STRUCTURAL CONSOLIDATION AND STRENGTHENING OF MASONRY: HISTORICAL OVERVIEW AND EVOLUTION

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Abstract

Mass consolidation of stone and brick masonry is considered, with exclusion of pure crack repair. The aims of consolidation are explained, and the inherent advantages and disadvantages of distinct strengthening and consolidation techniques are given. An historical overview of consolidation methods and of development of consolidation grout materials is given, which explains how technology evolved to the actual procedures. The consolidation of the tower of our Lady's Basilica in Tongeren (1992-1994) and the consolidation of the foundation masonry of the same church to allow for archaeological excavations inside the building (1999-2002) are described as examples of design principles and materials choice.

Keywords
Consolidation, strengthening, blended lime-cement-pozzolan grout, stone masonry, anchors, polymer.

1. Introduction

To develop and use structural consolidation techniques, the designer must start from the study and thorough understanding of the real nature and stress-strain behaviour of masonry. Masonry is a composite material, made of stones and mortar, bricks and mortar, or stones, bricks and mortar. Not only the nature of mortar and stones can account for the type of deterioration of the masonry, also the structural built up plays an important role. The deterioration in regular brickwork masonry differs from that in a wall, composed of an inner and outer leave of natural stone, with a rubble masonry core in between.

Degradation of the composite material brick or stone masonry is caused by several deterioration phenomena, which can be categorized into different main types. Physical deterioration is the damage, caused by temperature variations, fire, frost and thaw, erosion by water, corrosion of metal parts in the wall, dust. Physico-chemical deterioration phenomena are the swelling due to water absorption, crystallisation or hydration pressures in the pores at crystallisation of salts or hydration of crystals. Chemical corrosion is mainly the formation of gypsum due to atmospheric pollution. At last, we distinguish biological deterioration, caused by micro-organisms, plants, men.

Deterioration phenomena appear in the mortar as well as in the stones. As a result, the quality of both, and the quality of the bond between stone and mortar diminish. The mechanical action on the masonry walls normally causes distributed vertical compressive stresses in the masonry, but at every discontinuity such as cracks, holes and pores, interfaces between stones and mortar, also tensile stresses will appear [1,2]. Their magnitude is of the same order as the compressive stresses. The tensile stresses can cause cracking or micro-cracking in the stones, the mortar or in the bond between them. This cracking can be intensified by vibrations, shocks, wind loads etc. It must be stressed that compressive stresses are mostly not harmful to masonry, except in some rare cases were buckling might occur, or in arches and vaults with excessive crack openings.

The choice of the methods and products for consolidation must be determined by the type and degree of degradation. Having in mind that tensile stresses are causing masonry failure, it is evident that every strengthening method must introduce elements or systems, capable of withstanding these tensile stresses. Grouted anchors and injected grouts are potential methods, but each of them has its specific application fields, and design will always be problem oriented. Sometimes they are alternatives, sometimes they are complementary, but sometimes it will be only one of the two that offers an appropriate solution.

2. Strengthening by means of grouted anchors

Grouted anchors enable to increase the transverse tensile strength of existing masonry. Steel, stainless steel or fibre reinforced polymer rods are inserted in bored holes and bonded to the masonry with an appropriate grout. The principle is shown in Fig. 1. The figure also indicates the application area: multiple leaf masonry with different stiffnesses of core and external leaves, or masonry loaded by concentrated vertical forces.

