Characterization and damage of brick masonry

Paulo B. Lourenço, Rob van Hees, Francisco Fernandes, Barbara Lubelli

Abstract Clay brick is among the oldest used masonry materials. Given the technological evolutions since the industrial revolutions, old brick are much different from todays' bricks. This chapter provides a review on the chemical, physical and mechanical properties of mortar, brick and masonry. In addition, a discussion on the possible causes of damage and the usage of expert systems in building diagnostics is also given.
Key Words: Clay Brick, Brick Masonry, Mortar, Mechanical Properties, Physical Properties, Chemical Properties.

3.4.1 Introduction

Clay brick masonry, often in combination with stone masonry and timber floors, is well distributed all over the world. Clay brick, in its forms of sun dried and burnt, has been around since the beginning of civilization. Brick was easily produced, lighter than stone, easy to mold, and formed a wall that was fire resistant and durable. The characterization of old clay bricks is a hard task due to the difficulties in collecting samples, the scatter in the properties, and the lack of standard procedures for testing [1]. Still, characterization is relevant to understand damage, to assess safety, to define conservation measures, and even to make a decision on reusing or replacing existing materials, as modern materials can be unsuitable from a chemical, physical or mechanical perspective. Information about old and handmade bricks is scarce. Ancient materials generally differ from modern ones and, frequently, exhibit high porosity and absorption, and low compressive strength

Paulo B. Lourenço
ISISE, Department of Civil Engineering
University of Minho, Azurém, P 4800-058 Guimarães, Portugal
email: pbl@civil.uminho.pt

Rob van Hees
TNO, Netherlands Organisation for Applied Scientific Research
PO Box 49, 2600AA Delft, Netherlands
& TU Delft, Faculty Architecture, Delft, Netherlands
email: rob.vanhees@tno.nl

Francisco Fernandes
ISISE, Department of Engineering and Technologies
University Lusíada, Largo Tinoco de Sousa, P 4760-108 Vila Nova de Famalicão, Portugal
Email: francisco.fernandes@fam.ulusiada.pt | fmcpf@civil.uminho.pt

Barbara Lubelli
TU Delft, Faculty Architecture
PO Box 5043, 2600GA Delft, Netherlands
& TNO, Netherlands Organisation for Applied Scientific Research, Delft, Netherlands
email: b.lubelli@tudelft.nl

and elastic modulus. The mechanical properties of brick are relevant for the performance of historical constructions, as this is the main influence factor on the compressive strength and durability of masonry. Here, the properties of historical brick masonry and its components are addressed in detail.

In addition, existing buildings often exhibit damage and knowledge based diagnostic systems are much helpful for practitioners. Through a damage atlas, integrated in a diagnostic part, visual observation can be extensively used and a correct definition of the observed degradation and damage can be made, or at least one or more hypotheses can be proposed. Possible intervention techniques are not usually automatically generated by a diagnostic module, but can be available in a background information section. These aspects are also addressed next.

3.4.2 Chemical, physical and mechanical characterization of old mortars

Mortar is a material composed of one or more inorganic binders, aggregates, water and admixtures used in masonry to provide bedding, jointing and bonding of masonry units, or used for functions like plasters and renders. Main focus here is on lime mortars, as the most diffused type of mortar found in historic buildings. Figure 1 shows a thin section of a mortar, with binder and aggregates clearly visible.

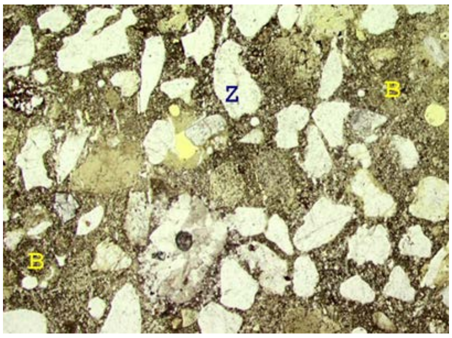

Fig. 1 Thin section of a lime mortar, originating from an early 18th C canal bridge in Amsterdam. B=binder, Z=aggregate.

The use of lime, $Ca(OH)_2$, dates back to pre-historic times even if the Egyptians used burned gypsum ($CaSO_4.½H_2O$) as a mortar in between the limestone blocks for the construction of the pyramids [2]. The first examples of lime as a binder in mortar date back to the 6th century BC in Greece [3]. The Romans developed a new type of (pozzolanic) mortar, a sort of concrete, with hydraulic properties. Vitruvius [4] describes the Roman knowledge of lime technology, with details on different types of lime binder, process of calcination and slaking as well as recipes for mortar composition and origin of the best sand.

In the end of the 19^{th} century, these mortars were replaced by cement based mortars. This occurred mainly because cement binders can harden and develop strength much quicker than lime binders. Incompatibility problems in the use of cement based mortars for conservation lead to the re-discovery of lime based products. Currently lime mortars are increasingly popular in conservation because of their good compatibility (physical, chemical and mechanical) with materials present in ancient buildings.

A binder can be defined as a material with adhesive and cohesive properties, which bonds mineral fragments in a coherent mass. A first distinction can be made between air-hardening (non-hydraulic) binders, which slowly harden in air, and hydraulic binders, which set and harden by chemical interaction with water. Air-hardening binders include air lime and gypsum. Hydraulic binders include hydraulic lime, lime-pozzolan, lime-cement, lime-cement-pozzolan and cement. The lime binder is obtained by a calcination process, the burning of (pure) limestone at ca. 900ºC. The obtained quicklime is slaked with water to become dry hydrated lime or, in case of an excess of added water, putty lime.

Natural hydraulic lime is obtained by calcination of limestone containing a certain amount of clay. Lime pozzolan binders are obtained by the addition of a pozzolan (natural or artificial) to the lime while mixing mortar. A natural pozzolan is a volcanic material, which originally derives from Pozzuoli, an Italian region around Vesuvius. Pozzuoli earth was used in the Roman mortars but other natural pozzolans are Santorini earth (Greece) and trass (Germany). Artificial pozzolans include metakaolin, silica fume, brick dust (preferably low fired brick) and others such as fly ash.

An aggregate can be defined as particles of rock, from natural origin or artificially crushed, with a range of particle sizes from 63μm to 4mm, or even 8mm. Apart from rock aggregates, light aggregates exist such as expanded clay, vermiculite or perlite. The most common aggregate used in lime mortars is calcareous or siliceous sand, which is constituted by grains of minerals and stone. The role of sand in mortar is to make the mortar less fat, to reduce crack formation due to shrinkage during drying, and to give strength, hardness and porosity to the mortar. The grain size distribution of the sand has a great influence on the final porosity and pore size distribution of mortar. For example, the presence of both fine and coarse grains results in a low porosity. Porosity strongly influences hardening, mechanical strength, physical properties and durability. The ratio between the mortar components may vary depending on the quality of lime, sand and on the final use of the mortar. Historical mortars have a binder-sand ratio which may vary between 2:1 and 1:4 by volume.

