcium hydroxide), which tend to coalesce in flocs of different sizes. The penetrability capacity is then significantly decreased.

The action of ultrasonic waves on systems containing particles of colloidal or semi-colloidal size is reported in the bibliography. An ultrasonic treatment can easily disperse very fine substances such as gels or sediments. Furthermore, dispersivity depends on time of exposure, power and frequency of the ultrasounds. There exists an optimal frequency for which dispersion is the best and, if the particle size increases, the frequency corresponding to the maximum dispersion is moved towards lower frequencies.

Aim of this project was the application of this technique to cementitious systems and the investigation of the effect of the mixing procedure on the injectability performance and rheological behaviour of grouts composed of cement, lime, natural pozzolans and silica fume. Two mixing procedures were thus compared: high-turbulence and ultrasonic.

The penetrability performance has been tested by means of a modified sand-column test (AFNOR P 18-891), whereas the rheological has been studied with a Contraves Rheomat 108 E/R coaxial viscosimeter. The penetrability target was set to voids with a diameter smaller than 300 μm with a usual raw materials particle size distribution.

The research program permitted the study of the parameters that characterize flow: apparent and plastic viscosity, yield and shear stress, type and evolution of flow curves with time. It was shown that both mixing procedures produce a Bingham-type rheological behaviour. However, ultrasonic dispersion drastically decreases the apparent viscosity and yield value of the grout but has little, though measurable, influence on plastic viscosity. It was shown that the high-turbulence mixing procedure was unable to ensure a constant penetrability. If the suspension contains SF, the high-turbulence mixing procedure is unable to produce an injectable grout, unless the water and superplasticizer contents are drastically increased. The ultrasonic mixing procedure permits the production of high penetrability grouts with a limited W/S, even if SF is used. This is due to its high dispersion capacity, which permits to deflocculate even very small particle clusters.

4.3 Effect of the mechanical properties of hydraulic grouts on the mechanical behaviour of injected walls

For a few decades now, design of *new* masonry structures (plain or, mainly, reinforced) is making rapid progress, based on an extensive amount of theoretical as well as experimental data; more rational analysis and dimensioning has become possible. On the contrary, redesign of *existing*, and especially *damaged*, masonry structures has not yet known the same degree of refinement. There are a certain number of reasons for it: uncertainties related to the assessment of the damaged condition, highly non homogeneous materials and interfaces present, non linear mechanical behaviour of the masonry components alone (which is reflected in a complex way to the behaviour of the structure as a whole), existence of cracks and discontinuities etc. The problem is more pronounced in the case of masonry buildings, whose walls are made of the so-called three-leaf stone masonry: additional uncertainties are encountered, related to the lack of knowledge and the scattering of the mechanical characteristics of such *non-engineered structures*. All these factors make the application of existing (even sophisticated) analysis tools initially designed for the analysis of *engineered structures* doubtful. Much field and experimental research is needed before the factors affecting the behaviour of masonry components and their interactions are identified and subsequently translated to computer codes. The set up of experimental protocols is, in addition, made difficult by the required size of specimens, which should be big enough so as to yield reliable and extrapolable data.

With the aim to contribute to the understanding of the behaviour of such structures, an experimental program was set up together with the laboratory of R.C. of the NTUA. The program consisted in the study of the behaviour of model masonry wallets of an appropriate size under compression and diagonal compression before and after strengthening with injection grouts presenting different mechanical characteristics. Aim of the program was (a) to test the reproducibility of the model specimens developed and proposed in the NTUA for the study of such structures and (b) to identify the grout design parameters, to which the behaviour of the specimens is sensitive. Moreover, the study of the structural behaviour after failure and the acquisition of the descending branches of the stress-strain curves took, for the first time to our knowledge, place in this research area.

The obtained results ascertained, first, the reproducibility of the model and allow its adoption for the study of three-leaf masonry walls. Furthermore, it has been possible to identify the grout parameters that influence the response of the injected walls. This result made possible the development of a grout design methodology that reconciles mechanical and durability requirements for masonry structures. Finally, the study of the stress-strain curves, especially on the post-peak domain, in combination with shear bond test results (obtained in a previous research program) permitted the definition of relations between the mechanical properties of the individual components and the shape of the stress-strain curves. The latter is important, in order to design repair materials that enhance the ductility (or, equivalently, limit the brittleness) of unreinforced masonry structures of this type.

5. 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

6. The application of composite materials

6.1 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

Fig. 13: External reinforcements using CFRP (Tienen (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).

6.2 Strengthening of wooden structures

6.2.1 Common techniques for strengthening wooden parts

Techniques, similar to external reinforment of concrete, 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. 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

6.2.2 Strengthening of wooden beams by means of internal reinforcement.

This creative application of reinforcement was applied at the castle of Horst. A wooden beam broke because of a mindless decision to pour concrete on the first floor without supporting the bearing structure, as shown in Fig. 14.