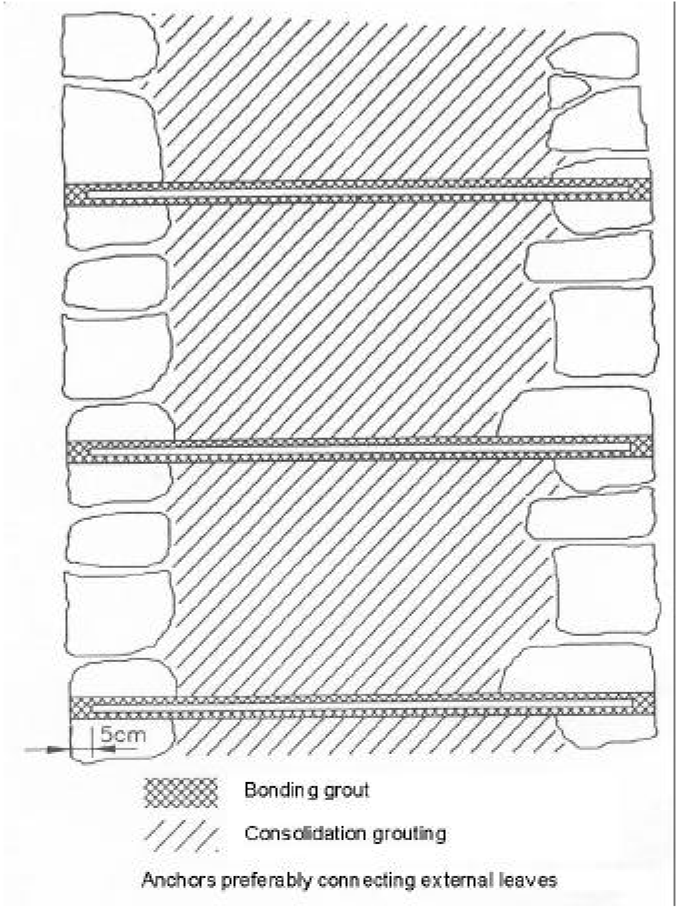

Figure 1: Grouted anchors in multiple leaf masonry

The calculation of forces in the anchors is made according to the principles of structural analysis and determination of splitting forces in structural elements under concentrated loads. Experiments [7] have shown that steel anchors made out of concrete reinforcement rods with improved adhesion and diameter d from 8 to 16 mm, bonded in brick masonry by means of cement mortar, need an anchoring length of $l_e = 90 + 9.d$ (in mm). In stone masonry an anchoring length of $l_e = 120 + 12.d$ (in mm) is required. These anchoring lengths lead to plastic yielding of the anchor at tensile loading (f_y = 400 MPa). For other types of anchors and other types of grout, the anchoring strength must be determined experimentally, eventually by a pull out test on the site. Under concentrated loads and at the top of the wall, additional vertical and inclined anchors will be needed to avoid splitting of the wall masonry and ineffectiveness of the anchors.

One could think that by increasing the number of anchors an overall strengthening effect can be obtained, and that a kind of reinforced masonry is realised. For some types of masonry, that might be possible, as shown in figure 2 [8]

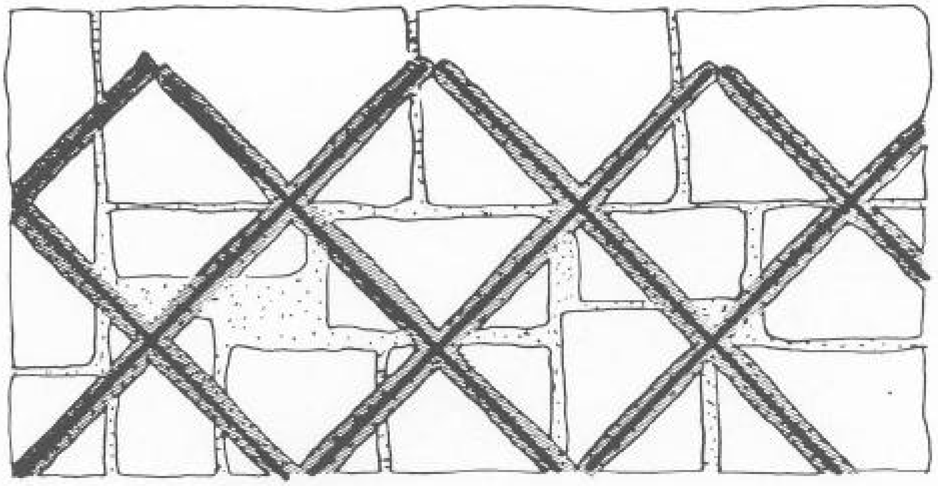

Figure 2: Overlapping inclined reinforcements (reticolo cementato)

The basic element is a steel rod; 2 to 3 m long, grouted in the borehole with a cement of polymer grout, connecting the outer leafs through the core. The grout is injected under low pressure and provides the bond between the anchor and the masonry mass. With an appropriate overlapping scheme the masonry is provided with a certain tensile strength. One anchor, or one row of anchors can never give a relevant tensile strength. The beneficial effect is only reached with different reinforcement layers, close enough and with good overlaps.

However, the grouted anchor system is a system on which the saying “it can’t do any harm and it may do some good” is not applicable. If the anchoring system is not designed in the proper way, it will further lower the already low strength of the treated masonry. This was clearly shown in several experiments [9,10], where due to the drilling of holes for the anchors the strength was lowered with about 10 %. A clear picture of this situation is given in figure 3, [ref. 9], found in experiments executed at the University of Karlsruhe (D).