Air lime hardens by reacting with carbon dioxide from the air to form a carbonate. Gypsum hardens by hydration of the hemidrate form to the di-hydrate form. Hydraulic lime contains a mix of hydrated lime, silicates and aluminates. Hardening occurs through reaction with water and by carbonation. Pozzolans, used in combination with air lime to obtain a hydraulic mortar, have in common a considerable content of silica and alumina. The knowledge of the chemical properties of a mortar is important for understanding damage processes and for designing a repair mortar, chemically compatible with the existing one. For example a gypsum based repair mortar is chemically not compatible with a dolomitic lime mortar, since, in presence of water, harmful magnesium sulphate may be formed.

Moisture transport behavior is one of the most relevant physical properties of mortar, since it strongly influences its durability. Moisture transport behavior mainly depends on the porosity and the pore size distribution, which can be subdivided into sorption pores (< 100nm), capillary pores (between 0.1μm and 100μm) and coarse pores (> 100μm), see Figure 2. Small capillary pores (< 1μm) result from evaporation of water from the binder fraction. Wider capillary pores are formed by the intergranular space that is not completely filled by the binder. Figure 3 shows the pore size distribution of a mortar with a bimodal distribution.

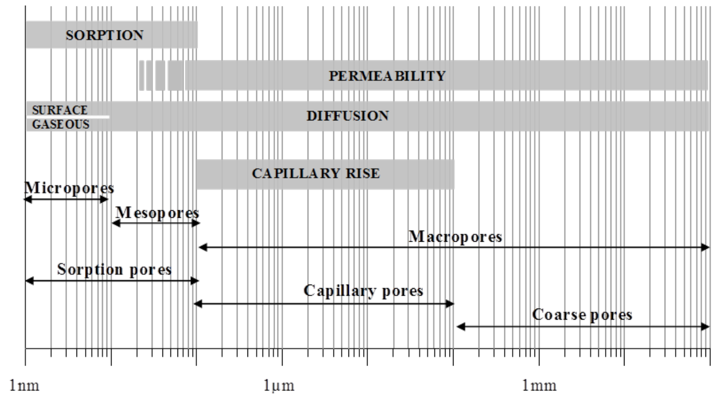

Fig. 2 Classification of pores and moisture transport mechanisms.

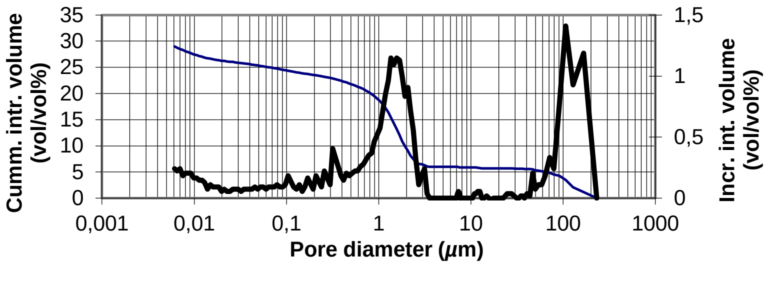

Fig. 3 Pore size distribution of a mortar, assessed by mercury intrusion porosimetry (MIP). The total porosity (ca. 29%) can also be obtained by this technique.

Air lime mortars are known to have a low mechanical strength, in comparison with hydraulic lime and even more in comparison with cement based mortars.

However, their capability of deformation is much higher than that of cement mortars. The strength of air lime mortars develops due to carbonation. This process may take several years, especially in very thick masonry. Therefore the strength of air lime mortar will be very low, especially in the first period after brick lying. However, if good conditions for carbonation are present, sufficient strength is developed over time guaranteeing a long service life. The strength of a mortar is greatly affected by the porosity and decreases with an increase in porosity. Compressive strength of air lime mortars ranges around 1.5-2N/mm^2, whereas hydraulic lime mortars may reach ca. 10N/mm^2. Apart from the mechanical strength of the mortar joint, the bond strength between the masonry unit (brick or stone) and the mortar joint is important. A low binder/aggregate ratio, poor grading of the aggregate or inadequate tooling of the mortar may limit the bond strength.

3.4.3 Characterization of old bricks

Clay bricks also exhibit different properties, which are important in the evaluation of the strength, durability and resistance to deterioration processes. These properties are closely related to the quality of the raw clay and the conditions of manufacture, namely drying and firing processes. The properties of construction materials can be grouped as chemical, physical and mechanical. Progressive ageing of bricks and permanent loads lead to material deterioration such as cracking, peeling or efflorescence, meaning that the properties exhibited currently by old clay bricks are affected in some degree and are not necessarily the original properties.

Bricks are constituted by a mixture of raw clay and water. The first step to characterize the raw clay is by means of chemical and mineralogical studies [5], [6], which are fast to perform and only require small amounts of material. This information can be also used to identify suitable raw materials for the production of missing parts or the replacement of deteriorated ones, as long as the production processes are as close as possible from the original.

The chemical composition of brick samples can be determined by x-ray fluorescence spectrometry, much used for old ceramics [7], which allows the identification of the following abundant chemical oxides and elements: silicon oxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), potassium oxide (K_2O), titanium dioxide (TiO_2), sodium oxide (Na_2O), calcium oxide (CaO) and magnesium oxide (MgO). Silicon and aluminum oxides constitute the base elements of the clay. As an example, clay bricks from the 12-13th century presented 38% of silicon oxide, 21.5% of aluminum oxide and 32.5% of ferrous oxide, in weight [8]. In Portugal, several samples from clay bricks (Figure 3) from monuments spread through the country and from the 12th-19th centuries were studied in [9]: Outeiro (OU, 17th century), Pombeiro (PO, 12-16th century), Salzedas (SA, 12-18th century), Tarouca (TA, 12-17th century), Tibães (TI, 17th century) and Tomar (TO, 18-19th century). The results reported in Table 1 show that the base chemical components of the raw clay used on the bricks is relatively uniform, consisting of 54 to

61 % of SiO_2 and 22 to 32 % of Al_2O_3. The presence of CaO and Na_2O is often due to contamination by lime mortars or salt, respectively.

