# Ancient stone masonry constructions

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# 11

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## 11.1 Introduction

In much of the world, the largest part of the built heritage, both living and monumental, consists of masonry buildings. A feature of this heritage is the great variability of local architectural characteristics that resulted in a very wide range of structural diversity. In the various architectural styles, construction techniques have evolved with a strong link with the environment, cultural context, and available resources. Techniques evolve, respecting of the essential laws of mechanics, in almost Darwinian fashion. Building techniques must be preserved and enhanced, because they characterize the society and the identity of the very people, just as a spoken language (Fratini et al., 2011; Gamrani et al., 2011; Rovero and Tonietti, 2012; Sani et al., 2012).

The knowledge and study of building techniques form the basis of every operation of conservation, not only to preserve the building material heritage but also to preserve the body of knowledge, handed down orally or rediscovered, that underlie them. Such heritage of knowledge has produced sustainable building systems, in equilibrium with the environment, and therefore can suggest strategies in the modern context.

In addition to reintroducing masonry construction techniques for new construction thanks to the development of innovative systems for the extraction and cutting, the rich existing heritage of masonry buildings has shown great environmental adaptability, as demonstrated by the historical centers of many European cities that remain densely inhabited. Interesting challenges are therefore the reuse and rehabilitation, in respect of safety, linked to seismic risk and energy efficiency.

In this chapter, after an overview of historic vernacular applications of masonry buildings, the physical and mechanical properties of the different components of the masonries are discussed and the more common types of masonry walls are presented. Finally, some considerations are given to mechanical and environmental performance of masonry constructions and applications in modern architecture and innovative uses.

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## 11.2 Overview of ancient applications

The widespread use of stone in all historical periods is mainly due to its availability, strength, and durability, qualities that allow it to overshadow the difficulties of quarrying, processing, and transport. Since the dawn of human civilization, man has learned to exploit the rocky outcrops to make symbolic constructions and religious buildings. Tombs and religious constructions are made of large stones using interlocking systems without the use of mortars: megalithic structures, as *dolmen*, *menhir,* and temples, have been found in large areas of the Middle East but also in Asia and across Europe. Other wonderful examples of great skill in the use of stone in antiquity are pyramids (Egypt and Middle East) and step pyramids (in Central America), huge structures built of stone and sometimes mortar, some of which are among the world's largest constructions: the Great Pyramid of Giza (Egypt) is one of the largest in the world, with a base of over 52,600 $m^2$ in area; and the pyramid of Cholula, Puebla, Mexico, stands 55 m above the surrounding plain and in its final form measured 400 × 400 m.

The first man-made constructions are artificial caves carved into the rock. Splendid examples are found in many geographically and chronologically diverse civilizations: the great façades with superimposed orders of the Nabatean tombs of Petra in Jordan dug into the multicolored sandstone, the rock-hewn church in Lalibela, northern Ethiopia, the Byzantine churches of Cappadocia dug into volcanic formations, the rock architectures dug into limestone in many areas of the southern Mediterranean, including Spain (Andalusia) and Italy (the "sassi di Matera," the troglodyte settlements of Cava d'Ispica and Pantalica, inhabited in alternate phases until the second half of the nineteenth century, and the houses in the historical centers of Modica, Scicli, and Ragusa) (Sani et al., 2012).

Throughout history, rocks were used to build walls and define spaces, using both large blocks, more or less worked and built without mortar, and small blocks, processed and put in place with the aid of mortars.

In Ancient Rome, special masonry techniques, known as *opus*, have been developed thanks to the use of mortars with the addition of *pozzolana*. These walls were made of two external leafs with an internal core made of rock fragments bound by lime mixed with *pozzolana*. Significant among these are *opus quadratum* (stones cut into parallelepiped shape arranged in horizontal rows), *opus caementicium* (stone and mortar), *opus incertum* (stones randomly placed in the mortar, with the main face outward), *opus reticulatum* (stones with a square base arranged diagonally; this method is known to have excellent seismic performance), and *opus mixtum* (*opus reticulatum* with corner pieces in bricks).