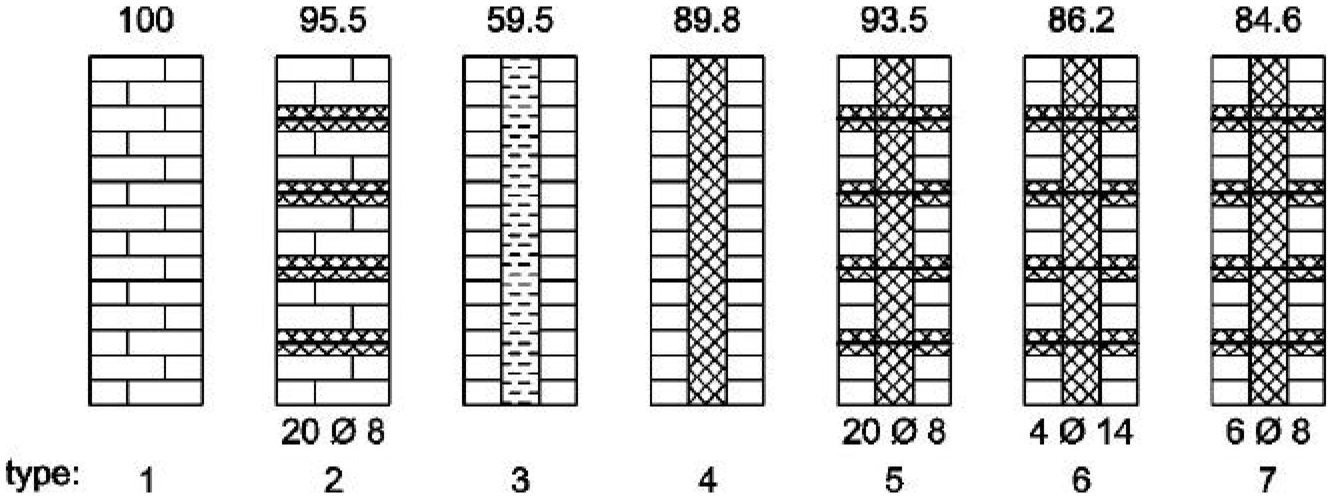

Figure 3: Decrease of strength due to drilling of anchors

Grouted anchors are an effective strengthening technique for the creation of masonry ring beams, as explained in the paper by S. Ignoul [11], or to resist splitting forces, as shown hereafter in the case study of Tongeren.

3. History of consolidation grouting for masonry

Restoration of old masonry in buildings and monuments used to be done by rebuilding of damaged areas, and replacing of defective natural stonework or brickwork with new stones. However, due to different erosion of old and new areas or bricks under atmospheric action, such restored buildings looked like patchwork quilts after a few years. Guided by the Venice Charter, and driven by the above negative experiences, impregnation and grouting or injection of masonry has been developed in the period 1975-1985 for the consolidation of masonry [3,4]. The grout must fill the voids and holes in the masonry, to allow the force flow to be distributed uniformly over the masonry mass and thus avoiding splitting forces. Moreover the grout must increase the internal cohesion of the original mortar as well as the adhesion of the mortar to the stones. Most used for consolidation purposes at the beginning were solvent free reactive epoxy resins. The first applications in Belgium were made at the strengthening of columns in the Cathedral of Our Lady at Antwerp (B) in 1979-1981 and at the consolidation of walls in the 17th Century monument “Oud Gasthuis” at Herentals (B) in 1984 [4]. Some attempts were made to use polyurethane resins that formed elastic polymers inside the masonry. Through the addition of fillers the mechanical characteristics could be changed in a wide range. Consolidation of stone with the method of methyl methacrylate impregnation in the form of solutions of monomer in alcohols, or by monomer impregnation under vacuum, is reserved to the restoration of statues and art objects. It needs a very strict process control, which is difficult to apply on the restoration site.

In 1986 M. Ullrich reported about one church tower, which had to be torn down because the resin based grout, that had been injected 12 years before, was still not hardened and continued to drop out of the masonry [5].

This negative experience, combined with the cost of the resin grouts and the high consumption rate in masonry, forced designers to develop new consolidation procedures and systems. Indeed, the volume rate of voids in masonry mounts up to 20-30 %. If a pure polymer such as epoxy resin is used, the technique becomes very expensive. Within the framework of the consolidation of the 15th century tower of St. Mary's Basilica at Tongeren, figure 4, a two-step injection was developed to overcome this problem [6].

Figure 4: Tower of St. Mary's Basilica at Tongeren

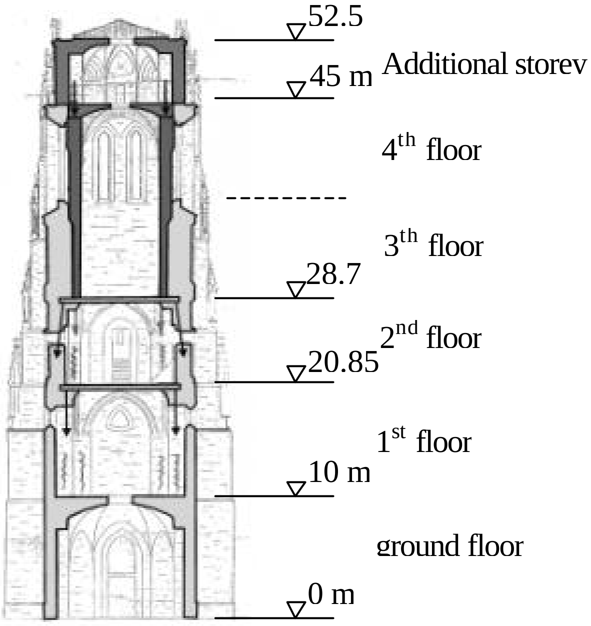

Figure 5: Load transfer scheme in tower. Injection at 1st and 2nd floor

The walls of the tower are up to 4 m thick. The top level was added in 1877-1882. A supplementary supporting brick masonry structure was provided at the inside of the tower, transferring the additional load to the top of the second floor. However, this strengthening measure turned out to be insufficient. Consolidation injections were carried out on the first and second floors, combined with the construction of two reinforced concrete diaphragms above the first and the second floor, as shown in Fig. 5.
In a first step the larger holes and voids were filled by means of injection of a cement-based grout. The grout contained slag cement CEM III A 42.5, bentonite stabilizer, a sulfonated naphtalene superplasticizer and water. High turbulence mixing is needed to produce a very flowable and stable grout. In a second step a solvent free reactive epoxy resin was injected to improve the internal cohesion and the adhesion between mortar and stones. An extensive control program was executed to study the consolidation procedure and its performance. Moreover, a lot of research efforts has been devoted to the development of non-destructive test methods, allowing to investigate the internal condition of masonry masses, and to predict the necessary grout consumption [12, 13, 14].