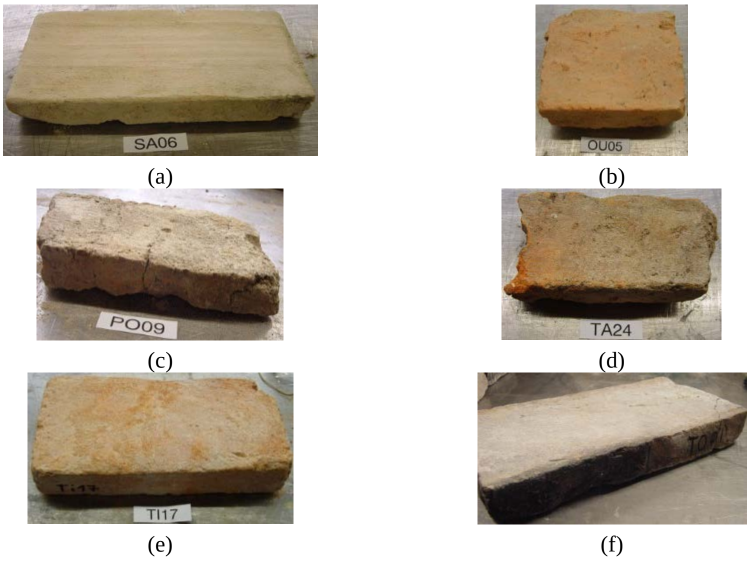

Fig. 3 Photographs of typical old Portuguese bricks: a) Salzedas (SA), b) Outeiro (OU), c) Pombeiro (PO), d) Tarouca (TA); e) Tibães (TI) and f) Tomar (TO).

Table 1 Average chemical composition of old Portuguese bricks (coefficient of variation in square brackets).

	SiO_2	**Al_2O_3**	**Fe_3O_4**	**K_2O**	**Na_2O**	**TiO_2**	**CaO**	**MgO**
OU	56.2 [9%]	25.3 [5%]	11.4 [41%]	3.5 [14%]	0.5 [40%]	1.0 [10%]	0.3 [47%]	1.5 [29%]
PO	57.5 [5%]	25.1 [10%]	8.4 [18%]	4.9 [12%]	0.5 [33%]	1.3 [10%]	0.4 [106%]	1.6 [19%]
SA	54.4 [5%]	32.2 [8%]	4.1 [61%]	5.1 [17%]	2.0 [35%]	0.3 [87%]	0.8 [66%]	0.9 [41%]
TA	55.6 [7%]	30.9 [13%]	4.1 [22%]	5.0 [15%]	1.9 [41%]	0.4 [26%]	0.9 [84%]	1.0 [29%]
TI	53.8 [6%]	29.4 [9%]	8.1 [18%]	4.4 [11%]	0.5 [31%]	1.2 [8%]	0.9 [60%]	1.4 [20%]
TO	60.8 [4%]	21.6 [10%]	7.0 [9%]	3.6 [22%]	0.4 [23%]	0.8 [12%]	3.6 [81%]	2.2 [15%]

These results were processed using statistical analysis, which compares the chemical composition the bricks with the chemical composition of known ceramic samples [7]. The analysis revealed that SiO_2 contributes very little to the distinction between old samples and that no single component was found to strongly influence the provenance of the old bricks. The chemical composition of the clay found in bricks is different from ceramics and suggests that the raw clays used in the manufacture were obtained locally.

Firing of clay bricks produces a series of mineralogical, textural and physical changes that depend on many factors and influence the porosity [6],[8]. Porosity is again an important parameter concerning clay bricks due to its influence on properties such as chemical reactivity, mechanical strength, durability and quality of the brick. Generally, the quality of the brick, both in terms of strength and durability, increases with the decrease of the porosity. Commonly, historic clay bricks exhibit high porosity values, ranging between 20 and 50% [10],[11]. The dimension and distribution of the pores are influenced by the quality of the raw clay, the amount of water and the firing temperature. If the firing temperature increases, the proportion of large pores (3 to 15μm) increases and the connectivity between pores is reduced, whereas the amount of thin pores diminishes [6],[12]. This has a strong impact on the durability of the bricks as it has been shown that large pores are less influenced by soluble salts and freeze/thaw cycles. Several studies [1],[6], [13] reported that the formation of thin pores (< 1.5μm) is promoted by carbonates in the raw clay and by a firing temperature between 800 and 1000ºC. Such a pore size influences negatively the quality of bricks as their capacity to absorb and retain water increases. The density or bulk mass is related with mechanical and durability properties, and typical values range between 1200 and 1900kg/m^3 [5], [8], [10]. Table 2 presents the results from old Portuguese clay bricks, with resulted in average values for the bulk mass of 1750kg/m^3 and 29% for porosity. No correlation can be found between the physical or chemical properties and the mechanical properties.

Table 2 Average porosity, bulk mass and compressive strength for old bricks from Portuguese monuments and the coefficients of variation between square brackets [7].

	Porosity (%)	**Bulk mass (kg/m^3)**	**Compressive strength (N/mm^2)**
OU	33.0 [13.9%]	1742 [1.7%]	8.5 [28%]
PO	26.3 [25.5%]	1754 [2.2%]	9.2 [54%]
SA	28.2 [10.6%]	1800 [1.9%]	14.5 [32%]
TA	29.2 [14.5%]	1747 [1.8%]	8.7 [41%]
TI	30.4 [14.7%]	1739 [1.5%]	6.7 [55%]
TO	27.5 [14.2%]	1656 [3.0%]	21.8 [31%]

The evaluation of the mechanical strength of olds bricks is difficult due to their scatter. They may also be deteriorated by weather or chemical agents such as soluble salts, ice-thawing cycles or load-unload cycles. Additionally, the experimental test set-up conditions (dimensions and moisture content of the sample, boundary conditions, temperature, etc.) can also influence the results. Typical values of the compressive strength of old clay bricks are reported in Table 3, with a wide range of values (from 4 to 32N/mm^2). The average compressive strength of Portuguese old clay bricks as well as its dispersion is reported in Table 2. A large variability on the compressive strength was obtained, with coefficients of variation up to 50%. It is possible to observe that the bricks with lower f_c exhibit also a higher dispersion. The wide range of strengths found is between 6.7 and 21.8N/mm^2, with an average of 11.6N/mm^2 considering the total sample and 8.3N/mm^2 considering the four weakest bricks.

Another relevant mechanical parameter is the modulus of elasticity. It is not always clear how authors measured the values presented, even if most standards refer the use of the linear part of the stress-strain curve in a range of 10 to 50% of the maximum stress value, which is also characterized by a large variability. The values found range from 1 to 18GPa, which represent between 125 and 1400 f_c, where f_c is the compressive strength. Most common values are in the range of 200 f_c, with an average for the values in Table 3 of 350 f_c.

Table 3 Typical average values for the compressive strength and modulus of elasticity of old bricks found in the literature.

