CHAPTER 3
DAMAGE ANALYSIS AS A STEP TOWARDS COMPATIBLE REPAIR MORTARS

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1. Introduction

The aim of this chapter is to gain a better understanding of the factors (including environmental) that influence the way in which degradation of materials and especially mortars in monuments occurs. As part of the damage analysis the most common forms of degradation of mortar, as well as the type of investigation, required to diagnose the cause of the damage, are described. On the basis of the assessed decay form and decay process, the most adequate repair method and the most suitable repair mortar are also shown.
The diagnosis of the cause of damage is often ignored in some repair methodologies, even though this is a fundamental step to guarantee a durable restoration. Such negligence can lead to major incompatibility problems when carrying out mortar repairs. The approach adopted in this document can lead to a better understanding of the causes of incompatibility and help in producing guidelines for compatible repair mortars, based on the specific conditions of the individual monument.

2. Factors affecting degradation processes

The most important factors affecting degradation processes are related to:
- environment
- materials
- design
- workmanship and construction procedures
- maintenance

Principal factors related to the *environment* are:
- moisture supply: rainwater, moisture penetrating from the ground or surface water, snow melt, floods, …
- salt supply from the ground, ground or surface water or from the previous/ continuing use of the building (e.g. stables, salt storage) or via the air (aerosol), floods, de-icing salts
- air pollution
- variations and extremes in temperature
- exposure to fire
- dynamic load (earthquakes, wind, traffic, vibrations)

- soil settlement

Principal *material* factors are:

- composition of the mortar (type and quantity of binder, grain size distribution of the sand,..)
- properties of brick, stone and mortar and their boundary interface (capillary transport, adhesion,..)
- presence of salts in those materials

Design factors are:

- original structural design of the building and / or subsequent modifications
- choice of materials or combinations thereof
- detailing of the building (especially water shedding details like gutters, downpipes, window sills, copings, flashings, roof overhangs, …)
- choice of repair methods and materials (treatments, cleaning operations, ….)

Factors deriving from *workmanship and construction procedures* are:

- quality of execution
- mortar mixing on site
- the way materials are cured and curing conditions
- protection of (fresh) mortars
- lack of knowledge on traditional workmanship

Factors related to *maintenance* are:

- prompt repair (lack of maintenance: no prompt repair of water shedding elements, damaged mortar joints, …)
- inappropriate maintenance programme (time span, monitoring)

The environmental factors, combined with material factors, exert a major influence on the development of degradation processes.
Orientation and architectural details finally determine the extent to which moisture supply and drying may play a role [Maurenbrecher,1998]. Table 2.1, summarises all important factors.

Processes
All building materials are to a different extent prone to degradation processes. These are up to a certain point natural processes, which can be more or less influenced by man or man's activities.
Degradation processes exert a stress on the building materials (physical, chemical, physico-chemical, mechanical), which, under certain conditions or after a certain time leads to damage. Degradation is the more or less gradual increase of damage, as well as the decrease of quality.

Damage can be defined as 'a form of degradation of the building material, which becomes evident at a certain moment' (varying from e.g. discoloration to complete loss of cohesion) and can be both an aesthetic and a functional issue.
The degradation process is not by definition identical to the cause of the damage [van Balen al.,1996], [Franke et al.,1998]. There are in general a number of essential conditions, without which nothing can happen, notwithstanding the presence of the process.

The main degradation processes based on environmental factors are given below:

- action of freeze-thaw *cycles*

- action of salt crystallisation *cycles*
- action of chemical conversion leading to the formation of expansive compounds (including chemical air pollution components activity, i.e. dry deposition and wet deposition)
- action of dissolution and leaching
- action of wind and water erosion
- action of hygroscopic moisture absorption due to salts
- action of biological deterioration (bio-deterioration)
- action of swelling and/or shrinkage, due to temperature and/or moisture variation
- action of differential movements and crack propagation (static or dynamic load, settlement of soil, creep phenomena)

The presence of water is a necessary condition for many of the degradation processes.
Each of different processes will be dealt with on the basis of case studies, which will consider the damage type, the cause of damage and also the essential influencing factors. This approach allows the environmental influence on masonry (with lime mortar) to be considered together with factors connected with materials.

The following examples, concerning cases of (in)compatibility, will be shown:
- frost damage, related to the choice of a re-pointing mortar
- salt crystallisation related to re-pointing (efflorescence and crypto-florescence)
- formation of expansive compounds, e.g. thaumasite (ettringite, Friedels salt, ..) in the original bedding mortar
- gypsum formation, black crusts, bursting: the effect of air pollution
- swelling gypsum formation inside buildings (windmills, church towers)
- leaching / encrustation of mortar constituents
- erosion of mortar due to mechanical forces of water and wind
- weak mortar (early weathering) due to a wrong mortar composition and to lack of knowledge on traditional workmanship
- effects of sea salts on lime mortar
- hygroscopic behaviour of mortars containing salts
- biological growth on masonry
- large displacement, without cracking
- poor execution or lack of maintenance
- damage due to creep of historic masonry
- damage due to lateral load
- earthquake damage (cracks) due to shear stresses

Table 2.1 Important factors for damaging processes

Environment	Moisture supply	Rain, snow
		Ground water
		Surface water
		Floods
	Salt supply	Soil or surface water
		Use (stable, salt storage)
		Air (aerosol)
		Floods
		De-icing salts
	Air pollution	
	Temperature factors	Variations
		Extremes
	Exposure to fire	
	Dynamic loads	Earthquakes
		Wind
		Traffic
		Vibrations
	Differential settlements	
Materials	Mortar composition	Binder type
		Binder quantity
		Grain size distribution sand
	Properties brick/stone and mortar system	Porosity
		Capillary transport
		Adhesion / bond
	Presence of salts in the materials	
Design	Original structural design of the building or modifications	
	Choice of combinations of materials	
	Detailing of the building	
	Choice of repair methods and materials	
Workmanship & construction procedures	Quality of execution	Quality of execution Mortar mixing on site
		Way materials are cured and curing conditions
		Protection of fresh mortars (masonry)
	Lack of knowledge on (traditional) workmanship	
Maintenance	Lack of maintenance	
	Inappropriate maintenance Programme	

3. Case Studies

This chapter provides illustrated case studies of monuments that were originally built, using lime mortars that are suffering from some form of damage. Natural weathering processes, as well as degradation due to incompatibility with new mortars used in restoration will also be taken into account.
For each example, an ordered logical approach to the problem based on expert experience has been given to diagnose the cause of the damage. Although it may seem obvious, it is vital that any investigation should include an evaluation of the environmental circumstances that could be responsible for the damage process, as well as an assessment of the type of construction involved.
Reference has also been made to particular analysis techniques that may be useful in diagnosing the problem. With regards to sampling (often necessary for reaching a sound diagnosis), a general procedure can be found in [Hughes&Callebaut, 2000]. Finally a methodology on how the damage and repair could be dealt with is also provided.

3.1 Frost damage related to the choice of the re-pointing material

Frost damage to fresh (not carbonated) lime mortar is well known as a damage form. A (pure) lime mortar needs more time (as carbonation is a slow process [van Balen, 1991]) than cement mortar to develop enough strength to withstand the combination of moisture and frost. Generally speaking it is advisable that masonry construction using lime mortar should be seasonal, and not undertaken for a few months before any possible frost period. Any existing new mortars should be provided with very good protection to prevent it from becoming wet.
The fact that frost damage can also occur to old lime mortars became evident several years ago. In the EU 5th Framework Programme, research was carried out into the causes of the mechanism and the factors that play a role within it [Contract ENV4-CT98-706]. An example of this type of damage follows.

Description of damage

Bulging of the brick masonry in the upper section of a small tower (see Figure 3.1.1), which is part of a surrounding wall. Pointing mortar has been pushed out which in most cases was accompanied by layering of the bedding mortar in layers parallel too the bed face of the bricks.

Fig. 3.1.1 Bulging of masonry. This part of the wall was already furnished with new pointing.

Fig. 3.1.2 Layering of the bedding mortar.

Investigation

The investigation commenced with a visual inspection of the external masonry. The damage appeared to concentrate on the prevailing (driving) rain side of the building (SW). The visual examination was followed by the removal of some masonry by means of drilling cores in the bulging masonry. Once the cores were removed the layering in the bedding mortar became visible (see fig. 3.1.2).

Such expansive damage types can be caused by the formation of large volume chemical compounds or by frost damage to the bedding mortar and therefore further investigation was required.

Using XRD (X-ray diffraction analysis) it was found that no swelling compounds were present in the mortar and as a result, cores with undamaged bedding mortar, from a less exposed zone of the same building were submitted to a frost test. The damage resulting from the frost test was the same as the one found in practice (see fig. 3.1.3) .

Fig. 3.1.3 Layering of the bedding mortar caused by frost test on a core of Ø 50 mm.

In addition to the evidence above Fig. 3.1.4 shows the moisture distribution over the wall height, as measured in the wall between the towers, which showed the very obvious high moisture content in the mortar and the low moisture content in the brick. This phenomenon is regularly found in cases of frost damage to bedding mortar.

The most likely cause for the observed phenomena is probably due to the pores of the mortar being finer than those of the brick. Investigations into pore size distribution of bedding mortar and brick using mercury porosimetry could clarify the matter; see chapter 'Porosity of Mortars'.
The moisture distribution as found over the height of the wall is indicative of the presence of rising damp; however it is possible that rain water penetration could have contributed to the high moisture content.

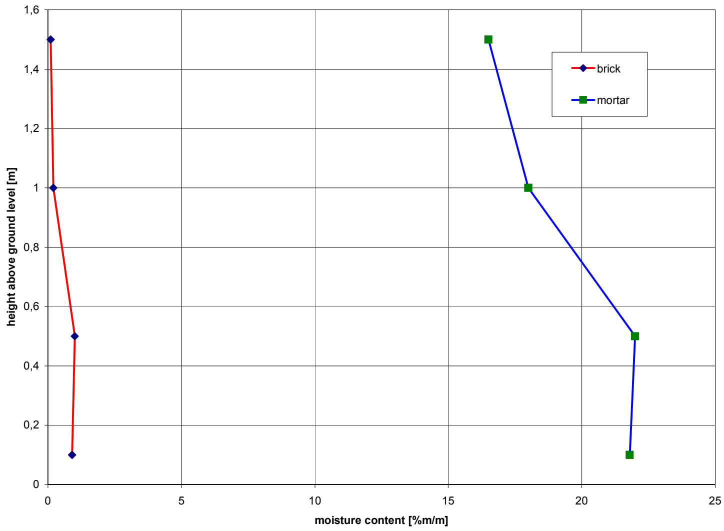


Fig. 3.1.4 Moisture distribution over the wall height for both mortar and brick.

Cause
The damage process is due to frost action on the (too) wet bedding mortar. Damage to the bedding mortar (layering) occurs together with an increase in volume, which takes place preferentially on the external side of the wall, where the damage is the most severe. The irregular damage distribution over the wall section leads to bulging and results in the pointing mortar being forced out. Bulging only occurs in the case of relatively thin walls, for thick walls the increase of volume can lead to masonry spalling with layers of the masonry, up to a few cm thick becoming detached.