4. Mechanical properties of injection grouts

The properties of blended lime-cement-pozzolan grouts have been studied thoroughly in the laboratory and on the site [15,16,17,18]. An overview of properties of polymer, cement and blended grouts is given in [19].

It is interesting to repeat some of the findings concerning the evolution of compressive and bending strength with time for different blended grouts, and concerning the adhesion or bond strength between the grouts and brick or stone.

Test were done on samples 40 x 40 x 160 mm according to the Belgian Standard NBN B14-208 for compression and bending, and with a Casagrande shear set-up under normal stresses of 0,1; 0,3 and 1 MPa.

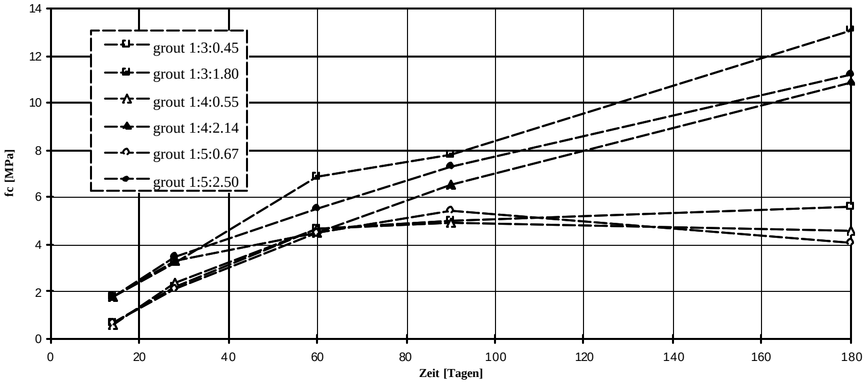

Figure 6: Time-evolution of compressive strength of blended grouts

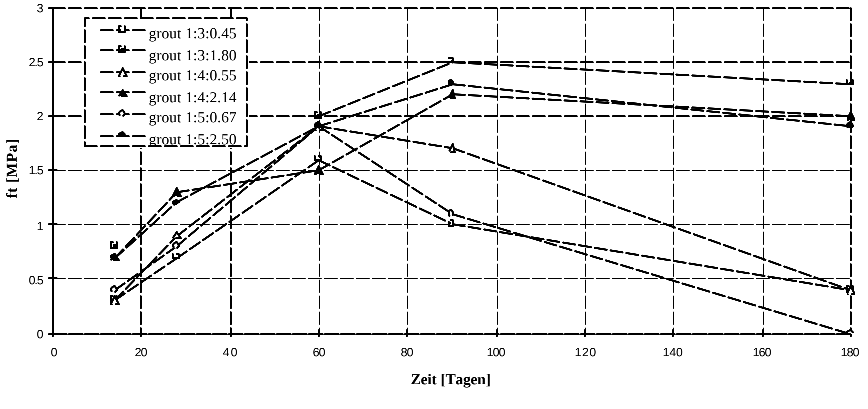

Figure 7: Time-evolution of bending strength of blended grouts

Compositions are indicated as grout 1:3:0,45, indicating the composition in weight parts: 1 part of hydrated lime: 3 parts of Rheinisch Trass; 0,45 parts of Portland cement. The compositions represented in the figures 5 and 6 contain or 10 % or 30 % of cement in the total binder amount.

The development of strength at the beginning is due to and determined by the cement content. This is not surprising, because the hydraulic activity of the pozzolans only starts after about 4 weeks. In the mixes with 30 % of cement, the initial strength is not related to the lime to pozzolan ratio. Only after 60 days a significant difference arises. After 180 days the compressive strength reaches about 10 to 12 MPa for the 30 % mixes. The evolution of the bending strength shows that a minimum of 30 % of cement should always be present in the grout mix, because otherwise the tensile bending strength, which is also a measure for the bond strength, drops to zero after half a year. This is due to the delayed hydraulic reaction of the lime and the pozzolans, which chemically attacks the initial hydrated structure of the cement fraction, and exerts destructive forces on the hydrated cement skeleton [18].

The shear bond characteristics for a brick and a limestone substratum were tested in a Casagrande shear box apparatus, which enabled the measurement of shear stress versus slip under specific normal stresses. The general shear stress – slip curve is shown in figure 8. The shear bond characteristics for a brick and a limestone substratum are given in Tables 1 and 2.