Date (century)	Local	Compressive strength (N/mm^2)	Elastic modulus (kN/mm^2)
1-5th	Walls, pillars, vaults and ovens from the Byzantine period	9.2-18.0 [10]	2.6-10.8 [10]
11-13th	Vaults of Our Lady Monastery, Magdeburg, Germany	13.1-14.1 [14]	-
13-17th	Siena’s exterior wall, Italy	27.9 [14]	-
15th	Colle Val d’Else exterior wall, Italy	19.9 [14] 30.0 [15]	4.1 [14]
	Pienza Episcopal Palace, Italy	-	7.3 [14] 11.6-18.6 [15]
16th	Monastery of Monte Oliveto Maggiore library wall, Italy	31.1 [14]	6.3 [14]
17th	Salzedas monastery vaults, Portugal	5.2 [16]	7.3 [16]
18th	Lazzaretto de Ancona, Italy	18.5 [14]	5.8 [14]
18-19th	Centenary chimney from the ceramic industry, Spain	20.8 [15]	-

It is difficult to relate the tensile strength of the masonry unit to its compressive strength due to the different shapes, materials, manufacture processes and volume of perforations. For the longitudinal tensile strength of clay, calcium-silicate and concrete units, Schubert [17] carried out an extensive testing program and obtained a ratio between tensile and compressive strength ranging from 0.03 to 0.10.

3.4.4 Mechanical characterization of brick masonry

The properties of brick masonry are strongly dependent upon the properties of its constituents. Traditional masonry is subjected to compressive stresses and the compressive strength of masonry in the direction normal to the bed joints is required for design and safety assessment purposes. Experimentally, this property can be obtained according to the European norm EN 1052-1 [18], see Figure 4a. This configuration seems to return the true uniaxial compressive strength of masonry. Mann and Betzler [19] observed that, initially, vertical cracks appear in the units along the middle line of the specimen, i.e., through the vertical joints. Upon increasing deformation, additional cracks appear, normally vertical cracks at the smaller side of the specimen that lead to failure by splitting of the prism. This persuaded researchers to investigate semi-empirical and analytical relations to predict masonry strength based on the components characteristics and on the type of masonry. Several semi-empirical relations can be gathered from the literature, e.g. [20],[21],[22], and from the codes [23],[24].

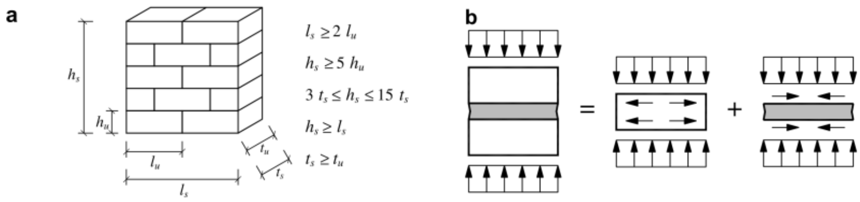

Fig. 4 Uniaxial compressive behavior of masonry: (a) test specimen according to the European standards (for units with $l_u \leq$ 300mm and $h_u \leq$ 150mm) [17] and (b) schematic plane representation of stresses in masonry components.

Masonry compressive failure is mainly governed by the interaction between units and mortar. A relevant factor is the difference in elastic properties between the unit and mortar. Assuming compatibility in the deformation of the components and a mortar that is more deformable than the units, the difference in stiffness leads to a state of stress characterized by compression/biaxial tension of units and triaxial compression of mortar, see Figure 4b. In the pioneer work of Hilsdorf [25], this phenomenon was described and an equilibrium approach was developed to predict the masonry strength, assuming that failure of mortar coincides with failure of masonry. Later [26], this hypothesis is overcome by considering a limit strain criterion based on the lateral strain exhibited by brick units at failure. Other contributions were given in [27],[28],[29].

The bond between unit and mortar is often the weakest link in masonry. The nonlinear response of the joints, controlled by the unit-mortar interface, is related to two different phenomena that occur at the unit-mortar interface. One associated with tensile failure and another one associated with shear failure. Different test set-ups have been used for the characterization of the tensile behavior of the unit-mortar interface. These include flexural testing, (three-point, four-point, bond-wrench) [29], indirect tension testing (splitting test) [31] and direct tension testing [32].

Experiments on the biaxial behavior of bricks and blocks are scarce. The influence of the biaxial stress state has been investigated up to peak stress to provide a biaxial strength envelope, see Figure 5. Basically, two different test set-ups have been utilized, uniaxial compression orientated at a given angle with respect to the bed joints [33] and true biaxial loading at a given angle with respect to the bed joints [34],[35].

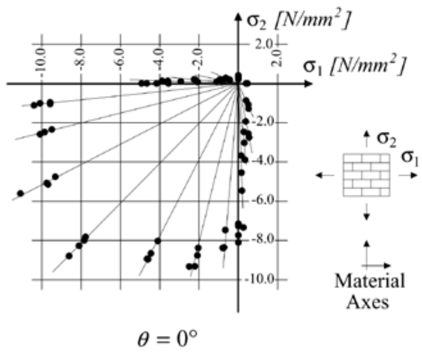

Fig. 5 Biaxial strength of solid clay units masonry [36],[37].

3.4.5 Deterioration and damage mechanisms

The most important factors influencing degradation and damage to masonry are related to: environment; materials; building's design; craftsmanship in the construction of the building and its maintenance.

Environmental factors include, for example, the presence of moisture and salts, air pollution, temperature changes, dynamic loads and soil settlements. Moisture may come from sources like rain penetration, capillary rising damp or flooding. Salts may be originally present in the material (for example, a mortar which has been made using sea water or beach sand), they may come from the environment (aerosol, de-icing salts, etc.) or from the use of the building in the past (for example, chloride from salt storage, nitrates in the case of stables). Temperature variations may give rise to degradation phenomena in masonry due to differential thermal dilation, whereas dynamic loads resulting from earthquakes and vibrations provoked by wind or traffic may cause crack patterns.

Material factors are mainly related to the composition of the mortar (binder/sand ratio, grain size distribution of the aggregate) and the properties of the masonry unit/mortar combination (porosity, capillary moisture transport, adhesion, mechanical strength). Many degradation processes may only occur in the presence of water; consequently the speed at which a material absorbs and releases water has a strong influence on its risk of degradation. Therefore, moisture transport properties, which are related with porosity and pore size distribution, are of primary importance when considering the durability of a mortar and the masonry as a whole.

The design of the building, i.e. its shape, orientation and above all the details, may strongly influence the occurrence and the severity of the degradation. Also craftsmanship in the form of quality of the execution and of adequate conditions for hardening of mortars is an important factor that affects the susceptibility of the mortar to damage.

The degradation processes (chemical, physical and mechanical) exert stresses on the materials, which weaken the material until it fails and damage becomes visible. Degradation can be defined as an increase in decay, which corresponds with a decreasing performance of the material. Thus, damage can be defined as an unacceptable reduction of the performance of the material, affecting its durability. An overview of the factors influencing the durability of masonry is given in Table 4 while Table 5 gives an outline of the most important damage processes affecting masonry and damage types related to those processes.