Fig. 14: The wooden beam broke due to overloading and deterioration

This was partly due to overloading, but the wooden beam was also thoroughly penetrated by the deathwatch beetle. The only possibility to save the valuable stucco consisted in removing the old timber as much as possible, and to replace it with epoxy mortar. At first the broken floor was lifted with hydraulic jacks to its original position. During the lifting operation the stucco was supported by strongly deflected thin glass fiber reinforced polyester rods. They could straighten during the lifting operation and thus provide a continuous support for all the loose stucco parts, preventing them from falling off, and keeping them in place for later fixing with epoxy adhesive.

A large groove was sawed in the topside of the beam, as shown in Fig. 15. In this groove a strong steel reinforcement has been placed, and the groove has been refilled with epoxy mortar. At the topside some dowels are placed already now, to allow for a later strengthening of the beam by applying an additional layer of mortar. The dowels will than serve as shear connectors (Fig. 16). Fig. 15 also gives a view of the beam, filled with epoxy mortar and with the dowels standing out from the mortar. Fig. 18 shows the repaired beam and the saved strucco.

Fig. 15: A large groove is milled out of the wooden beam and reinforced with steel bars and filled with epoxy mortar

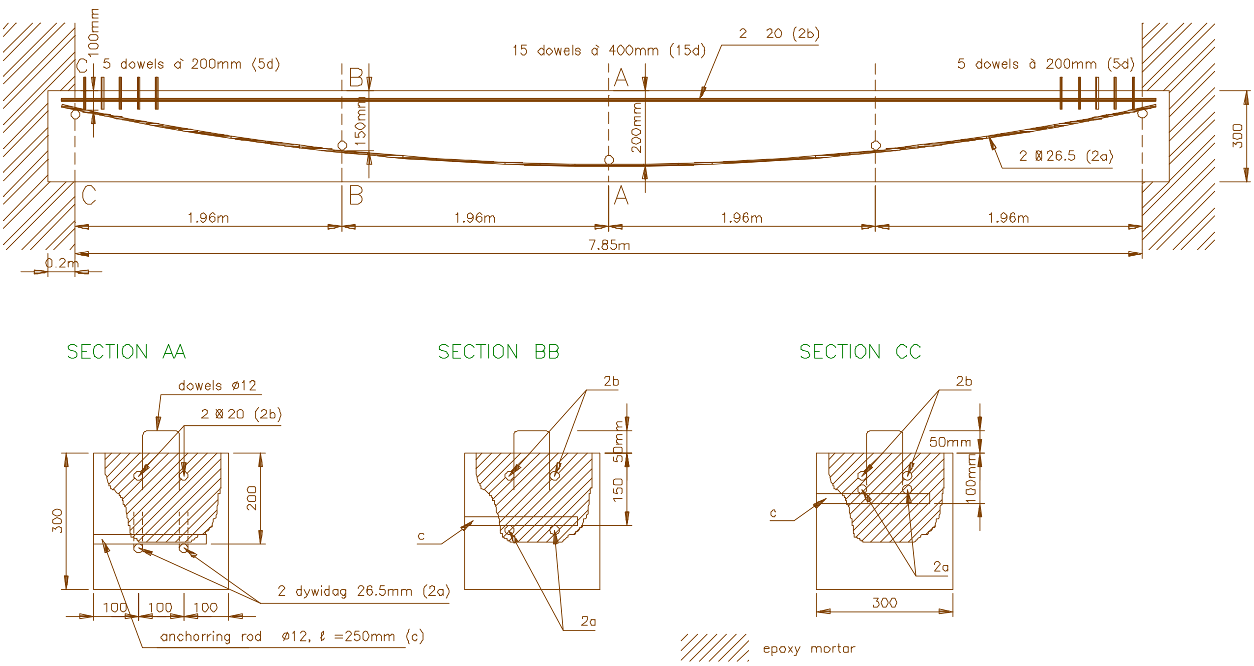

Fig. 16: Repair schema of the wooden beam

7. Conclusions

A short overview of the restoration activities in Belgium is given. Rather than giving a broad list of techniques that are commonly used in Belgium, the choice is made to illustrate thoroughly three domains of interest. *Non-destructive testing* can be a valuable support for diagnosis, realisation and control of restoration interventions. A list of non-destructive techniques is given but our research group proposes geo-electrical measurements as a powerful and affordable technique.

Restoration materials need to be designed carefully, an example is given about the composition, the mixing and the behaviour of *blended grouts*. Finally, the application of *composite materials* for restoring cultural heritage needs to be considered. Externally bounded reinforcement if applied with care, overcomes structural problems.

8. References

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