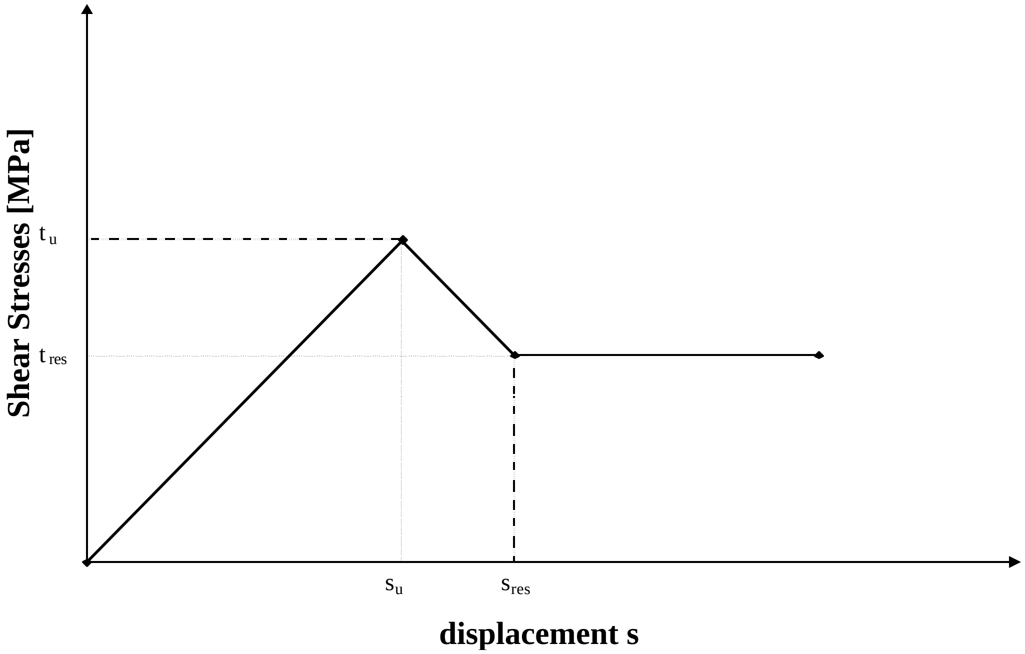

Figure 8: Shear stress-slip relation for grout-substratum interface

Normal stress	13b-0		13b-10		Cb-0	
[MPa]	t_u [MPa]	s_u [mm]	t_u [MPa]	s_u [mm]	t_u [MPa]	s_u [mm]
0.1	0.38	0.39	0.67	0.38	0.65	0.32
0.3	0.68	0.39	0.99	0.37	1.01	n.a.
1.0	0.84	0.50	1.13	0.31	1.98	0.75

Table 1: Shear bond characteristics for a brick substratum

Normal stress [MPa]	13b-0		13b-10		Cb-0	
	t_u [MPa]	s_u [mm]	t_u [MPa]	s_u [mm]	t_u [MPa]	s_u [mm]
0.1	0.44	n.a.	0.67	n.a.	n.a.	n.a.
0.3	0.35	0.17	n.a.	n.a.	n.a.	n.a.
1.0	0.83	0.33	1.12	0.54	1.19	0.22

n.a.: not available

Table 2: Shear bond characteristics for a limestone substratum

The grout composition is 1 part of lime to 3 parts of pozzolan, with 30 % of cement, with addition of 0 or 10 % of silica fume; grout Cb-0 is a pure cement grout. J_u is the shear bond strength at slip s_u in the shear box test. The grouts were injected in test wallets, which were previously loaded in compression till cracking in the post peak zone. The test results are given in Table 3 [18].

From the results it is obvious that grout compressive strength is not the main factor controlling the strength of the grouted walls. Of much more importance are the stiffness of the grouts, and their bond traction and shear bond strength. These grout properties limit the horizontal deformability of the different leaves of the masonry, thus reducing crack opening, and increasing the vertical compressive stress required to accelerate the transverse horizontal crack opening, which causes collapse of masonry.

	Grout	Modulus of Elasticity	$f_{wc,0}$	$f_{wc,inj}$
		[MPa]	[MPa]	[MPa]
BC1	13b0	2238.2	-	5.04
BC2	13b10	1564.9	2.41	3.15
BC3	Cb0	1404.8	2.09	2.91
BC4	13b0	1040.4	2.18	3.00
BC5 (t.l)	13b0	1170.2	2.28	3.86
Average excl. BC1 & BC5		1336.7	2.23	3.02
Average excl. BC1, incl. BC5		1295.1	2.24	3.23
SC1	13b0	1622.2	2.02	3.25
SC2	Cb0	1558.6	2.07	3.36
SC3 (t.l)	13b0	1187.8	2.65	3.51
SC4	13b0	1014.5	2.71	3.29
Average excluding SC3		1398.4	2.27	3.30
Average including SC3		1345.8	2.37	3.35

(t.l. = with transverse connecting leaves)

Table 3: Strength of the walls under compression loading, before and after injection
(B brick; C compression; S natural stone)
(Wall size: 400 mm x 600 mm x 1200 mm)

5. Consolidation and underpinning of the foundations of St. Mary's Basilica at Tongeren

5.1 Introduction

Tongeren is an old Roman city, with a history of more than 2000 year. The city centre is an accumulation of remains of successive civilisations and cultures. Archaeological excavations in the 'Vrijthof' market place next to the church indicated that the gothic church was built just on top of a most interesting and crucial archaeological site [21]. Archaeological research in the Vrijthof-market at the south side of the church goes back to 1844. At that time J.L. Guioth discovered a series of foundations, which he and his successors in the 19th century interpreted as the remains of a Roman fortress. At the re-arrangement of the Vrijthof site in 1994-1996 extensive excavations revealed that these remains are parts of two different defensive walls of the medieval Minster, one dating from the 10th century and one from the 12th century. At the same time a Roman town house with bathhouse from the 2nd and 3rd century was discovered, as well as a tower and connecting sections of the 4th century town wall. The archaeologists were convinced that the remains of the bathhouse were only the southern exterior walls of a rich urban residence, of which the remaining parts are situated under Our Ladies Church.