Some of the most important damage processes are discussed next. For processes in which water is involved, the crystallization of soluble salts is probably the most widespread process causing damage to historical masonry buildings. Salt damage can only occur in the presence of both salt and water. Salt moves in the capillary system of the material and accumulates where evaporation occurs. Salt accumulation and crystallization create pressures, which can exceed the mechanical strength of the material and consequently lead to damage.

As the mortar (e.g. bedding or pointing mortar, plaster, render, etc.) and brick or stone are used in masonry in combination with each other, the risk and location of salt damage will depend on the pore size distribution of the mortar/substrate combination [38]. Since moisture (and salt) transport by capillarity moves from larger to smaller pores, a fine porous mortar applied on a coarse porous material will have a larger risk of decaying than a coarse mortar applied on a fine porous substrate (this does however not necessarily imply that a fine porous mortar on a coarse porous substrate would be the wrong choice). Important damaging salts are sulphates (for example Na_2SO_4) and chlorides (for example NaCl). Salts precipitating in the pores of a mortar may create pressures, which may lead to damage [39],[40]. As a consequence of salt crystallization, a mortar can show damage in the form of sanding, scaling, exfoliation or crumbling, whereas the masonry units may show damages like powdering, exfoliation and spalling. Sometimes salt crystallization causes damage to a lime bedding mortar because a physically incompatible pointing mortar was chosen. This is the case of a too dense pointing applied on a more porous lime mortar (Figure 6). Because of the hindering of the drying caused by the new cement pointing, crystallization of salts that were already present in the masonry occurs at the bedding mortar-pointing interface. This results in the detachment of the pointing (also called push-out) and also in a form of loss of cohesion (crumbling or sanding) of the underlying lime bedding mortar.

Table 4 Overview of factors influencing the durability of mortars and masonry.

Environment	Moisture supply	Rain, snow
		Ground water
		Surface water
		Floods
	Salt supply	Soil or surface water
		Use of the building (e.g. stable, salt storage)
		Air (aerosol)
		Floods
		De-icing salts
		Cleaning, surface treatments
	Air pollution	
	Exposure to fire	
	Temperature	Variations
		Extremes
	Dynamic loads	Earthquakes
		Wind
		Traffic
		Vibrations
	Differential settlements	
Materials	Mortar composition	Binder type
		Binder/aggregate ratio
		Grain size distribution of the sand
	Properties brick/stone and mortar system	Porosity
		Moisture transport properties
		Adhesion/bond
	Presence of salt in materials	
Design of the building	Original structural design of the building or modification	
	Choice of combinations of materials	
	Detailing of the building	
	Choice of repair methods and materials	
Workmanship and construction procedures	Quality of the execution	Quality of execution
		Mortar mixing on site
		Way materials are cured and curing conditions
		Protection of fresh mortar

	Lack of knowledge on (traditional) workmanship	
Maintenance	Lack of maintenance	
	Inappropriate maintenance program	

Table 5 Overview of the most important damage processes and related damage types.

Physical / chemical	Most important damage types
Moisture Salts Frost Pollution	Biological growth Efflorescence Spalling Exfoliation Powdering (Black) crust
Structural	
Overloading, creep Settlement Thrust arches / vaults Earthquakes	Crack patterns Displacement / deformation

Fig. 6 Push-out of cement re-pointing due to crystallization of salts at the interface of new pointing and old bedding mortar.

Apart from pure crystallization, the formation of expansive compounds due to the reaction of salts with mortar components may also cause considerable damage, not only to mortars, but to the masonry as a whole. Sometimes the resulting crack patterns may be mistaken for structural damage (Figure 7a), where only after drilling cores from the masonry it became clear that the cracks originated from swelling of the mortar inside the pier. Additional investigations with optical and electron microscopy revealed the presence of secondary ettringite concentrations, initiating the cracks. Sometimes the pointing mortar is bursting, i.e. it looks like it swells because of an increase of volume (Figure 7b). In this last example, the damage in the form of bursting of the pointing was shown to be due to the formation of trichloride.

Other examples of such expansive compounds, which may cause damages, are thaumasite and ettringite [41]. Thaumasite and ettringite are the results of the reaction of sulphates (coming for example from the air or from bricks) with components of the hydraulic mortar. Thaumasite ($CaCO_3 \cdot CaSO_4 \cdot CaSiO_3 \cdot 15H_2O$) may form by the reaction of water with calcium carbonate, calcium sulphate and hydrated calcium silicate, which again are present in concrete or mortar mixtures as binders. The composition of hydrated calcium silicates, which may vary within a relatively wide range, is indicated by the generic formula C-S-H. Ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) may form by the reaction of water with calcium sulphate and the alumina bearing hydration products ($4CaO \cdot Al_2O_3 \cdot 13H_2O$, $3CaO \cdot Al_2O_3 \cdot 6H_2O$, $C_3A \cdot CaSO_4 \cdot 12 \cdot 18H_2O$, etc.). These products, sometimes indicated as C-A-H, are formed by hydration of Portland cement or other binders, such as hydraulic lime or mixtures of lime and pozzolan [40].

Hydrated lime (air lime) mortar cannot be affected by the reactions described above. In this case another form of expansive reaction, the one consisting in the conversion of the $CaCO_3$ into $CaSO_4 \cdot 2H_2O$ (gypsum), can take place. Sulphates present in the polluted air or coming from the brick react, in the presence of moisture, with the $CaCO_3$ in the mortar to form $CaSO_4 \cdot 2H_2O$, i.e. gypsum.

(a)

(b)

Fig. 7: Crack pattern in masonry, looking like structural damage but caused by expansive reaction in the internal part of the mortar (a). Bursting of pointing mortar due to the formation of $CaO.Al_2O_3.3CaCl_2.31H_2O$ (trichloride) (b).

Damages due to structural causes are generally showing as cracks, often in combination with deformations. The first important step to make a diagnosis of structural damages is the survey and interpretation of the crack pattern. However, the possibility of occurring damages due to non-structural causes has also to be taken into account. The signs of damages given by the crack direction and opening have to be well evaluated.

The crack patterns may be caused by structural failures like overloading, settlements or due to extreme events like earthquakes. The main structural failures that may cause damages affecting the structural stability include: (i) dead load in heavy massive structures; (ii) soil settlements; (iii) horizontal actions due to thrust in arches and vaults; and (iv) extreme events like earthquakes or landslides. The position, the direction and the width of the cracks indicate where the local stress value reaches the strength of the material and hence, indirectly, the type of stress to which it is subjected. Knowing typical causes, which can produce damage to the structure such as vertical and horizontal actions, soil settlements, interactions between walls and floors, roofs and walls, can help understanding the visible effects (cracks, deformations, leaning, etc.) of these actions on the structure.