Factors
Rain water penetration (damage preferentially occurring on the side of the building facing the prevailing rain) and partially rising damp are the factors related to moisture transport. Within the bedding mortar-brick combination there is such a difference in capillary pore size distribution (the mortar has much finer capillaries than the brick); that the mortar is most likely to draw moisture from the brick, whereas the opposite is unlikely. The bedding mortar, can therefore remain very wet for a long time, and is thus more prone to frost damage.

Because the damage had appeared after re-pointing (using cement mortar) research was undertaken to discover whether the new pointing could have delayed the drying process enough to explain the occurrence of the damage. The research showed [van Hees et al., 2002] that the drying behaviour indeed may have been influenced by the choice of the pointing mortar. Other factors, like conversion of parts of the binder material into gypsum, may have caused an additional weakening of the bedding mortar.

Restoration - repair

The ingress of moisture should be avoided as much as possible. Because the old, frost susceptible, bedding mortar is maintained in part of the wall section, it is possible that new frost damage could occur: in fact this part of the mortar can still become wet. When the temperature drops below freezing for a relatively long period of time, even the presently damage free section could freeze. Therefore it is advisable to consider the possibility of treating the masonry against rising damp [van Hees&Koek,1996] and even of protecting it against rain water, using a water repellent.

As far as the choice of the repair mortar is concerned the following philosophy might be adopted. The new mortar should be as durable as possible, without causing any damage to the original materials. A 'sacrificial' mortar, i.e. a mortar with a rather low internal coherence could prevent damage to the brick, because it would collapse before the load is transferred to the brick. By creating a mortar with a high porosity, frost damage to the new mortar can be prevented. Research in this field was undertaken in the EU research project 'Pointing in historic buildings' (Contract ENV4-CT98-706), [van Hees et al., 2001].

It seems that an adequate restoration technique would be to remove the damaged mortar and replace it with a repair mortar, which used a sand whose particle size distribution produced a mortar with a greater porosity than the one it was replacing.

In addition the use of an air entraining agent (leading to a better frost resistance [Ashurst&Ashurst, 1989]) could be proposed. This mortar should be applied in a semi-plastic consistency in a number of layers and should be directly tooled (no distinct pointing should be made on top of the substituted bedding mortar). A depth of 80 – 100 mm, for a joint width of 10 mm, would be the maximum that could be treated in this way.

3.2 Salt crystallisation related to re-pointing

Some of the most frequent problems encountered in monuments are those connected with salt crystallisation. Those salts, which are considered to be the most damaging, include sulfates, chlorides and nitrates. The origin of the salts can be due to the soil (ground water), the environment (e.g. close to the sea), the use of the building (e.g. stables, salt store), or the building material itself (e.g. clay brick which can contain a significant quantity of sulfate, depending on type of clay, firing temperature and type of fuel).

Types of damage that may occur are:

- crypto-florescence; in this case salts crystallise in the material or in the zone where two materials have an interface; this phenomenon could cause spalling of the material or push out of pointing.
- conversion of mortar components containing salts to produce compounds with a larger volume, such as ettringite and thaumasite.

Two examples of salt damage are given, the first is an example of pure crystallisation, the second is an example of the formation of expansive compounds.

Description of the damage (due to pure crystallisation)

In the freestanding walls surrounding a church the (new) pointing has been forced out; and crypto-florescence is visible. Fig. 3.2.1 shows a close-up of the damage.

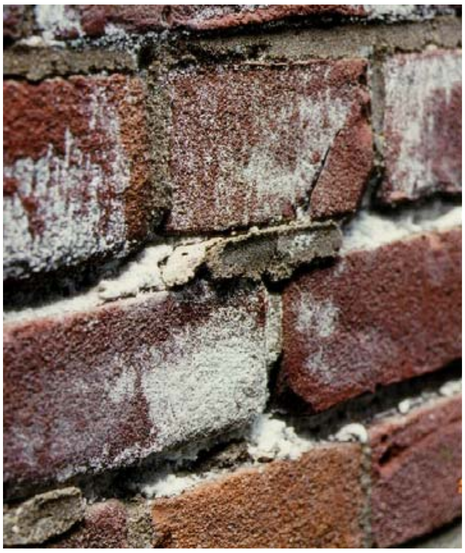


Fig. 3.2.1 As a result of salt crystallisation at the interface between bedding and pointing mortar the pointing has been forced out.

Investigation
Initially a visual inspection is carried out during which, pointing in zones that appear undamaged are checked to hear whether it sounds hollow; sampling is then carried out to investigate the bond between bedding and pointing mortar as well as for the analysis of salt content. XRD is a useful technique to determine the composition of the efflorescence. In addition, an investigation can be carried out to determine the source of moisture responsible for salt transport: was it only due to rain penetration or were there other possible sources of moisture for example rising damp? The answers to these questions are important when considering the appropriate remedial actions.

Cause
Salt crystallisation has occurred behind the ('new' cement) pointing where if the space was full new crystallising salt can exert a very high pressure; causing the pointing to be forced out.

Factors
Rainwater or under some circumstances, rising damp, transports the salts. Salt (and moisture) transport take place from the wetted (rain) side of the wall to the opposite side.
The brick most probably contains a lot of sulphate.
Between the old (lime) mortar and the new cement mortar very little moisture transport is possible during the drying process, as a result of (i) a difference in capillary system, see chapter 'Porosity of Mortars' or (ii) voids, due to the fact that the pointing mortar was not pushed in enough during application.

Restoration - repair
An adequate protection against water penetration is considered to be the most important step in treating the problem.
The presence of a coping unit on the (free-standing) wall is essential. In the case of rainwater penetration at only one face of the masonry (and drying at the other face) the wetted face

should be protected. A rendering or a water repellent treatment [van Hees,1998] at the rain oriented face could be used. After taking the measures against water penetration, the use of a repair mortar, with characteristics, comparable to those of the original bedding mortar should be considered. When applying the mortar every effort should be made to ensure that the pointing mortar is pressed up well against the bedding mortar.
If protection against water penetration is not possible and if the salt efflorescence is composed of sulfate, there are certain risks involved in the use of almost all types of mortar binders: the use of air lime in the re-pointing may lead to swelling of the new mortar, as a consequence of gypsum formation. The use of hydraulic lime may lead to thaumasite formation (see next section), whereas the use of a non sulphate resistant cement may lead to the formation of ettringite.

3.3 Formation of expansive compounds, like thaumasite in the original bedding mortar
Sulphate may form expansive compounds such as ettringite or thaumasite with components of mortars. In case of hydraulic lime or trass lime mortars mainly thaumasite may be formed (van Hees, 2002). The sulfate may derive from the atmosphere (SO_2) or from the brick (due to low firing of sulfate containing materials).
Thaumasite ($CaCO_3.CaSiO_3.CaSO_4.15H_20$) is a compound that can be formed by the reaction of mortar components with calcium sulphate and water but has no binding capacities. The conditions required for the conversion include a high sulphate content combined with a (very) high moisture content at a relatively low temperature (generally < 5 ºC is considered the threshold temperature however, from some of the examples shown in this section higher average temperatures are possible).
The reaction/conversion results in an increase in volume causing the mortar to swell.
The mortar needs to contain calcium carbonate and calcium (mono)silicate. Sulphate is necessary in the form of calcium sulphate (gypsum). A high moisture load is necessary, not only because the compound itself contains water), but also in order to allow sulphate transport from the brick into the mortar. More specific information can be found in (Puertas et al., 2000), (van Balen et al., 2001).

Description of the damage
A typical damage case is the spalling of masonry (brick and mortar). Sometimes the damage shows in the form of pointing that is being pushed out and is accompanied with swelling of the bedding mortar. The damage pattern can appear very similar to frost damage.
In other cases severe vertical (and sometimes horizontal) cracks may show in the masonry and that can be confused with structural cracks (fig. 3.3.1).
In the examples of fig. 3.3.2 and 3.3.3 spalling of both brick and mortar in the masonry of the passage (way) of a historical arch bridge are shown.

Fig.3.3.1 Wide (vertical and also horizontal) cracks, on the first sight looking like structural cracks, were found to be caused by swelling compounds in the inner part of the masonry.

Fig. 3.3.2 Damage in the passage(way) of a historical arch bridge: spalling of brick and pointing is pushed out.

Fig. 3.3.3 Start of damage visible in the hole left by the drilled core (see arrow for location): a layer of the brick begins to detach, the bedding mortar shows loss of cohesion.

Investigation

This type of damage can be due to either frost damage or to the formation of expansive salts. Sampling is always necessary to determine the origin of the damage and to understand what moisture source(s) play a role in the process. Fig. 3.3.4 shows the moisture distribution with respect to distance from the bridge deck and distance from surface. The moisture content is extremely high, whereas the hygroscopic moisture content is relatively low, and especially in the exterior 25 cm of the masonry.

In addition to the powder samples, taken to measure the moisture distribution, cores were also drilled over the wall depth; during this operation it could be seen that a soft red brick was used from a depth of approximately 40 cm. These bricks, fired at a low temperature, could have a high sulphate content.

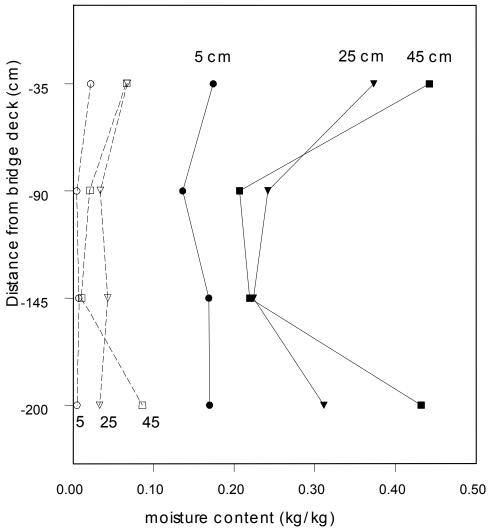


Fig. 3.3.4 The moisture content (and distribution) in one of the bridge pillars as a function of the distance from the bridge deck and as a function of drilling depth (5, 25 and 45 cm). The continuous lines indicate the moisture profile. The dotted lines represent the hygroscopic moisture content at 93% RH and give an indication of the salt profile.

Petrography (PFM) applied to thin sections of the material is a suitable method in determining the named compounds as well the composition of the mortar. [Larbi&van Hees, 2000], [Lindqvist&Sandstrom, 2000], [RILEM,2001]. The compounds can be further investigated by means of SEM/EDX. If thaumasite or ettringite are found it is advisable to locate the source of the sulphates.

The thin sections showed concentrations of crystals from which cracks start (see fig. 3.3.5); this sample came from a core taken at a distance of ≈ 200 cm. below the bridge deck(see fig. 3.3.4). The crystal concentrations are situated at a depth of 5-10 cm from the surface.
The picture in fig. 3.3.5 shows the transition between a decayed zone (A) and an undecayed zone (NA). In the decayed zone the binder is partly dissolved, resulting in a higher porosity (lighter colour) than in the undecayed zone (darker colour).
The decay appears due to the formation of needle like crystals, that are present as concentrated pockets (KR). By means of SEM/EDX it was found that these are mainly thaumasite. Thaumasite is not hygroscopic, which explains the low hygroscopic moisture content (fig. 3.3.4).