The idea grew to disclose the remains under the church. However, religious live in the church is very active, and the church is an important monument as well. One had to look for a solution that could combine the desires and needs of all parties involved. The proposed solution was the construction of an archaeological cellar under the church. This cellar will be an underground archaeological field. The cellar will have no solid concrete bottom floor. People will walk on bottom soil surface of the excavations, to keep the archaeological sensation as complete and as realistic as possible.

The Church-fabric of St. Mary's Basilica initiated the excavation project in 1994-1995. The project is designed by the architectural office Janssen and Loix in Tongeren. Libost-Groep consulting engineers, in collaboration with engineering consultant J. Maertens, make the structural design. The Reyntjens Laboratory of K.U.Leuven gives technological support. The project is supported by the Church-fabric, by the City Council of Tongeren and by the Department of Environment and Infrastructure of the Flemish Government. Excavations are made by the Institute for the Archaeological Patrimony IAP. The consolidation and underpinning works are executed by Denys n.v (phase I).

From the beginning on it was clear that the excavation of an archaeological cellar underneath the existing church structure would cause great structural problems. From existing small cellars it was estimated that foundation depth of walls and columns would be about 2.7 to 3.0 m. The necessary excavation depth for an accessible cellar, taking into account the necessary space for a roof plate and new flooring system for the church, would be 3 m. To give the visitors the real feeling of an archaeological site, and not of a crypt under the church, it was decided to excavate the central nave and the adjacent aisles as well as part of the choir. This presents a surface of about 20 m by 40 m, in which the column footings and the wall foundations would be stand-alone elements. Removing of the soil around the foundations also takes away its constraining action on the foundation masonry. Moreover, the direct foundations at depths of about 3 m than become direct foundations on the soil surface. The load carrying capacity of surface foundations is very limited und uncertain, and unconstrained rubble masonry of foundations has nearly no strength. Both effects significantly endanger the structure, leading to an almost certain collapse.

Therefore the project was preceded by a preliminary investigation to reveal the composition and quality of the foundation masonry, and to study possible injection grouts for both consolidation of the masonry, and to strengthen it sufficiently to be able to transfer the anchoring forces of the micro piles. The consolidation procedure was adapted according to the findings from the preliminary investigations.

5.2 Grout selection and execution of injection

The injectability of a cement grout depends in an important way on the fineness of the dispersion of the cement particles in the water phase. To prevent the dispersion from coagulation and segregation, the addition of stabilizers and superplasticizers is necessary. The effect of a superplasticizer lies in the generation of a positive ?-potential on the surface of each cement particle, strong enough to disperse them. Furthermore, the attraction between the positive particles and the water molecules strengthens this effect and finally, the sterical disturbance of the molecules on the surface of the cement particles prevents the dispersion from coagulation. The materials used in the preliminary test program are:

- Cement: CEM III A 42.5
- Additives: Bentonite Bentonil CV15
  Superplasticizer Rheobuild 716 (sulphonated naphtalene with polyhydroxylated polymer)
- Water

The mixing procedure is determining for the physical and mechanical properties of the cement grout. The following routine was adopted:

- dry mixing of cement and bentonite
- addition of 50 % of the water and mixing
- after 2 minutes, addition of 50 % water with 50 % of superplasticizer amount and mixing
- addition of 50 % superplasticizer and mixing

Component	Quantity
Cement IIIA 42,5	100 kg
Bentonite CV15	2 kg
Water	67.7 kg
Superplasticizer Rheobuild 716	1.0 kg

Table 4: Composition of the injected grout mix

The mixing procedure is determining for the flow of the grout and the final mechanical properties. The flow time of the mix through the AFNOR funnel n° 4 only reached 13 seconds. The final mechanical properties of this grout, measured on prisms 40 mm by 40 mm by 160 mm are given in table 5.

	Tensile strength MPa	Compressive strength MPa
After 7 days	4.4	26.8
After 28 days	4.0	31.8

Table 5: Mechanical properties of the injected grout (NBN B12-208)

5.3 Consolidation and strengthening: concept and execution

The whole project is divided in two phases. Phase I is the excavation and re-arrangement of the west part of the church (1999-2001); phase II concerns the east part of the church (scheduled 2003-2005). Excavation works and consolidation and strengthening as well as re-arrangement works are going on simultaneously. This means a lot of organisation and compromise between archaeologists, contractor, designers and users.

Figure 9 shows a plan of the nave, aisles and chapels of the church. The massive west tower is not represented. The first phase of the excavations is shown in the left part of the plan.