3.4.6 Diagnostic systems and expert systems

The use of expert systems for diagnosis in building practice or for mitigation of the effects of decay and damage to buildings belonging to the cultural heritage is still not very common. The development started fifteen years ago, when the first version of MDDS (Masonry Damage Diagnostic System) was delivered as the outcome of an EU project [38], [42]. The approach concerning the assessment of damage to (historic) masonry buildings is quite comparable to the one used in medicine. In medicine it consists of three steps: anamnesis, diagnosis and therapy. In building diagnostics, generally, steps like survey, (visual) assessment, diagnosis and intervention are commonly used.

Such an approach was already adopted in the early MDDS, although this system would be very restrained in proposing interventions. The MDDS contained a damage atlas, a series of damage processes and a reasoning mechanism that made use of essential conditions to assess whether the occurrence of a certain damage process might be possible or probable. Already in the original system, the damage atlas was a very important tool, initially limited to damages concerning brick. Restricted as that was, it certainly had an important function: the use of a common language (damage terminology). Figure 8 gives an overview of the damage processes included in MDDS. A process is defined by a number of “essential conditions” that would allow the process to occur; together with a set of well-defined damage types (damage atlas), this constituted the backbone of the original system.

In the practical situation of conservation works, an assessment of the state of the building condition is the first and necessary step to properly define the problem that is to be solved. This step also includes the decision on which investigations have to be performed. An assessment will usually start with a visual inspection, or survey, of the building. A correct diagnosis is the “*conditio sine qua non*” for a proper assessment of the damage phenomenon and, subsequently, for the definition of the intervention. The part on structural damages in MDDS was initially underdeveloped, as the system main focus was on damage related to the interaction between materials and environmental factors.

Quite some additions have afterwards been made to the initial system: the reasoning has been very much refined; it is possible to introduce measurement data such as moisture content, salt content, etc. in the reasoning process in order to have a more refined hypothesis and diagnosis. Moreover, other materials have been introduced, like natural stone, mortars, renders and concrete as well as composite constructions such as masonry structures. Systems such as the current MDDS (**Monument** Damage Diagnostic System, successor of the **Masonry** Damage Diagnostic System) intend to facilitate multidisciplinary teamwork by offering a structured, transparent and consistent method for analyzing and diagnosing damage [43],[44]. Additionally, several additions and improvements have been made into this extended system, such as those following from the EU COMPASS project [44]. Although MDDS does not fully cover structural damages yet, a structural damage atlas is already available on the basis of the research of de Vent [45],[46] and a more complete structural analysis module will be added.

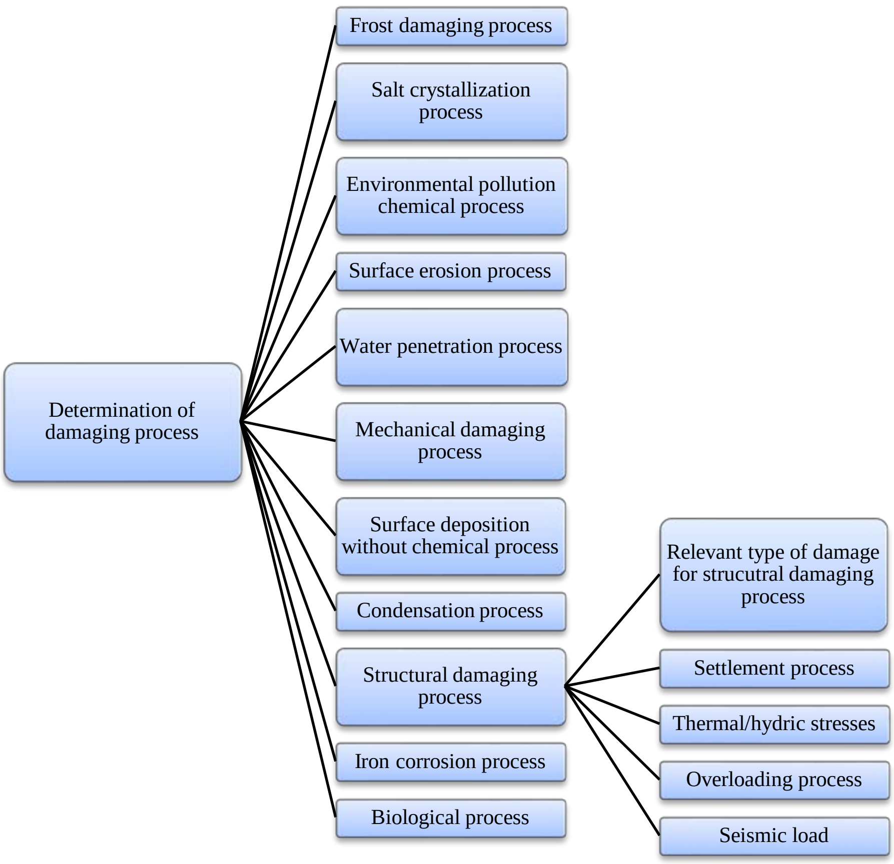

Fig. 8: Tree structure of damage processes contained in the first MDDS.

An investigation carried out with the help of MDDS will start, like any investigation, with the survey: gathering data and performing a visual inspection of the building showing damage. The aim of this first phase of the work is to enable the inspector to acquire more insight in the situation and to structure his observations with the help of the system. The system helps in handling each situation found in a building as part of a context. Its approach is based on the way of reasoning of an expert. All information considered relevant may be inserted in the system, which is structured in such a way that at three levels, building, construction and material, descriptions can be made and data can be added. The user is free to make annotations on the building, even if they are not directly related to its decay, but will serve other purposes (e.g. statistics). Pictures and drawings can also be inserted in the consultation file, which will eventually be part of the dossier of the building.

The assessment of the type of damage found can be done at distinct levels in the system: at the level of the construction (for example a wall as a whole) and/or at the level of each constitutive material/construction system (for example masonry unit, brick, stone, plaster, bedding mortar, paint, etc.). With the support of the damage atlas, which has been integrated in the diagnostic part, a correct definition of the observed damage type at both levels is possible (Figure 9) and the results of the visual observation (i.e. descriptions, photos, drawings, etc.) can be included.