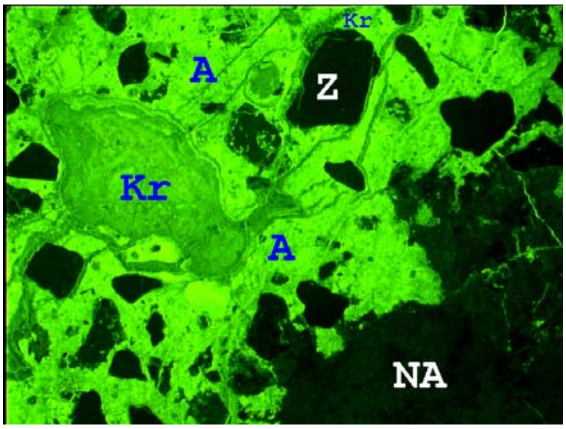


Fig. 3.3.5 PFM picture (fluorescence) of decayed mortar. The dark not decayed zone has lower porosity than the left part (lighter colour) the porosity is clearly higher; this is due to the dissolution of the binder. 'A' is used to indicate the decayed zone, 'NA' for the undecayed zone. The decay is shown by this phenomenon as well as by concentrations of structures in crystal form indicated by 'Kr'. Dimensions of the section shown are 2,7 x 1,8 mm (magnification: 50x). Location -/- 200 cm below bridge deck, depth 5 to 10 cm from the wall surface (see fig. 3.3.4).

Cause
The formation of thaumasite in the bedding mortar (a lime mortar with hydraulic, trass like components), led to micro cracks; which on a macroscopic scale became apparent as spalling of the masonry.

N.B. Spalling is the consequence of the increase of volume caused by expansive salts forming near the surface of the masonry, which leads to compressive stresses. In the case of thin masonry this could lead to bulging however, for thicker masonry this is not possible and thus spalling occurs.

Factors
Water penetration, (downwards through the bridge deck on top and the bridge vaults) is the first important environmental factor. The presence of sulfate is the secondary factor the source of which can originate from the masonry materials themselves, namely from the soft red brick and from the environment, namely from the diesel engines of the canal touring boats. A determining material factor is the presence of a hydraulic lime mortar or of certain hydraulic components within the lime mortar.

Restoration – repair
Reduce moisture penetration as much as possible by inhibiting the ingress of moisture through the bridge deck and the bridge edges)
The production of the SO_2, from the diesel engines of the canal touring boats, should be limited as much as possible.

For the repair mortar, a low strength mortar with characteristics similar to the old bedding mortar should be considered. However it is possible for similar damage to reoccur sources of moisture were not successfully eliminated. The use of a sulphate resistant binder might help to reduce risks.

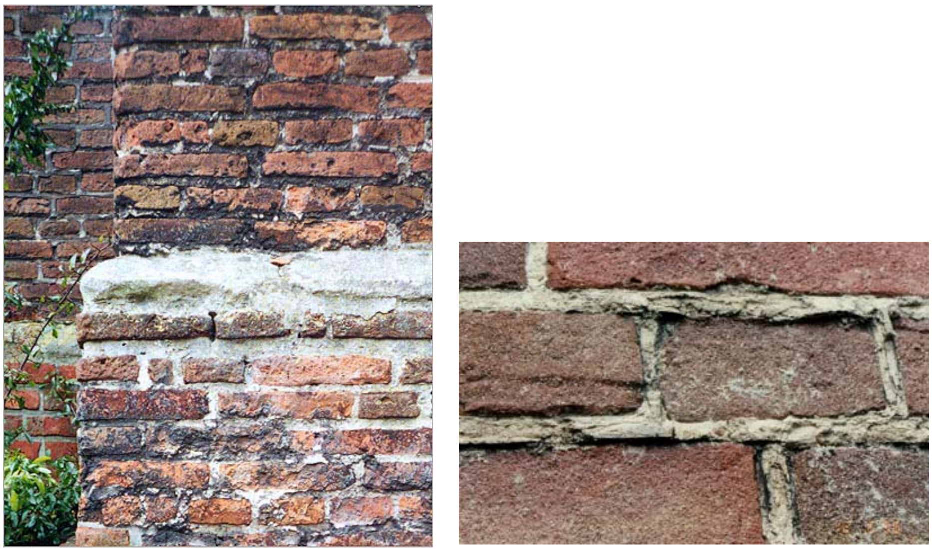
Further requirements are: i) achieve a good contact between the repair mortar and the old mortar, aiming at making moisture transport (and possibly salt transport) towards the exterior possible (drying of construction and transport of salts to the surface) and ii) aim for rather low adhesion of the repair mortar to the brick, so that in the case of salt crystallisation, the new mortar can be pushed out, without causing damage to the surrounding brick.

3.4 Gypsum formation, black crusts, bursting: the effect of air pollution

Gypsum formation in lime mortar pointing can occur due to action of SO_x in the atmosphere, especially in the form of dry deposition, a gypsum crust may appear on elevations, which are not exposed, to strong rainfall. Such a crust appears originally white however if great quantities of soot particles are present in the atmosphere the surface of the gypsum crust turns black. The formation of gypsum is accompanied together with some swelling and as such, after growing to a certain thickness, the gypsum crust can detach, leaving a damaged surface behind. This process can occur more than once so the effect can be progressive. Sulfate can also be present in the brick; from which, it can migrate to the mortar. The formation of gypsum in the mortar can cause swelling and eventually bursting. During this process, under given circumstances, so much pressure can be exerted on the surrounding brick or stone to cause it to exfoliate or spall.
N.b. in some European regions gypsum mortars have been in use for re-pointing; according to [Knöfel & Schubert, 1993] they were sometimes treated with oxalates for better durability.

Description of the damage

In fig. 3.4.1a and 3.4.1b two typical examples of the damage are shown. Fig. 3.4.1a shows bursting of the pointing mortar. In the external part of the mortar loss of cohesion also occurs. In fig. 3.4.1b the presence of a black crust on the mortar is visible, part of which has already detached.



b. a.

Fig. 3.4.1a Detail of the pointing mortar bursting.
Fig. 3.4.1b Partially detached black crust on mortar joints.

Investigation
Investigation of the decayed material by means of soluble salts analysis or alternatively using XRD or SEM/EDX is generally all that is required. Petrographic examinations on a thin section can be carried out, but this is not usually essential. Samples of the brick should be investigated in order to assess the source of the sulphate (is the brick or the environment the main source?).

Cause
Gypsum formation occurs, due to the conversion of lime into gypsum. This conversion is accompanied with an increase of volume, which makes the pointing eventually burst open. A consequence of the conversion and increase in volume is that the mortar becomes weaker and crumbling occurs when more sulphate is formed. In parts of a building, not exposed to driving rain, dry deposition of air pollutants (including soot particles) may lead to the crust appearing black.

Factors
When a black crust is present, the main environmental factors leading to the decay are *dry deposition of air pollutants* (especially SO_2 and soot particles) and the presence of moisture. The most important material factor is the presence of *lime mortar* (because of its content of $CaCO_3$).
In the case of bursting, without a black crust, the sulphate may mainly originate from the substrate, together with the same other factors as described under black crust.

Restoration - repair
In the case of black crust formation, where the sulphate source is external and where the deposition rate is low and the black crust formation only develops slowly, a lime mortar comparable to the original could be used.
In the case of sulphates originating from the brick, it is important to eliminate all possible moisture sources.
In the case of gypsum formation from inside, where the supply of sulphate would be fast and concentrated, the use of a sulphate resistant binder might be considered.

N.b. When re-pointing is done with ordinary Portland cement mortar, similar damage as described above can take place.

3.5 Swelling gypsum formation inside buildings (windmills, church towers)
The type of damage and the damage process described in this section relate to walls exposed to driving rain, causing water penetration, and can be found on the elevations of church towers which face the prevailing wind. For windmills, due to their often inclined shape, problems may be found on all elevations. Sulphate may originate from air pollution or from the masonry brick (see also the description in sections 3.3 and 3.4). The process may lead to severe spalling of the masonry inside the buildings concerned. Generally a very high ventilation speed (chimney effect in towers and windmills) is observed in these cases and it appears that it is the combination of that fact and a high moisture load that are the important factors in this process.

Description of the damage
Fig.3.5.1 and 3.5.2 shows the damage inside a windmill and focuses on were the layering within the brick and plaster occurred, together with crumbling of the bedding mortar inside the wall and finally crumbling of the brick surface.
In this specific case a water repellent had been applied to the exterior face and damage was

reported to have increased after that treatment.

Fig. 3.5.1 Exfoliation (layering) of plaster and masonry inside the windmill.

Fig. 3.5.2 Crumbling and bursting of the brick inside the windmill.

Investigation

It is of primary importance to know how the moisture reaches the interior of the windmill. Therefore the moisture distribution over the wall depth was measured (see fig. 3.5.3).

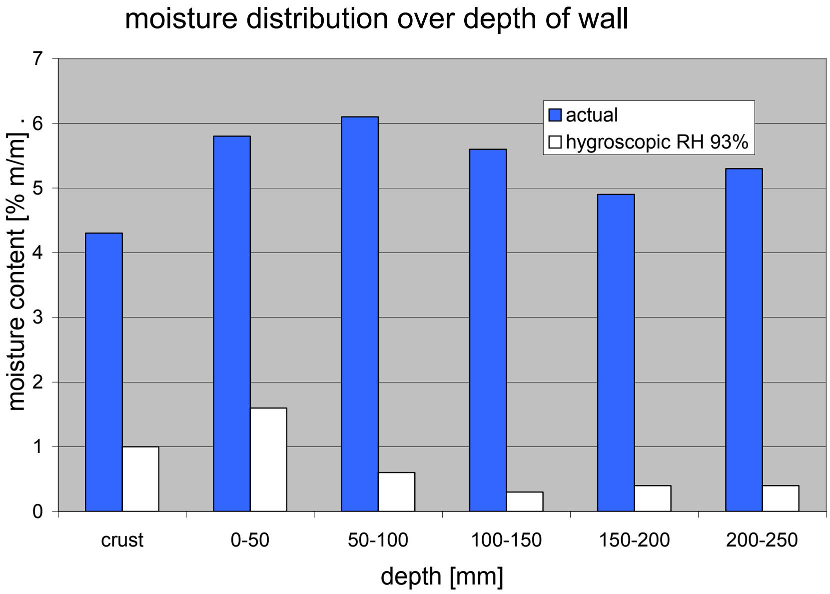


Fig. 3.5.3 Moisture distribution over the section of the wall (depth from the inner surface). Also the hygroscopic moisture content is shown.

The hypothesis was that the damage was caused by salt crystallisation and as such the efflorescence and/or the detached material should be investigated by means of XRD or of SEM/EDX or alternatively by a soluble salt analysis (see fig. 3.5.4 and 3.5.5). If necessary the composition of the mortar can be ascertained by means of PFM microscopy applied to a thin section.
The moisture profile over the wall depth showed a rather high moisture content, which indicated that the moisture derived from an external source (rain water). The hygroscopic moisture content indicated that the hygroscopic salt concentration was low; which agreed with the results of the SEM/EDX investigation, showing that calcium sulfate (a non-hygroscopic salt) was present.