Walls with large hewn stone in the Greek and Roman world were strengthened with lead clamps that were cast in their molten state into holes carved in the stones. This technique has been used in many temples of the Acropolis in Athens and in the Coliseum in Rome, as well as in many other important structures of the period.

In the medieval period, stone was the basic material for the construction of houses and castles. The masonry types are innumerable and adjusted according to the type of stone used and to the type of building constructed. A medieval stonemason would often carve a personal symbol onto their block to differentiate its work, providing at the same time a simple means of quality assurance and determining payment.

Starting from the Middle Ages, the use of brick coexists with the use of stone, becoming predominant in regions rich in clay soils. Stone remains the predominant building material for vernacular architecture in areas with abundant rocky outcrops but is also used for the construction of buildings of higher value, such as churches.

In the sixteenth century in Florence, and in the other cities that have been center stage for the Renaissance, the technique of stone working improves, creating façades decorated with precious ornamental stones (ie, marble, serpentinite) or with stones carved to create volume and play of shadows in perspective (ashlar stones, cornices, etc.).

In all ages, the realization of structural supports (pillars, columns, and arches) and the realization of coverings through vaulted systems led to the development of sophisticated techniques of stereotomy (descriptive geometry) for the design and cutting of the stone elements.

In the history of architecture, stone is also the main material used for cladding, flooring, decoration, and, together with tiles, roofing. Slabs used for roofs are documented in some villages of the northern Apennine (Italy), in the famous "trulli" of Apulia (southern Italy), and in many regions of France like Provence (Rovero and Tonietti, 2014; Dipasquale, 2012).

## 11.3 Stone masonry materials

Stone masonry is formed by stone blocks, of natural origin, that is, derived from the rocks, and by mortars of artificial origin, that is, man-made products. This section deals first with stone blocks, describing rock classification and a review of rock types used in architecture. Next, we address mortars, describing the raw materials, the processes of preparation, and the most representative types.

### 11.3.1 Natural forms of stone material: the rocks classification

Rocks constitute the outer part of the Earth crust and are natural associations of one or more types of minerals, being the final result of a rock-forming process. In their turn, the minerals are defined as natural materials, in the great majority of cases solid, inorganic, and homogeneous from chemical and physical points of view. When solid, they are in a so-called crystalline state. The crystalline state is characterized by a regular and ordered arrangement of atoms and/or molecular components. This ordered structure also determines the anisotropic properties of these natural bodies. Rocks are generally constituted by a limited number of mineral species. In some, only one mineral is present such as in limestone and marble, made up almost exclusively of calcite. In others, such as conglomerates, there are many types of minerals. In the following, a simplified classification is reported.

#### 11.3.1.1 Magmatic rocks

Magmatic rocks are formed after the crystallization of a magma, a mixture of a liquid, gaseous, and crystalline phase at a temperature above 700°C. The main components are: silica (40–75%), alumina (10–20%), iron oxides (2–12%), calcium (1–12%), magnesium (trace-12%), sodium (1–8%), and potassium (trace-7%). In the gaseous phase, the main component is water and, to a lesser extent, carbon dioxide, hydrochloric acid, sulfur dioxide, etc.

**Figure 11.1** Granite ashlars in a building of Giglio island (Tuscany, Italy). Photograph: F. Fratini.

### 11.3.1.2 Intrusive rocks

Intrusive rocks are formed through crystallization of magma within the earth's crust. Due to the slow crystallization process, they are characterized by granular structures (Fig. 11.1). A typical intrusive rock is *granite*, widely used in the architecture of northern Portugal, Galicia, Brittany, northern Sardinia, and Corsica.