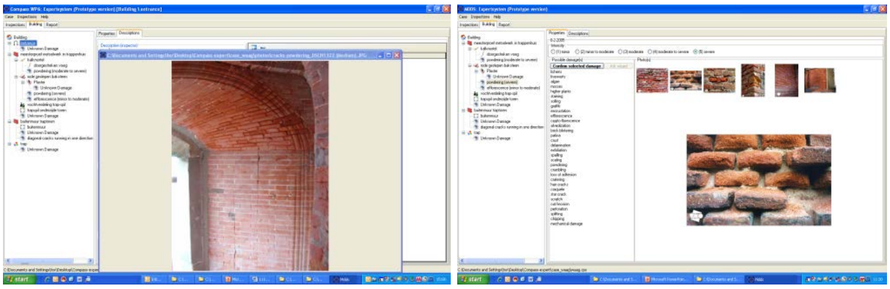

Fig. 9: MDDS damage atlas at construction level (left) and at material level (right).

The damages related to environmental conditions and material properties are mainly caused by environmental causes like water, frost, salts, pollution, flooding, etc., generally in combination with material properties. See also chapter 3.4.5. All degradation processes that take place under those conditions are related to the presence of moisture. The system will, apart from assessing the correct damage type and coming with a hypothesis on the basis of the observations, also allow to insert measuring data, for example on moisture and salt distribution in a wall, for a more precise diagnosis.

The damages due to structural causes are generally perceived as large isolated cracks or as a diffused pattern of cracks, as addressed above. In the identification process of a structural damage pattern, the following characteristics should be taken into account: width of the crack(s) and variations over length; as far as possible: depth of the crack(s); direction of the crack(s); combination of crack(s) with deformations or displacements. Together with the visual characteristics of a pattern, the following should also be considered: the behavior of the crack(s) in the course of time: comparisons of the actual damage found with previous damage and monitoring of its behavior; the building materials constituting the construction; the building techniques used; the building element showing damage (e.g. wall, column, arch); and conservation measures performed over time (previous history).

For the time being, MDDS works with an integrated atlas in the diagnostic part of the system, which makes it possible to suggest one or more hypotheses, on the basis of the structural damage pattern that was assessed (Figure 10). Investigations should also be carried out to ascertain whether the damage pattern has appeared together with other forms of deterioration: for example, a crack may occur together with a displacement or other non-structural types of damage. There are also damage types that appear to be structural, but are actually caused by salt or frost damaging mechanisms. An interesting example is that of the church tower of Noordwijk, the Netherlands (Figure 11) [47]. The damage pattern is constituted by vertical cracks running along the corner of the tower. They are crossed by less evident horizontal cracks, running through the mortar joints. This damage pattern appears, at first sight, likely to be caused by a structural deterioration process, but it was in fact due to the formation of swelling compounds in the mortar.

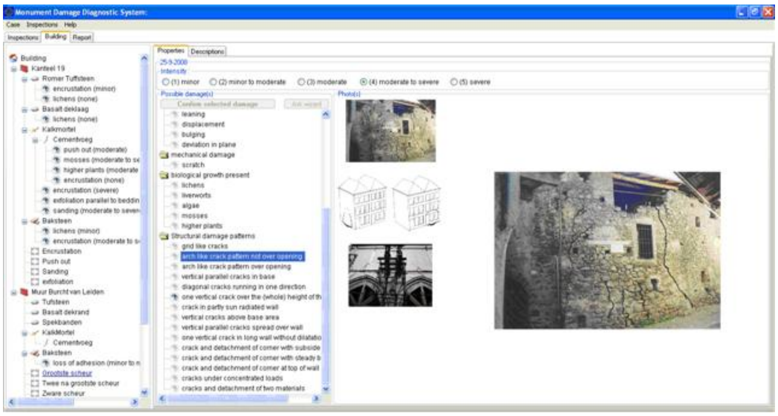

Fig. 10: Structural damage atlas, integrated in the diagnostic section of MDDS.

Fig. 11: Damage pattern that may at easily attributed to a structural mechanism.

3.4.6 Conclusions

The present chapter addresses the properties of historical brick masonry and its components. First, historic mortars are discussed with respect to binders, aggregates, the role of porosity and mechanical strength. The strength of a mortar is greatly affected by the porosity and decreases with an increase in porosity. Compressive strength of air lime mortars ranges around 1.5-2N/mm^2, whereas hydraulic lime mortars may reach ca. 10N/mm^2. The bond strength between the masonry unit (brick or stone) and the mortar joint is also important and a low binder/aggregate ratio, poor grading of the aggregate or inadequate tooling of the mortar may limit the bond strength. Subsequently, old bricks are characterized in terms of chemical composition, average porosity, bulk mass and mechanical properties. The compressive strength of old clay bricks have a wide range of values (from 4 to 32N/mm^2), with some concentration between 7 and 20N/mm^2. For the modulus of elasticity, values range from 1 to 18GPa, with an average value of 300 times the compressive strength. The ratio between tensile and compressive strength ranges from 0.03 to 0.10. Finally, the strength theories and experimental results of brick masonry under uniaxial and biaxial compression are briefly reviewed.

With respect to deterioration and damage, the most important influencing factors are discussed: environment; materials; building's design; craftsmanship in the construction of the building and its maintenance. The use of expert systems for diagnosis in building practice or for mitigation of the effects of decay and damage to buildings belonging to the cultural heritage is still not very common. In building diagnostics, generally, steps like survey, (visual) assessment, diagnosis and intervention are commonly used. With the support of a damage atlas in expert systems, a correct definition of the observed damage type is possible, providing a more objective and user-independent result.

References

[1] Elbert K, Cultrone G, Navarro R, Pardo SE. Durability of bricks used in the conservation of historic buildings – influence of composition and microstructure. Journal of Cultural Heritage 2003;2:91-99.

[2] Boynton RS. Chemistry and technology of lime and limestone, Wiley New York 1980.

[3] van Balen K. Lime Mortar Carbonation and Its Influence on Historic Structures. PhD thesis, K.U.Leuven 1991.

[4] Vitruvius P. The ten books of architecture. Rowland ID, Noble Howe T. eds., Cambridge University Press, Cambridge 1999.

[5] Baronio G, Binda L. Physico-mechanical characteristics and durability of bricks from some monuments in Milan. Masonry International 1985;4:29-35.

[6] Cultrone G, Sebastián E, Elert K, De La Torre MJ, Cazalla O, Rodriguez-Navarro C. Influence of mineralogy and firing temperature on the porosity of bricks. Journal of the European Ceramic Society 2004;24:547-564.

[7] Castro F, Oliveira P, Fernandes I. Development of a methodology for estimation of the provenance of archaeological ceramics. Method and Theory in Historical Archaeology. Method and Theory in Historical Archaeology 1997;10:123-125.

[8] López-Arce P, Garcia-Guinea J, Gracia M, Obis J. Bricks in historical buildings of Toledo City: characterization and restoration. Materials Characterization 2003;50:59-68.

[9] Lourenço PB, Fernandes FM, Castro F. Handmade Clay Bricks: Chemical, Physical and Mechanical Properties. International Journal of Architectural Heritage: Conservation, Analysis, and Restoration 2009;4(1): 38-58.