Fig. 3.5.4 SEM photo of the decayed zone of the brick showing calcium sulfate (most probably gypsum) crystals.

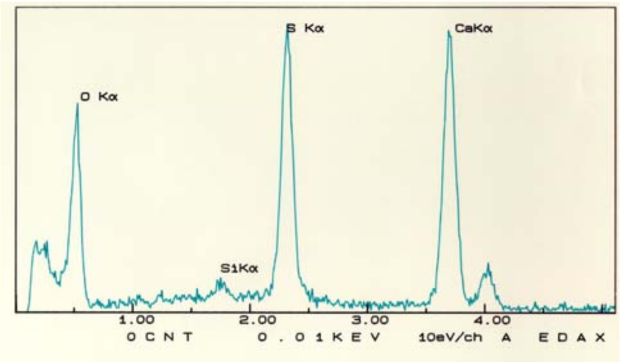


Fig. 3.5.5 EDX showing the presence of Ca, S and O: $CaSO_4$.

Cause
The cause of the damage was the formation of gypsum: both the lime in the mortar and the lime present in the brick have been transformed into gypsum. The formation of gypsum leads to an increase of volume in the part of the masonry concerned, which resulted in a kind of layering of the rendering and to spalling or scaling of the masonry. Also the bursting of the brick can be attributed to the transformation of parts of the surface layer into gypsum (cf. fig. 3.5.2). Finally frost action may have and could still contribute to the damage (cf. fig. 3.5.1).

Factors
The main environmental factor is the penetration of rainwater (the initial water repellent treatment did not work successfully at the mortar – brick interface, leading to an even higher moisture load at the interfaces). The main influencing material factors are in this case: the lime mortar ($CaCO_3$ available) and the low fired brick on the inner part of the wall (this type of brick most probably contains a high amount of Na_2SO_4). In this case the brick is the most probable source of sulphate. Furthermore the indoor climate in the windmill (strong air movement) plays a role in this damage phenomenon. Due to the water penetration from outside and the strong drying action on the inner face of the wall, gypsum was formed near the inner surface.
A second degradation process, possibly playing a role in this case is frost action. The most important environmental factor is the (Dutch) climate in which typical frost damage conditions may occur. Frost damage conditions are characterised by a period of extreme moisture load, immediately followed by frost. Both mortar and brick may, in the case of the windmill concerned, become very wet on the interior face of the masonry. The determining material factors for the damage are both the rather weak, low burnt brick on the inside and the mortar, of which the structure has been weakened by the formation of gypsum.

Restoration - repair
Prevention of water penetration from outside can generally be considered as a repair option, however in the case of windmills (due to movements), it is very difficult to achieve with a water repellent, as is shown by the case study.
Rendering and loose parts of the masonry have to be taken off. The bedding mortar has to be taken out over the decayed depth (loose parts), until sound material is reached. A repair mortar based on either a kind of sacrificial mortar or a mortar based on a sulphate resistant binder should be considered.
Finally the interior walls can be finished using an open porous (sacrificial) render.

3.6 Leaching / encrustation of mortar constituents

In the case of leaching, mortar components are transported towards the wall surface, where they can form encrustations.

Description of the damage

The following are examples of the described phenomenon; a wall, which is part of the fortifications of a monumental city, a restored historical bridge and a tunnel (see figures 3.6.1 a,b, c). All are cases of encrustation due to leaching of the binder.

a. Fortification walls (Naarden – NL)

b. Historical bridge (Amsterdam)

c. Tunnel (Nanjing – China)

Fig. 3.6.1 Examples of encrustations. Especially in the case of the wall belonging to the fortification (a) the hard and glassy structure, which is difficult to remove, is clearly visible. Leaching may sometimes lead to the formation of stalactites as the Nanjing example (c) is showing.

Investigation

Initially a visual inspection of the building details in relation to rain penetration is required. Moisture distribution (in the case of the fortification) in the *earth retaining* wall may also be investigated. In addition an analysis of the encrustation should be carried out in order to determine its material composition. (Calcite and or a combination of calcite and silicate or perhaps products from alkali-silica reaction are possible components).

Cause

This phenomenon is caused by the deposition of leached mortar components (not yet carbonated lime). In the case of lime mortars the deposition is composed of calcite-like material, but, in the case of hydraulic lime and especially cement mortars, it may also contain silicates. In that case the encrustation is more or less glassy and the adhesion to the substrate may be very good. The leaching process often starts in joints that lie approximately two to three stone/brick courses lower than where the rainwater penetrates and relates to the fact that masonry can 'bear' a certain water pressure (water column of penetrated rain water).

Factors

Rainwater penetration, which in most cases travels downwards, or water that penetrates from the back side of earth retaining walls are the determining environmental factors in these cases. Also the acidity of the rain can be an additional factor in this process.

Also under certain circumstances excessive pre-wetting of the masonry before re-pointing and excessive rainfall shortly after re-pointing may be contributing factors to this degradation process.

The type of mortar (binder) and, perhaps the presence of an air entraining agent determine the severity of the deposition. The influence of the air entraining agent could be related to a lower water retention of the mortar and as a result more lime containing water may be absorbed by the surrounding bricks. The result will produce a relatively strong calcite efflorescence; whether a stronger leaching (encrustations) will also result is not clear yet.

Restoration - repair

It is of primary importance to eliminate the harmful moisture. Excessive ingress of water should be avoided by for example covering of the upper part of the wall, filling of fissures/cracks, sealing the backside of earth retaining walls.

With regards to cleaning: pure calcite efflorescence may disappear over the years as calcium carbonate (not very soluble) is first transformed, due to the acidity of (natural) rain water, into calcium bicarbonate (easily soluble), which will eventually be washed off. A very carefully chemical treatment with HCl (hydrochloric acid) could work quickly, however it is generally not advisable and not necessary.

Encrustations (combinations of calcite and silicate) should be preferably taken off mechanically (manually) or can be (carefully) treated with HF (hydrofluoric acid); if the adherence is very strong, abrasive techniques often give the best result. The application of these techniques depends strongly on individual cases and adequate and appropriate expertise is always necessary.

In the restoration of buildings it should be noted that lime mortars can cause calcite leaching, whereas cement mortars can cause both calcite and silicate leaching. Calcite is easy to eliminate, whereas the combination of calcite and silicate can lead to hard, well adhering and difficult to eliminate encrustations. The chance of leaching seems to be reduced when trass lime is used.

3.7a Erosion of old mortars due to mechanical forces of water and wind

Description of the damage

Erosion damage is frequently observed on walls that are exposed to heavy wind and rain loads and is often seen in castles or town walls standing on hills. Initially the softest material (generally the mortar) becomes gradually loose and detached, but later even stone and brick may exhibit symptoms of erosion. Apart from the orientation of the masonry, the fine material carried by the wind appears to play a major role in initiating and the intensity of the erosion. If this material is siliceous, the attack will tend to proceed at a higher rate. Fig. 3.7.1 shows the tower of a Greek castle suffering from erosion.

Fig. 3.7.1 a. Tower of the castle of Serbia (N. Greece, 11th century) suffering from erosion; b/c. details of the eroded lime mortar.

Fig. 3.7.2 shows the masonry from an old town wall, constructed with a lime mortar; the mortar erosion depicted here, is a secondary effect after primary leaching of the binder due to rain water, flowing over the wall surface.

Fig. 3.7.2 Detail of eroded lime mortar of an old town wall.

Investigation
In general a visual inspection is considered sufficient to diagnose the problem. However, when quite fresh lime mortar already shows signs of erosion, further investigation should be carried out, in particular into the composition of the mortar and the possible presence of salts (in particular chlorides - especially in coastal areas).

Cause
Rain water, flowing over the masonry surface and driving rain, cause some of the lime to become dissolved. Carbonic acid from the rain water converts the less soluble calcium carbonate into easily soluble calcium bicarbonate: which leads to the deposition of mortar constituents on the wall surface. This may be followed by erosion due to the mechanical action of water and wind which in this case is a secondary effect.
The formation of the relief (little holes) in the structure of the mortar indicates differences in density or irregularity in the composition of the mortar (for example unequal compaction or bad mixing).

Factors
A severe rain/wind load carrying sand particles, together with material factors and especially the chemical properties of the mortar and the homogeneity of the composition of the mortar (mixture) are factors determining the rate at which this process occurs.

Restoration - repair
It is necessary to prevent as much as possible the high quantities of water, which flows over the masonry surface. Special attention should be given to prevent any detailing producing high volumes of water discharging over specific areas of the wall.

Lime mortar is not highly resistant to excessive rainwater streaming over its surface and mortar based on air hardening lime is even more susceptible. There is a difference between fresh mortar $Ca(OH)_2$ which is more soluble than carbonated mortar, $CaCO_3$. There are some alternatives, which include the use of hydraulic lime or trass lime. The latter should only be applied during the warm season and should be kept wet for a long time, in order to avoid the risk that, after a quick carbonation of the lime, the trass would remain as an inert aggregate, leading to a rather weak mortar, once again prone to the described decay.

3.7b Weak mortar (early weathering) due to wrong mortar composition and lack of knowledge on traditional workmanship
The choice of a pointing mortar should be designed so that it will appropriate for the conditions under which it will serve. The use of trass-lime mortars for example was very common in the Netherlands, especially in those structures that had to deal with a high moisture load (bridges, foundations etc.).
Trass is a pozzolanic material and is only reactive in the presence of $Ca(OH)_2$ and water. It is important to avoid quick drying of this type of mortar as failure to do so will result with a mortar of low coherence and as such, low durability.

In the past 10 to 15 years, trass-lime mortars have often been used for re-pointing in historic structures. The reasons for their use have generally been nostalgic, especially when used in historic structure to produce compatible mortars (less hard and stiff, but ‘tougher’ than cement mortars). However it has to be stated that this type of mortar was hardly ever used for re-pointing purposes in the past, the reasons for which are given below.

Description of the damage

Fig. 3.7.3 shows damage to one of the façades of a church tower. The specified pointing mortar for the restoration of the tower had a composition of 1 : 1 : 6 (trass : lime : sand) by volume. Because the craftsmen complained about workability, an addition of sand (15%) was made. After only two years the pointing mortar had weathered severely and especially on the west façade.

Fig. 3.7.3 Weak, decayed trass lime re-pointing.

Investigation

Initially a visual inspection was carried out. Most of the decay was found on the (most exposed) west façade. The mortar showed almost no coherence. The pointing hardness of undamaged parts was measured with a Schmidt pendulum hammer and found to have very low values, between 12 and 20, which showed that hardly any strength had developed. Further investigations and tests determined the exact composition of the mortar, its porosity and the degree of carbonation. Petrography on thin sections and also wet chemical analysis were also useful in this case. From the research it was found that the lime had carbonated almost completely over the full depth of the pointing and hardly any reaction had taken place with the trass.