Figure 10 gives a cross-section of the archaeological cellar. The micro pile system under the columns and walls is also presented. The load bearing capacity of the micro piles is 200 kN pro pile. As can be seen also the exterior walls are supported by micro piles, although no excavation will be made next to these walls.

The underpinning of the columns and uncovered walls is needed because the strength of the foundation soil becomes insufficient after removal of the soil layer of about 3 m, representing a surface load of 50 kN/m². This heavy load will be removed over a large area of about 20 x 40 m, and by that the strength of the foundation soil drops drastically under the column footings and under the foundation walls. Also the stress distribution in the soil all over the church surface changes considerably, and as a consequence also the deformations of the soil will change. This might lead to excessive differential settlements of structural elements, leading to cracking of walls and vaults. The underpinning of all the columns and walls in and adjacent to the excavation will avoid such differential settlements.

Ground anchors with tension capacity of 200 kN are installed in the north and south wall of the cellar. They secure these walls during the excavation, when exterior horizontal soil pressures are acting on the freestanding walls, not yet supported by the roof plate.

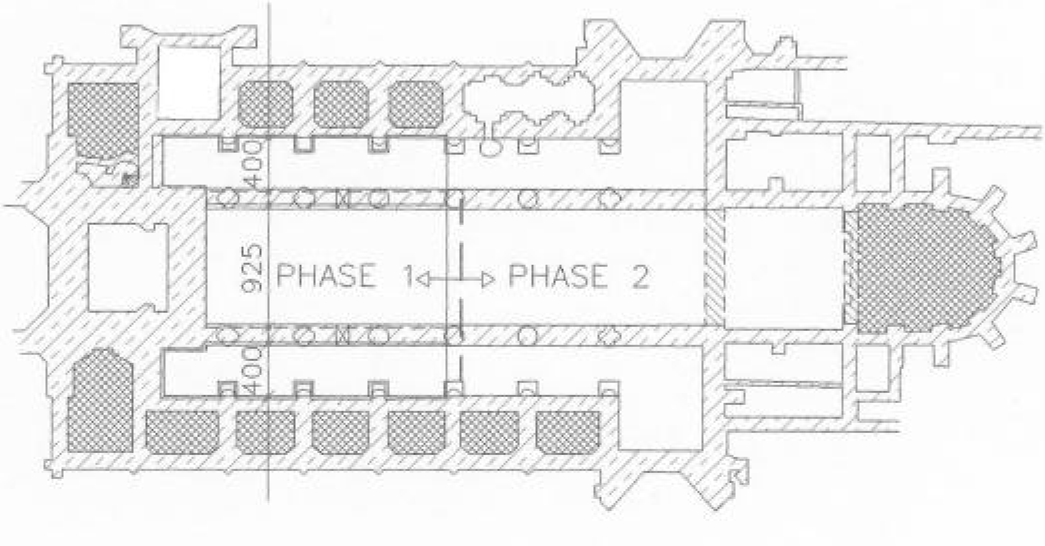

Figure 9: Plan of church with intended excavations

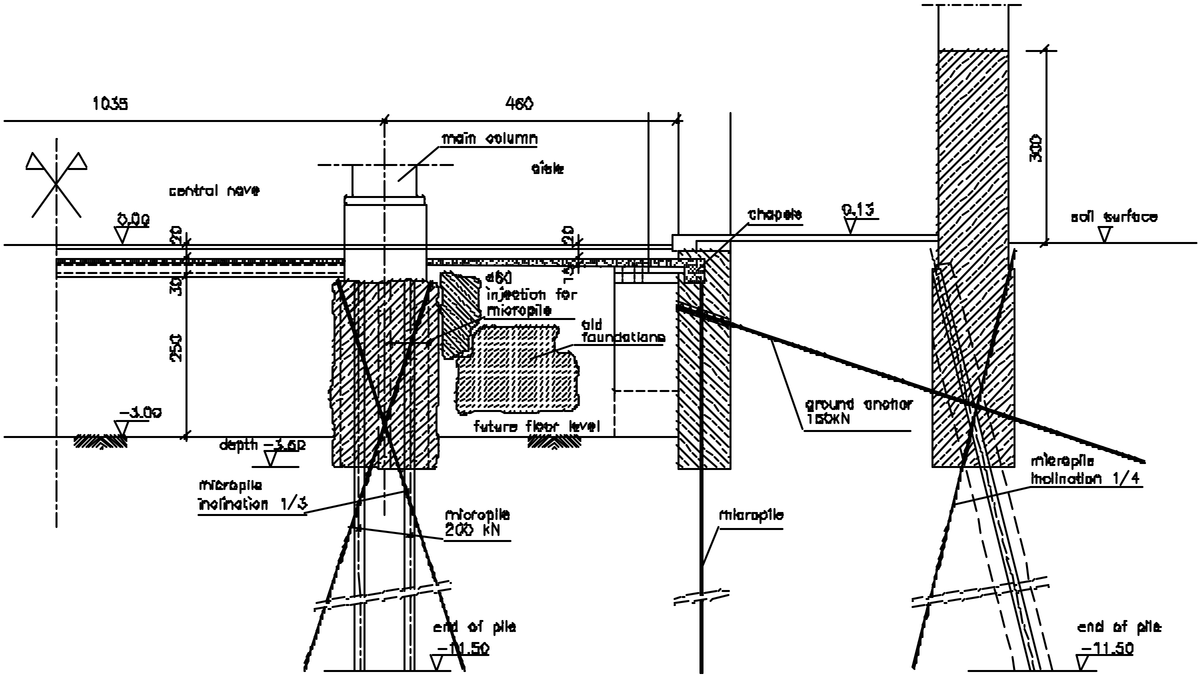

Figure 10: Cross-section of archaeological cellar

Micro piles and ground anchors must be anchored in a stable masonry, able to take up the concentrated forces from piles and anchors. Therefore the masonry walls are injected with the cement-based grout. The injection is made through vertical or slightly inclined boreholes, with a diameter of 50 mm. The grout consumption is calculated for an average filling rate of 25 % of the foundation masonry. Compressive strength tests on control coring indicated strength of 3 to 6 MPa for the injected masonry.

The injection holes are drilled at the same location as the micro piles. The following procedure is followed to place the micro piles. First a hole with 100mm diameter is drilled through the injected masonry. At the onset of the foundation, an auger type-drilling rod (type Ischebeck 40/16) is used to extend the borehole in the foundation soil to a depth of 12 m. The drilling rod is a thick walled tube with internal diameter of 16 mm and external diameter of 40 mm. With four screw-connected elements of 3 m the desired length of 12 m is obtained. The cutting bit has a diameter of 90 mm. The borehole is made under simultaneous injection of cement grout through the central hole of the drilling rod, with an injection pressure of ± 5 bar. At reaching the depth of 12 m the injection is continued until the grout is flowing out of the borehole. In this way a complete filling of the borehole with cement grout is guaranteed. The drilling bit makes a hole with a minimum diameter of 100 mm.