[10] Maierhofer C, Leipold S, Schaurich D, Binda L, Saisi A. Determination of the moisture distribution in the outside walls of S. Maria Rossa using radar. 7th International Conference on Ground Penetrating Radar 1998;509-514.

[11] Livingston RA. Materials analysis of the masonry of the Hagia Sophia Basilica, Istanbul. 3rd International Conference on Structural Studies, Repairs and Maintenance of Historical Building, 1993;15-31.

[12] Cultrone G, De La Torre MJ, Sebastian EM, Cazalla O, Rodriguez-Navarro C. Behavior of brick samples in aggressive environments. Water, Air and Soil Pollution 2000;119:191-207.

[13] Winslow DN, Kilgour CL, Crooks RW. Predicting the durability of bricks. ASTM Journal of Testing and Evaluation 1988;16(6):527-531.

[14] Marzahn GA, Jahnel R, Tue NV. Finite element analysis of two ancient groined masonry vaults. 13th International Brick/Block Masonry Conference 2004;147-156.

[15] Bati S, Ranocchiai G. A critical review of experimental techniques for brick material. 10th International Brick/Block Masonry Conference 1994;1247-1255.

[16] Lourenço, PB, Ramos, LF, Vasconcelos, G, Peña, F. Monastery of Salzedas (Portugal): Intervention in the cloister and information management. 6th International Conference on Structural Analysis of Historic Constructions, Taylor & Francis Group, 2008; 95-108.

[17] Schubert P. The influence of mortar on the strength of masonry. 8th Int. Brick and Block Masonry Conference, eds. J.W. de Courcy, Elsevier Applied Science, London, UK 1998;162-174.

[18] CEN. EN 1052-1:1999, Methods of test for masonry: determination of compressive strength. Brussels, Belgium 1999.
[19] Mann W, Betzler M. Investigations on the effect of different forms of test samples to test the compressive strength of masonry. 10th Int Brick/Block Masonry Conference 1994;1305-1313.
[20] Kirtschigg K. On the failure mechanism of masonry subject of compression. 7th Int Brick/Block Masonry Conference 1985;625-629.
[21] Haseltine B. International rules for masonry and their effect on the UK. Masonry Int 1987;1(2):41-43.
[22] Vermeltfoort A. Compression properties of masonry and its components. 10th Int Brick/Block Masonry Conference 1994;1433-1442.
[23] CEN. EN 1996-1-1:2005. Eurocode 6. Design of masonry structures. General rules for reinforced and unreinforced masonry structures. Brussels, Belgium, 2005.
[24] ACI. ACI 530-11/ASCE 5-11/TMS 402-11: 2011 Building Code Requirements for Masonry Structures. Detroit, USA, 2011.
[25] Hilsdorf H. An investigation into the failure mechanism of brick masonry loaded in uniaxial compression. Designing, engineering and construction with masonry products. Houston: F.B. Jonhson 1969.
[26] Khoo C, Hendry A. A failure criterion for brickwork in axial compression. 3rd Int Brick/Block Masonry Conference 1973;139-145.
[27] Francis A, Horman C, Jerrems L. The effect of joint thickness and other factors on the compressive strength of brickwork. 2nd Int Brick/Block Masonry Conference 1971;31-37.
[28] Atkinson R, Noland J, Abrams D. A deformation failure theory for stack-bond brick masonry prisms in compression. 7th Int Brick/Block Masonry Conference 1985;577-592.
[29] Ohler A. Zur berechnung der druckfestigeit von mauerwerk unter berucksichtigung der mehrachsigen spannungszustande in stein und mortel. Bautechnik 1986:5.
[30] Schubert P, Hetzemacher P. On the flexural strength of masonry. Masonry International 1992;6(1):21-28.
[31] Drysdale RG, Hamid AA, Heidebrecht AC. Tensile strength of concrete masonry. Journal of the Structural Division (ASCE) 1979;105(7):1261-1276.
[32] van der Pluijm R. Out-of-plane bending of masonry: Behaviour and strength. PhD Dissertation. Eindhoven University of Technology 1999.
[33] Hamid AA, Drysdale RG. Concrete masonry under combined shear and compression along the mortar joints. ACI Journal 1981:1314-320.
[34] Page AW. The biaxial compressive strength of brick masonry. Proceedings of the Institution of Civil Engineers, Part 2 1981;71:893-906.
[35] Ganz HR, Thürlimann B. Tests on the biaxial strength of masonry (in German). Report 7502-3. Institute of Structural Engineering, Zurich 1982.
[36] Page AW. The biaxial compressive strength of brick masonry. Proc. Intsn. Civ. Engrs., Part 2 1981;71:893-906.
[37] Page AW. The strength of brick masonry under biaxial compression-tension. Int. J. Masonry Constr. 1983;3(1):26-31.
[38] Huinink HP, Petkovic J, Pel L, Kopinga K. Water and Salt Transport in Plaster/Substrate Systems. Heron 2006;51(1):9-31.
[39] Charola AE. Salts in the deterioration of porous materials: An overview. Journal of the American Institute for Conservation 2000;39(3):327-343.
[40] Collepardi M. Thaumasite formation and deterioration in historic buildings. Cement and Concrete Composites 1999;21:147-154.
[41] van Hees RPJ, Wijffels TJ, van der Klugt LJAR. Thaumasite swelling in historic mortars. Field observations and laboratory research. Cement & Concrete Composites 2003;25:1165-1171.
[42] van Hees RPJ, Naldini S. The Masonry Damage Diagnostic System. International Journal for Restoration of Buildings and Monuments 1995;1(6):461-473.

[43] van Balen K, Mateus J, Binda L, Baronio G, van Hees RPJ, Naldini S, van der Klugt L, Franke L. Expert system for the evaluation of the deterioration of ancient brick structures. Research report no. 8, vol. 1, European Commission 1999.

[44] van Hees RPJ, Naldini S, Binda L, Van Balen K. The use of MDDS in the visual assessment of masonry and stone structures." Proceedings of the 1st International RILEM Symposium On Site Assessment of Concrete, Masonry and Timber Structures, L. Binda, M. di Prisco, and R. Felicetti, eds., RILEM Publications S.A.R.L., Varenna, Italy, 2008;651-660.

[45] de Vent IAE, van Hees RPJ, Hobbelman GJ. Towards a systematic diagnosis of structural damage. Structural Analysis of Historic Construction; Preserving Safety and Significance, Bath, United Kingdom, 2008;689-696.

[46] de Vent IEA. Structural damage in masonry. PhD Thesis, TU Delft 2011.

[47] van Hees RPJ, Binda L, Papayianni I, Toumbakari E. Characterisation and damage analysis of old mortars. Materials and Structures 2004;37:644-648.