Cause

Trass by itself is not a binder. It is a pozzolan, which means that it can only serve as a binder in the presence of both lime and water. Unfortunately, this reaction proceeds slowly, particularly at low temperatures (the re-pointing was done in December/January). Therefore it is more than likely that the water evaporated before any reaction had time to take place. Quick evaporation not only stops the pozzolanic reaction, it also gives the lime the opportunity to react with the carbon dioxide present in the surrounding air. Lime converted into calcium carbonate is no longer available for the trass-lime reaction. So, the trass-lime mortar will not develop sufficient strength. In this case the addition of extra sand made the mortar even weaker.

Factors

A lack of knowledge on traditional workmanship and the inappropriate choice of materials were the determining factors in this case.
The environmental conditions (winter) added a further undesirable factor.

Restoration – repair

Initially the pointing has to be removed. Trass-lime is not the most logical binder for a pointing mortar, as the risk of fast drying (burning of the mortar) is high. The use of a

hydraulic lime mortar is an alternative, but in this case it is crucial to use enough moisture. If a trass-lime is still preferred (a trass-lime: sand ratio of 1 : 2 by volume is proposed), as well as favourable conditions which need to be chosen or created. The latter should be applied during the warm season and should be kept wet for a long time, in order to avoid the risk of the trass remaining as an inert aggregate once the lime had carbonated, leading to the production of a weak mortar, once again prone to decay.
N.b. Other pozzolanic materials may react differently from the trass described above depending on the how fine the pozolan is ground and its pozzolanicity.

3.8 Effect of sea salts on lime mortar
Sea salts may have strong effects on mortar in masonry. Buildings in the neighbourhood (within kilometres) of the sea may be affected by salt spray, where damage is mainly located on the sea facing façade. A strong effect may also occur on buildings situated in a tidal zone, in which the continuous process of wetting and drying occurs (cf. the situation in Venice). Periodic sea floods may also be a source of the salts.

Description of the damage
Fig. 3.8.1 shows an example of mortar decay caused by sea salts.

Fig. 3.8.1 Decay of pointing mortar (voids) due to sea salt action. Notice that the decay starts at the interface between brick and mortar.

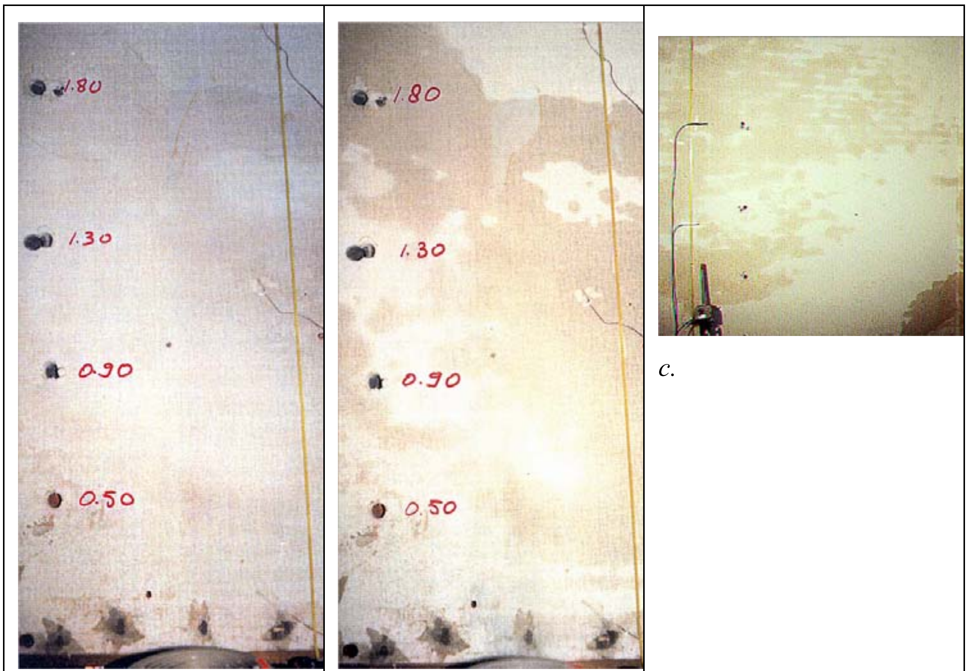
In the case of lime mortars in the neighbourhood of the sea, the conversion of $CaCO_3$ with NaCl into easily soluble $CaCl_2$ can occur allowing hard, cement based pointing mortars to be attacked. The mortar decay takes place preferentially at the interface with the brick (or stone). This is caused by the fact that the brick absorbs salts that are transported by the wind in the form of aerosols. The brick then acts as a source of salts, which then migrate into the mortar.

Restoration - repair
As the source is difficult to eliminate emphasis should be placed on the choice of appropriate materials. The best solution for historic monuments may be to use a mortar that is as much as possible comparable to the old existing mortar or else to use a sacrificial mortar.

3.9 Hygroscopic behaviour of mortars containing salts
Many salts can absorb moisture from the surrounding air, because of their hygroscopic

properties. Hygroscopic salts that are present near the surface in the pore system of a building material may show up as damp spots whenever the RH of the surrounding air becomes sufficiently high.

Description of the damage
An internal wall of a restored monument (residential dwelling) is shown in fig. 3.9.1. The damage occurs in the form of moist zones or damp spots, which seem to appear and disappear in relation to changes in the indoor and the outdoor climate.



a. *b.* *c.*

Fig. 3.9.1 Moist zones on a wall surface as a consequence of the increase of the RH of the surrounding air (in this case provoked by an in situ experiment). The numbers indicate the height of the locations of the samples above the floor. In fig. 3.9.1c the effect of the hygroscopicity of the underlying joints becomes visible.

Investigation
Powder samples (drilled) from the plaster mortar as well as from the substrate were obtained to determine their hygroscopic behaviour at different RH which will show whether or not hygroscopic salts are present; followed by an investigation (e.g. SEM/EDX, XRD or soluble salt analysis) into the type of salts that were present see fig. 3.9.2
In this specific case, an in situ experiment was undertaken: the air humidity of the room was artificially increased by means of a humidifier. The location where the wet spots appeared, corresponded with an increased hygroscopic behaviour of the powder samples obtained from the render and substrate [van Hees, 1990].

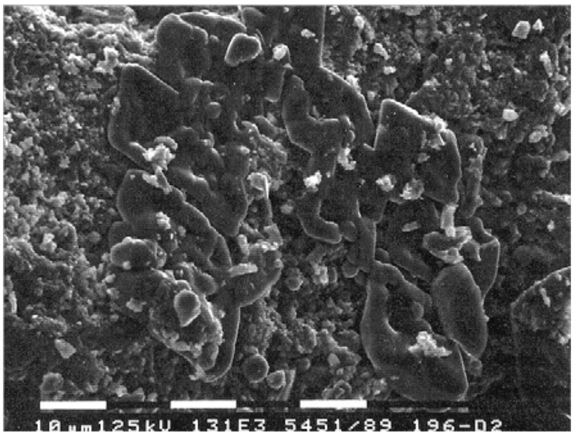


Fig. 3.9.2. SEM picture showing sodium salts (most probably nitrate, which in this case could not be ascertained using SEM/EDX) at the surface of the rendering.

Cause
Hygroscopic behaviour of salts, deposited at the wall surface and within the render, cause this phenomenon. The source of these salts may be the soil or may originate from the use of the building in the past (for example as a stable). Moisture transport (in this case due to rising damp) cause salts to be deposited at the surface.
The change in the RH of the surrounding air and the behaviour of the specific salt type can lead to the appearance and later (partial) disappearance of wet spots.

Factors
The type of salt present and changes in RH, exceeding the equilibrium RH of the specific salt type are the determining factors in this case.

Restoration - repair
If moisture sources like rising damp are present, they may have or still are contributing to the deposit of salts, this moisture source should be eliminated in order to obtain a durable solution.
Replacement of the affected plaster is necessary. This should be done with a mortar containing a very low level of soluble salts (NaOH or KOH) in the raw material. However, when the underlying structure and more specifically the joints, contain moisture and salts, the risk of new damage remains. The use of an open porous restoration mortar is worth considering in this situation.

3.10 Biological growth on masonry

Description of the damage
Biological growth of algae mosses, ferns, higher plants, is in most cases related to the presence water. Apart from technical aspects, like durability, esthetical appreciation and ecological arguments are associated with biological growths on buildings.
The growth of mosses and higher plants, with roots able to attack masonry components (especially mortars) is generally accepted by experts as damaging, as is the role of algae as being the first step to further biological attack by mosses. Therefore it is clear that in circumstances of severe algae growth on mortars in monuments the situation should be monitored and critically evaluated, extreme moisture loads should be avoided.

Figs. 3.10.1 and 3.10.2 give some examples of the growth of algae on masonry monuments.

Fig. 3.10.1 Examples of algae growth on an old city wall.

Fig. 3.10.2 Growth of algae caused by to low capacity of gutters and downpipe.

At present there seems to be no clear evidence that lime mortar is preferentially sensitive compared with cement mortar to biological growth (and more specifically algae). However several plants do appear to prefer lime mortar but for mainly physical factors such as higher water retention or quicker weathering, leading to accessibility for roots of plants) rather than in for example the alkalinity (pH is more or less equal for both mortar types).

Investigation

The investigation should generally be directed towards locating the source of the moisture.

Causes

The cause of biodegradation is mainly due to the presence of moisture. Very disturbing biological growth may appear especially when the detailing of a building is poor or gutters / down pipes leak.

Further aspects like exposition, drying circumstances and material factors like pore size distribution and water retention as well as its alkalinity may influence the growth [Decleene, 1995], [Adan&van Hees, 1998].

An important factor may also be the inclination of surfaces in relation to their roughness. It may be an important parameter for the possibility of colonisation of the surface by a sequence of algae, mosses and higher plants.

Restoration – repair
Special attention should be paid to detailing in order to avoid excessive moisture loads on the masonry. It is considered important that maintenance be carried out at an early stage in order to avoid colonisation and before roots can grow into the masonry. A general rule of thumb may prove useful to adopt: wood producing plants should be removed, whereas non wood producing plants, like, for example Hedera, should be kept under control.

3.11 Large displacement without cracking

Description of the damage
Deformation for example may be due to differential settlement of the foundations, leading to a vertical displacement of part of the wall or due to static overloading of the structure.
The favourable behaviour of lime mortars may under certain circumstances assist in the deformation without the appearance of (wide) cracks.
Lime based mortars have, in comparison with cement based mortars, a high capacity for accommodating deformations. This means that deformations, due to differential settlement etc. may under circumstances be absorbed without visible cracks appearing. Furthermore, lime mortars possess up to a certain level 'self healing' properties which allows little cracks to be filled up again over time, due to re-crystallisation (see fig. 3.11.1).