The columns transfer a concentrated load of 1800 kN to the foundation footing. These footings are connected with a chain wall, as shown in Figure 11.

The position of the columns on their footings and on the chain wall is mostly eccentric. This eccentric position introduces additional bending stresses in the masonry. The available strength of 3 to 6 MPa after the first injection is not reliable enough to secure the arising compressive and splitting stresses. Therefore, an additional strengthening is executed in the column foundations, Figure 12.

Three layers of cemented anchors with diameter of 25 mm are placed to take up the horizontal splitting forces caused by the concentrated column load. The layers are placed when the excavation reaches the corresponding depth. After drilling the anchor holes a second injection of the cement grout is made through these holes, to improve the consolidation of the adjacent masonry. The number of anchors per layer decreases with increasing depth.

When the archaeological excavations reached a depth of about 3 m some of the freestanding columns started to move inwards. Their movement was monitored and stabilizing measures were taken, as explained in [22,23].

Figure 11: Chain wall between columns

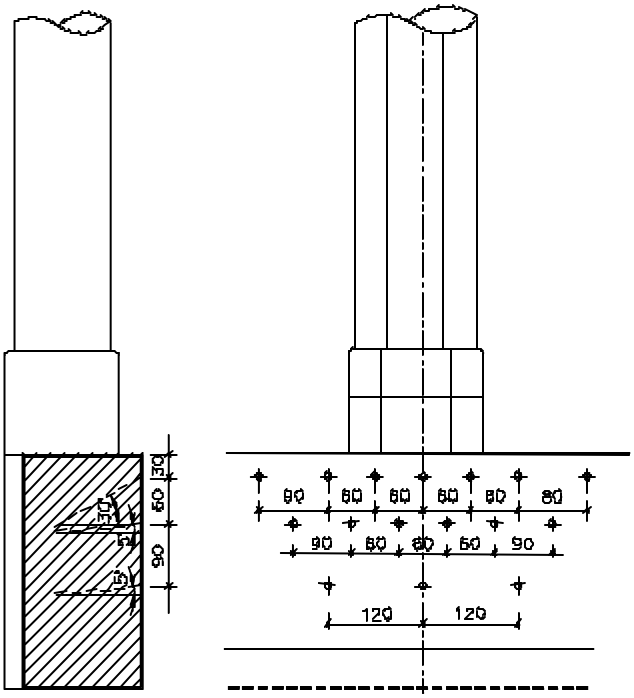

Figure 12: Cemented anchors in column foundation

6. Conclusions

Consolidation injection and strengthening of masonry seem to be rather simple techniques, but practice proves that consistent quality can only be obtained through constant quality control of procedures and materials, and constant involvement of dedicated and skilled designers. The production of stable grouts with appropriate flow and mechanical properties is a science as well as an art. The design engineers must acquire the science, the art must be taught to the technicians who execute the work.

Making an archaeological cellar under an existing monument is a challenging project, in which both archaeologists and engineers must discuss, persuade and compromise. The presence, location and magnitude of archaeological remains are unknown beforehand and archaeologists tend to excavate more, deeper and wider than originally planned. The design engineer must protect the monument as well as the archaeologists, but he also has to give them all the necessary help to discover and uncover as much as possible of the hidden objects, evidence and magnitude.

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