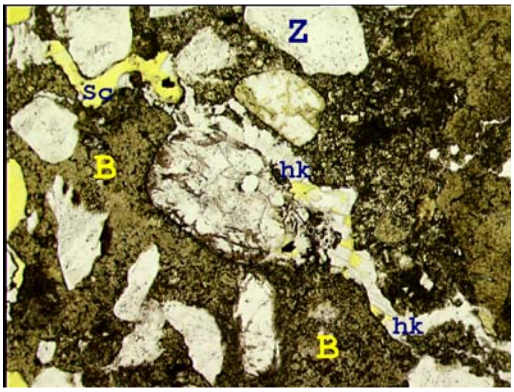


Fig. 3.11.1 PFM micrograph (size 2.7 x 1.4 mm) of a small diagonal crack in a historical lime mortar. Due to re-crystallisation the major part of the crack has been filled again (hk). Z: sand, B: binder

Fig. 3.11.2 is showing examples of deformation: a vertical deformation in a wall due to settling (a), bulging of a garden wall due to a horizontal load (b) and for the same garden wall, detachment of a cement re-pointing that can not accommodate the deformation (c).

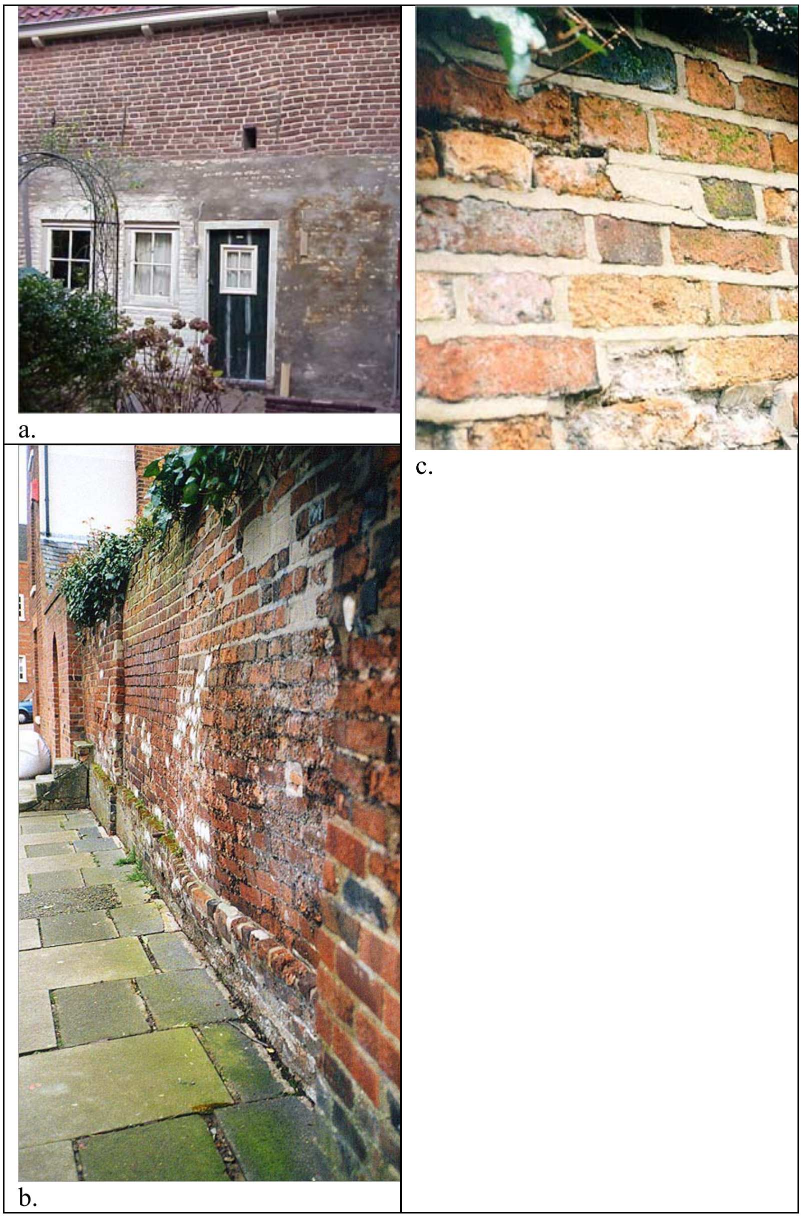


Fig. 3.11.2 Examples of deformation in lime mortars. (a). Setting of masonry in a façade. (b). Bulging of a garden wall. (c.)Detachment of cement re-pointing in the wall shown in b., not following the deformation.

Investigation

In case (a) deformation develops slowly over time, sometimes it can be ‘absorbed’ by the mortar, without (wide) cracks appearing. If wide cracks appear in this type of masonry it is indicative of a very high load, or deformation developing over a very short period of time. In such cases further investigation is necessary in order to assess the causes and carry out the required remedial measures. In the case of a very slow development of deformation, monitoring (generally at least every 3 months, in order to assess seasonal effects) would be advisable in order to prevent possible catastrophic damage in the future.

Cause
The cause of this type of deformation is generally due to the quality of the soil and may be initiated by changes in the groundwater level. It can also be associated with poor foundation construction. The reason why deformation can occur without cracking is due to the relatively low modulus of elasticity and high deformation capacity of lime mortars.

Factors
See cause.

Restoration – repair
In case study (a) deformation due to settlement over a long period time, intervention of any kind might not be required except form long term monitoring to ensure any future cracks do not develop. In case study (b) shown in fig. 3.11.2b it is important that the horizontal load should be removed and under some circumstances it could be advisable to start a monitoring exercise of the building or the structure.

3.12. Poor execution and lack of maintenance
Various types of damage to the mortar can be found due to either poor workmanship or poor maintenance and sometimes a combination of both.

Description of the damage
Figures 3.12.1 and 3.12.2 shows an area of masonry which is in a moist zone at the lower part of a column and is missing newly re-pointed mortar. The damage shown occurred only a few months after the restoration works was carried out.

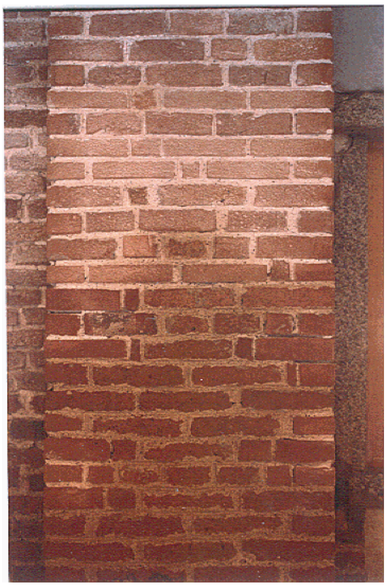


Fig. 3.12.1 Wet zone at lower part of one of the columns.

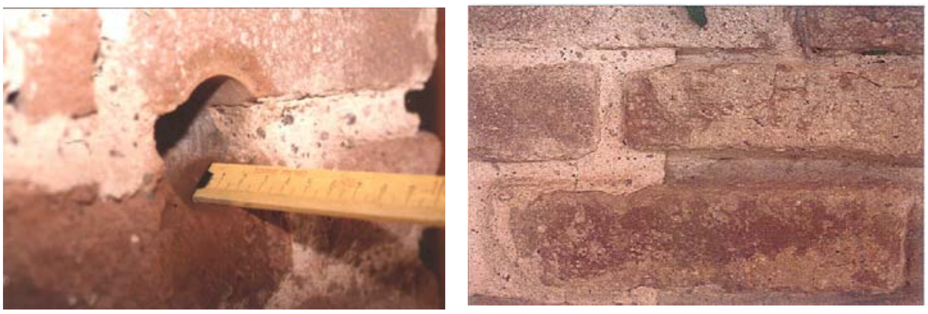


Fig. 3.12.2a/b Missing re-pointing and loss of bond (right part of a). Depth and shape (unfavourable V-shape) of the re-pointing can be seen in b.

Investigation
In the case shown, a pre-investigation had been carried out, assessing the presence of rising damp in the columns as well as the presence of salts, mainly magnesium sulphate. Magnesium sulphate most probably originates from the dolomite lime (binder and aggregates) mortar that had been used for the bedding mortar. The mortar joints showed severe weathering.
On the basis of this pre-investigation the following advice on the restoration works was given:

- to eliminate as much as possible the moisture source (water from the soil), by applying a drainage channel around the building;
- to clear the mortar joints to a certain depth and re-pointing using a mortar with a similar composition as the one used for the original bedding mortar (a hydrated lime mortar). It was further advised that re-pointing should only be carried out several months after the mortar joints had been raked out which would allow the structure to dry out and salts to crystallise.

Notwithstanding the advice given, a drainage channel was not built, a quite coarse aggregate was used and the work commenced almost immediately after the mortar joints had been raked out.
As a result of not following the advice given new damage was observed and a new investigation had to be initiated. Using the powder drilling method again, moisture profiles were obtained over the height of the structure and the presence of salts could be once again determined. Rising damp and salts were still present. By drilling some cores (see also fig. 3.12.2b.), comprising both brick and mortar joint, poor adhesion between re-pointing and bedding mortar could also be shown.

Causes
The cause of the damage types shown is rising damp due to a temporarily high ground water level, leading to the wet zone in the lower part of the columns and the crystallisation of salts behind the re-pointing (crypto-florescence). Due to poor workmanship and by not following the advice given the original cause of the problem had not been eliminated.

Factors
Rising damp is the major environmental factor. The presence of $Mg(OH)_2$ and $MgCO_3$, most probably together with sulphate from the low fired bricks, may lead to the formation of $MgSO_4$. The bad adhesion between re-pointing and bedding mortar, allows crypto-

florescence behind the re-pointing. Apart from these thermo-dynamic factors, the following factors have been of importance:

- missing drainage (bad planning and design)
- repairs that was carried out too soon after raking out the joints causing inadequate drying out of the masonry together with the efflorescence of salts on the surface;
- poor workmanship with regards to re-pointing, *V*-shaped instead of a square shaped raked joint and probably applied with insufficient pressure to produce a good contact between re-pointing and bedding mortar.

Restoration – repair

The re-pointing needs to be raked out again after which the initial advice given should be carefully followed. When carrying out the re-pointing it is important that the correct shape should be used, with joints that are fully filled with enough applied pressure to produce a good contact between old and new mortar.

Structural problems

In the previous chapters, we have presented typical mortar damage cases, identified the underlying mechanisms (causes) and reported advice on restoration and repair. In those sections, the reported damage cases have one major common point: their causes are related to damages mainly concerning the materials. In other words, the interpretation of the pathology needs to consider physicochemical actions and is firmly based on the evaluation of aspects related to microstructure.

The damage cases that follow present one important difference with the aforementioned. The mortar damage is not induced by physicochemical processes but by mechanical actions. It reveals the i n a d e q u a c y of the whole structure to withstand those actions with safety. The problem at the level of the structure (which could mean e.g. insufficient strength or overloading and stiffness, deficient connections, lack of diaphragms, foundation settlements etc.) is translated to a system of stresses, strains and crack openings at the level of the material. This is a very important issue, because it means that the advice for restoration and repair should not refer solely to materials issues (the mortar composition and restoration). They should include an analysis of the structure and the identification of the structural problems that are at the basis of the induced damage and consider their remedy. No materials repair is sufficient, if the structural problems are not evaluated and solved, where appropriate.

3.13 Damage due to heavy load and creep

Due to heavy load or under circumstances to creep, different types of damage may show, like vertical cracks in the masonry and leaning of the complete structure. Leaning can be related generally to heavy load (dead weight) in combination with soil settlement; this may go together with visible cracks.

Creep in historic masonry may be a serious problem. The order of magnitude of creep of historic masonry, can be considerable.

Creep in compression, due to dead loads, generally leads to (deep or trans-sectional) vertical cracks. This type of damage (passing through cracks) is typical of slender structural elements like stone or brickwork columns and piers and of heavy but tall structures like towers (and heavy structures as to be found in ancient churches, palaces or castles). It develops on a shorter or longer term, depending on the brittleness of the material and is due to the creep behaviour of the material when stressed beyond the elastic limit. Cracks can propagate very slowly for decades or even centuries, but at the end if the phenomenon is not stopped, the element or structure can collapse suddenly. Cracks affect both the mortar joints and the bricks (if the masonry is brickwork) but mainly the mortar joints if stonework is concerned (however when the situation is critical they may also affect stone units). Both wide and/or a large diffusion of thin cracks may appear in this situation. They do have however a common factor in that the cracks are either completely pass through the section of the wall or extend deep inside the wall.

a. Heavy load

Description of the damage

The damage was detected on a bastion of a fortification wall. The position of the bastion is shown in fig. 3.13.1. Quite large cracks had developed at the exterior of the walls (see fig. 3.13.2) as well as at the corresponding internal surface of the canon galleries located at the interior of the bastion. Moreover, large cracks developed along the keystone of the galleries.

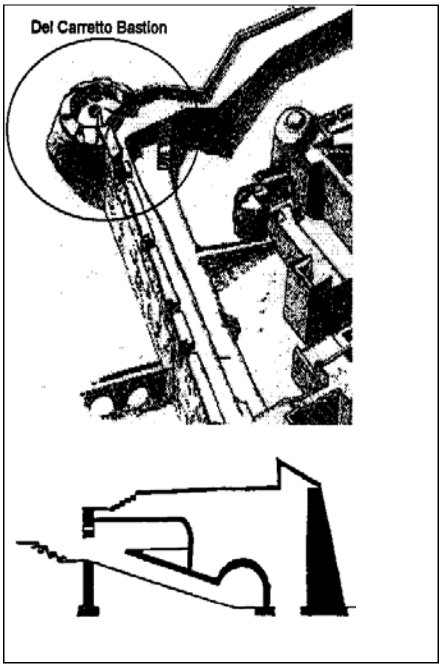


Fig. 3.13.1 Axonometric view and longitudinal section (N-S) of the Del Caretto bastion [Mauri, 1924].

Fig. 3.13.2 Vertical cracks located at two different areas of the bastion

Investigation

The in situ investigation commenced with a visual inspection and report of the crack pattern on the elevation drawings. Thus, the correspondence between the external and internal cracks of the bastion masonry could clearly be seen. The interior of the cracks was surveyed with an endoscope, whereas a monitoring system was applied, in order to follow the evolution of the crack openings in the long term. In addition, sampling of mortars and stones was performed, in order to characterise the building materials and to use their mechanical properties in numerical models for the interpretation of the observed structural pathology. It is known that these fortifications are resting partly on firm soil and partly on fill. Therefore, data regarding the properties of the foundation soil were sought, because they are necessary to evaluate how the soil contributes to the observed pathology.

To evaluate the behaviour of the structure against the dead loads and seismic action, two models were developed. The "detailed" model used the exact geometry of the external surfaces and internal vaulting system and comprised a network of brick- and shell finite elements and linear elastic materials laws were used. A network of, 92.863 nodes and 136.998 elements were generated (Fig. 3.13.3 left). The "approximate" model used the geometry of the external surfaces; the internal openings were however ignored. A network of 1053 nodes and 1343 brick- and shell finite elements was generated. In this case, the filling material was modelled following an elastic-perfectly plastic material law. The material of the external masonry leaf was considered elasto-plastic with descending branch for compression and elastic with a brittle linear branch after cracking (for tension) (Fig.3.13.3 right). With the use of the aforementioned models, several analyses were carried out (linear elastic and non-linear for the dead loads, push over analysis and dynamic analyses).

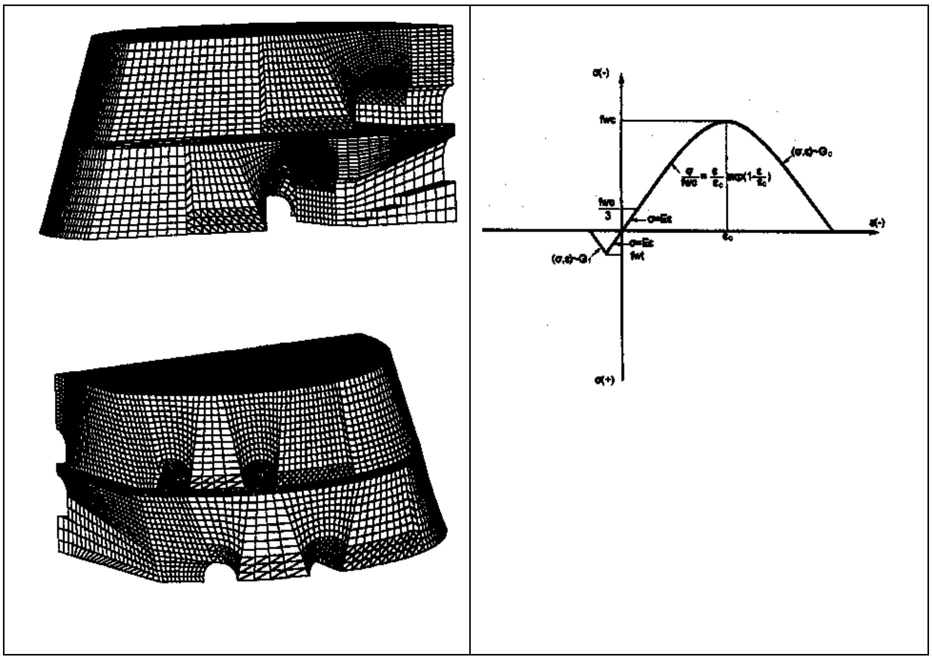


Fig. 3.13.3 Left: Axonometric views of the detailed model (half of the structure is shown) – Right: Constitutive law of masonry leaf material

Cause

The cracks recorded at the internal vaults' intrados and keystones are due to failure in tension of the material used. The static pressure exerted by the loose filling material, which might be enhanced by hydrostatic pressures generated by water penetration, resulted in the creation of plastification zones at the external surface of the masonry. The analysis carried out for earthquake actions showed that the latter could enhance the damage generated by the dead loads. Nevertheless, the structure exhibits a rather satisfactory post-elastic behaviour. In brief, the action of the dead loads was considered predominant for the explanation of the pattern of cracks recorded on the bastion [Papadopoulos al., 2001].

Restoration-repair

The analysis showed that no major structural problem is expected due to this pathology. It was nevertheless decided to continue the monitoring of the structure's displacements and crack openings in order to evaluate the behaviour of the foundation soil and of the construction itself.

In parallel to the monitoring exercise limited conservation measures were undertaken, mainly for durability reasons. Increasing the mechanical properties of the repair mortars in comparison to the existing ones was not considered necessary following the structural analysis (it would have practically no effect on the behaviour of a massive structure of this type). Special grouts were recommended in order to fill the voids induced by the opening of cracks deep inside the masonry mass. The good durability of the existing mortars permitted the choice of similar materials (with the addition of a limited Portland cement content) as basis for grout design.

This damage case is used to illustrate that structural issues were considered in priority, in order to take decisions regarding the composition and properties of the repair mortars and grouts.

b. Creep

Description of the damage

In a bell-tower vertical cracks were observed along the external surface which frequently passed through the structure (fig. 3.13.4); they appeared at a certain distance from the bottom (approximately equal to the dimension of the plan side or the diameter of the element) and continued for two thirds of the height (see fig. 3.13.5). Cracks can also appear at the corners of the structure or element (fig. 3.13.6). Diffused, thin vertical cracks can appear where stress concentration is higher. The affected area is usually large (fig. 3.13.7). When these cracks appear the situation can become very dangerous and not far from collapse.

Fig. 3.13.4 Cracks passing through in brick masonry of a bell tower.

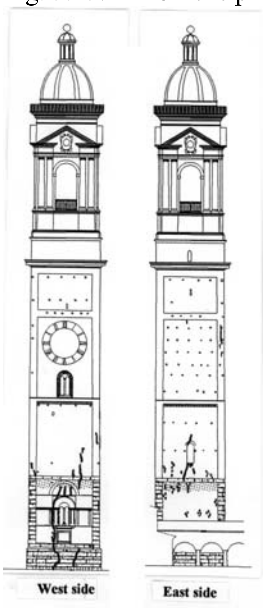


Fig. 3.13.5
Drawing of the crack pattern in a bell tower

Fig. 3.13.6
Cracks at the corner of the bell tower.

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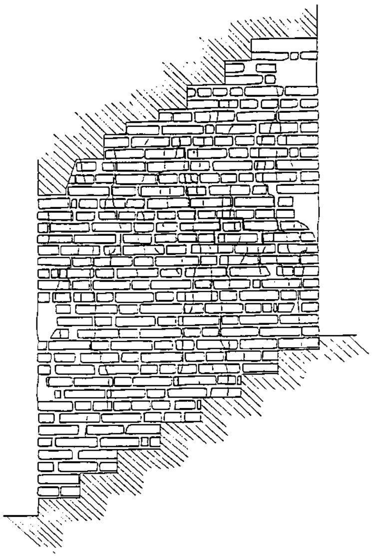

Fig. 3.13.7 Diffused crack pattern at the entrance (height 11 m) of the bell tower.

Investigation

The first step of the investigation was a complete geometrical survey on which the crack pattern was reported, which gave the first interpretation. The second step was to carry out a simple analytical calculation to find the approximate maximum values of the stresses caused by dead loads at the bottom of the tower. Single flat-jack tests were then carried out at different heights of the tower (see fig. 3.13.8) the results of which matched very well with the elastic Finite Elements modelling (see table 1). Monitoring data of the cracks was available since 1978 and was very useful in following crack propagation (see fig. 3.13.9).
Passive dynamic tests were also carried out in order to assess the influence of bell ringing on the behaviour of the damaged structures.

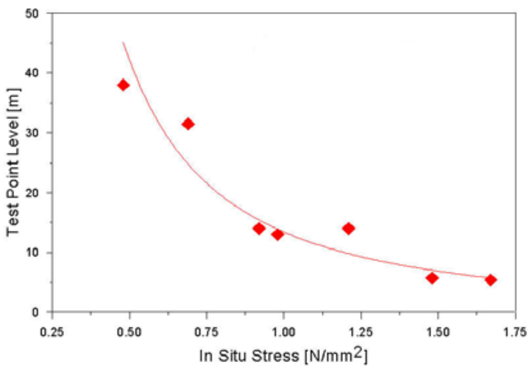

Fig. 3.13.8 The results of a flat jack test on the masonry.

Table 1: Calculated vs measured stresses

Test	Flat-jack No.	f_m (N/mm^2) FE calc.	f_m (N/mm^2) experim.
TMJ1	1	0.85 ÷ 0.95	0.98
TMJ3	3	0.95 ÷ 1.00	0.92
TMJ4	3	1.00 ÷ 1.10	1.21
TMJ5	2	1.00 ÷ 1.25	1.48
TMJ6	2	1.10 ÷ 1.40	1.67

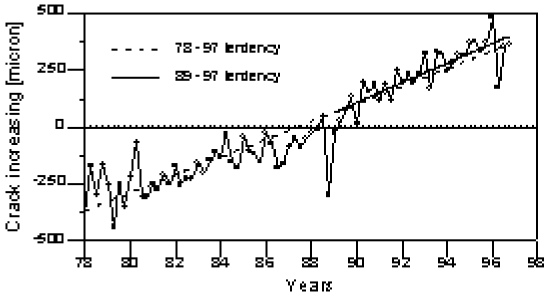

Fig. 3.13.9 Graph of the crack evolution in the bell tower.

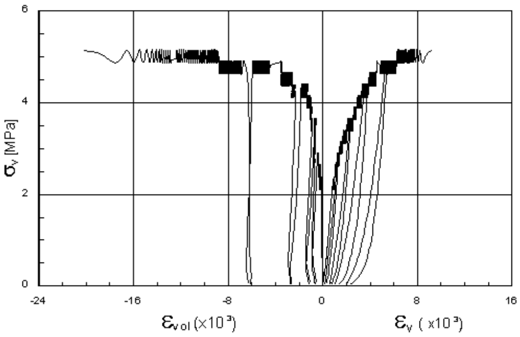

Fig. 3.13.10 Test results showing synergetic action.

Cause

The damaging process is the constant compressive stress caused by the dead load. Damage occurs very slowly by crack formation and propagation with time. The cracks are first formed near the bottom at a height approximately equal to the width of the structure. Cracks can also appear at the corners at a certain height.

Factors

The dead load is the first and most important factor, but synergistic effects like temperature variations and wind load, being both fatigue factors, may contribute and can lead to failure when the structure is under a high state of stress.

Restoration-repair

Measures can consist of setting up a provisional supporting structure if the situation is considered high risk. If the risk is not considered too high, the best choice would be to monitor the structure for a period of up to 4 to 5 years. No repairs to the crack should be

made until the appropriate intervention has been produced. Vibration due to bell ringing and to traffic should be avoided.
A possible repair method in this case could be the application of a deep re-pointing (70 – 80 mm), including stainless steel bars.

Creep damage to stone masonry
The same phenomenon as described before can occur on the pillars of churches (an example is Noto Cathedral, see [Binda, 2003]. The pillar section is composed of regular stones on the outside with rubble masonry on the inside. These pillars are frequently covered with a lime based plaster which prevents the damage from being clearly seen at the surface. Only diffused thin vertical cracks become visible on the plaster surface, hiding the more extreme damage in the stone blocks behind, see fig. 3.13.11.

Fig. 3.13.11 Example of creep damage in the pillars of the Church of SS. Annunziata, Ispica, Sicily. It is clear that the cracks on the putty lime plaster are thinner than the ones underneath it. In fact the plaster is also detached as visible in the upper part on the right of this photograph.

3.14 Damage due to lateral load and displacements
This type of damage may occur quite frequently, but it is not always possible to see clear direct signs of it. A non uniform distribution of normal stresses in a load-bearing wall, column or pier can be due to several reasons: eccentric normal actions, horizontal actions, differential movements. The non-uniform distribution of stresses can cause an increase of the developing compression stresses on one side of the cross section. It may eventually induce tensile stresses on the opposite side. Moreover, the non-uniform distribution of stiffness may induce different deformation patterns along the same structural element. At the boundary between areas of different mechanical properties, additional stresses and, possibly, cracks develop. The resulting damages can be separation, leaning or 'out of plumb' of the structural element, in some cases to such an extent as to cause the overturning of the element itself.

Description of the damage
The building shown in figs. 3.14.1 and 3.14.2, represents a simple example of this type of damage. The damage was surveyed on a stable belonging to a complex of rural buildings, where two of the approximately 4.50m high columns, showed a quite extreme leaning. Within one year the 'out-of-plumb' became more than 400mm (see fig. 3.14.1). A visible

and dangerous crack along the horizontal and vertical mortar joints appeared at the side where the tensile stress occurred (see fig. 3.14.2).

Fig. 3.14.1 Leaning columns.

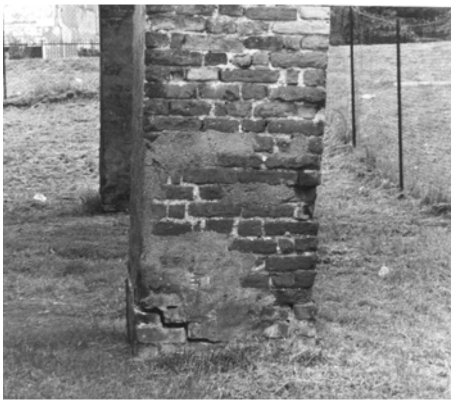

Fig. 3.14.2 Cracks in the mortar joints

Investigation

A visual inspection is usually the first step in the investigation of this type of damage, which may also occur to more complicated structures such as bell towers. When damage of this type occurs, a provisional supporting structure is needed to avoid the collapse of the structural element. If cracking is not visible it is always possible to detect the state of damage by surveying and measuring the 'out-of-plumb'; a monitoring system should be applied to follow the long-term behaviour of the structure. Analytical calculation may help in finding the state of stress, provided that the on site geometry is taken into account. It is also important to find the real causes of the stresses.

In this specific case, two main causes may have provoked the mechanical damage: (i) differential settlements of the soil and/or (ii) horizontal movements of the roof under wind loads.

Cause

On the basis of a visual and photographic survey, a geometrical survey and analytical calculation, both hypotheses outlined before appeared possible. Also a synergistic action of both could have occurred. The reason why the two columns did not collapse was the fact that the upper parts of the columns were practically constrained by the gutter.

Factors

The main environmental factors determining the damage were most probably the settlement of the soil and the wind load.

Restoration-repair

It was decided that in any case the roof should be repositioned. In the meantime, as both mortar and bricks were still in a very good state of preservation, the two columns could be repositioned without demolition. No special attention was necessary for the choice of the repair mortar in this case and the operation was successfully carried out (see fig. 3.14.3).

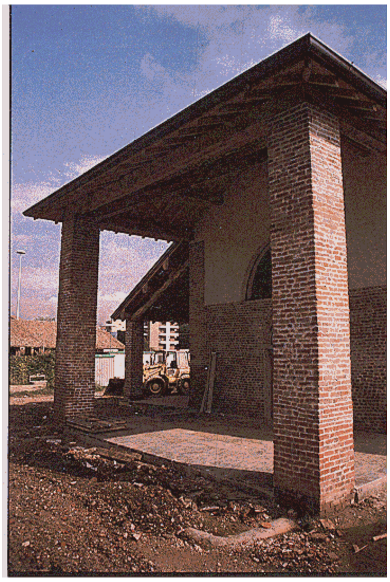

Fig. 3.14.3 The two columns after repair.

3.15 Earthquake damages (cracks) due to shear stresses

Damages to masonry structures due to seismic loads often occur in earthquake areas. In this chapter, we refer only to in-plane failure mechanisms. In the case of masonry walls, when the dynamic movement causes in-plane stresses, two possible mechanisms of failure may develop, due to shear stresses: (i) horizontal sliding at the interface between joint and brick (stone) or, more frequently, (ii) diagonal (shear) failure through bricks or stones. In the case of strong stones, the diagonal cracks pass through the mortar and the mortar-stone interface. In the case of weak stones or bricks, the diagonal cracks may also cross through them.

Description of the damage

In the case of regular stone masonry (see fig.3.15.1) the failure mechanism leads both to cracks in the horizontal and in the vertical joints, resulting in a diagonal damage pattern. The example shown represents a typical failure for masonry walls, i.e. detachment at the corner. A similar type of damage could have occurred in the central part of the wall. In both cases the wall behaves as a stiff homogeneous panel and the damage (cracks) can be repaired.
Fig. 3.15.2 shows the damage in a comparable situation, but in the case of a rubble wall. In this case the crack pattern is less clear and is complicated by the presence of smaller stones.

Fig. 3.15.1
Diagonal damage, running through
Horizontal and vertical joints

Fig. 3.15.2
Diagonal cracks involving mortar joints
and stones

Investigation
The investigation may commence with a photographic and a geometrical survey of the structure and a survey of the crack pattern. The results of such a survey are shown in fig. 3.15.3 and correspond to the damage of fig. 3.15.1. Fig. 3.15.4 shows the façade of the building where the damage of fig. 3.15.2 occurred. The complete survey, if possible should be presented in three dimensions, which can help in the interpretation of the mechanism of failure and in formulating a hypothesis regarding the causes of the vulnerability of the structure and finally in choosing the appropriate intervention techniques. Structural analysis, including numerical modelling may be applied to support the hypothesis.

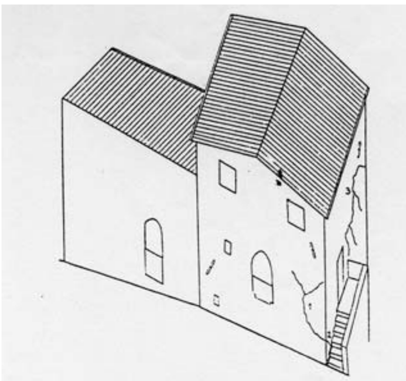

Fig. 3.15.3 Survey of the building to understand better the crack pattern that occurred

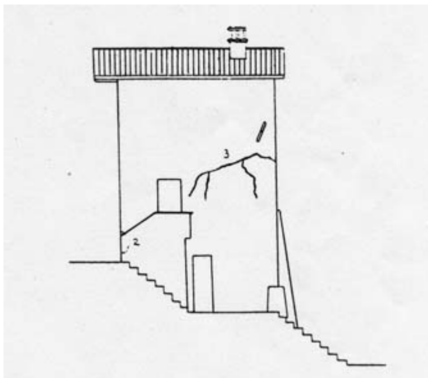

Fig. 3.15.4 Survey showing the diagonal shear failure of the wall

Cause
The damage shown in fig. 3.15.1 is caused by the failure of the corner due to the presence of openings (too) near to the corner itself (see fig. 3.15.3). The damage shown was caused by a difference in stiffness between the elements of the ground floor and those on the first floor (see fig. 3.15.4).

Factors
Dynamic horizontal loads in-plane together with the in-homogeneity and low quality of the stonework together with the poor connections in the corner of the building.

Restoration-repair
Heavy invasive techniques should be avoided as much as possible. In this case better continuity (interlocking) at the corners of the masonry should be improved, eventually by local re-instatement or reconstruction. Large openings near to corners should be closed or reduced, in case of low-strength non-reinforced masonry. Special attention could be given to deep re-pointing techniques. For diagonal cracks affecting the load bearing walls, structural analysis was carried out.

Acknowledgements
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