### 11.3.1.3 Volcanic rocks

Volcanic rocks are formed on the surface of the Earth; magma is brought to the surface through the phenomenon of volcanism (emission of lava). The rapid cooling of magma prevents the complete crystallization with the consequent formation of a porphyritic structure, characterized by a groundmass composed of small crystals in which a few large well-formed crystals (phenocrysts) are included. A typical volcanic rock is *basalt*, used, for example, in the architecture in the surrounding of Etna volcano (Sicily), in Ireland, and in northern Jordan. When the magma is viscous and rich in gas, the rocks will be particularly porous (vesicular structure) as in pumices and some kinds of rhyolites and trachytes (Fig. 11.2).

### 11.3.1.4 Sedimentary rocks

Sedimentary rocks are formed by granules (sediments) coming from the weathering of preexisting rocks. There are two distinct groups: clastic rocks derived from material transported in solid form and rocks of chemical and biochemical origin derived from material transported in solution. The processes that lead to the transformation in rock (diagenesis) are compaction, dissolution under pressure, and precipitation of new minerals (like calcite, silica, iron oxides), which leads to cementation of the sediment. Among the clastic rocks, the *conglomerates* are composed of detrital elements

**Figure 11.2** The Zenòbito Tower (XVIth century) in the Capraia Island (Tuscany, Italy), built in trachyte blocks.
Photograph: F. Fratini.

(clasts) of coarse size (from 2 mm to 25.6 cm) derived from the transformation in rock of gravels (Fig. 11.3). The term *breccias* refers to those conglomerates whose clasts have not undergone transport and therefore have maintained sharp edges; breccias originate mainly from talus fans. The *sandstones* have clasts size between 62 μm and 2 mm and result from the transformation of sands into rock. The main components of the sandstones are: quartz, feldspars, mica, and clay minerals. When limestone clasts predominate, the rock is called *calcarenite*. The sandstones have been widely used in the architecture of central Italy (Florence, Cortona, Arezzo) (Fig. 11.4) as dressed/cut stones, decoration, architectural elements, and, in thin slabs, for roofing. The *shales*

**Figure 11.3** A conglomerate block in “Fonte dell’Ovile” (XIIIth century, Siena, Italy).
Photograph: F. Fratini.

**Figure 11.4** “Pietra Bigia” sandstone in a building of Arezzo (Tuscany, Italy).
Photograph: F. Fratini.

have clast sizes of less than 62 μm and result from the transformation of clay muds into rock. They consist mainly of clay minerals which, due to their laminar structure, are deposited according to a preferred orientation parallel to the stratification, resulting in highly fissile rock. The shale cannot be used as a building material, but clay, mixed with water, is the raw material of much earthen architecture and of the production of bricks and terracotta. When the original mud is composed of tiny fragments of calcite, the rock that is formed is called *calcilutite* or *micritic limestone* (Fig. 11.5). There are also terms of transition to the shale (*marly limestones*, *calcareous marls*, *marls*). The *volcanic tuffs* can be included in the sedimentary rocks as they are the result of the

**Figure 11.5** Micritic limestone (Pietra Alberese) in the masonries of Certosa di Firenze (XIVth century, Florence, Italy).
Photograph: F. Fratini.

**Figure 11.6** Tuff masonry in Pitigliano (Tuscany, Italy).
Photograph: F. Fratini.

deposition and subsequent transformation into rock materials (blocks, lapillus, ash) originated from explosive volcanic eruptions. The volcanic tuffs were widely used in the architecture of central and southern Italy (province of Viterbo, Rome, Naples area) (Fig. 11.6).

## Rocks of biochemical origin

*Rocks of biochemical origin* derive from the removal of calcium and carbonate ions from seawater by organisms such as foraminifera and mollusks to form their own shell. The accumulation of the shells of these organisms produces the *organogenic limestones* that when poorly cemented are called *calcareous tufa*. *Dolomites, calcareous dolomites,* and *dolomitic limestones* contain, instead, major amounts of the mineral dolomite.

## Rocks of chemical origin

*Rocks of chemical origin* derive from the process of precipitation of calcium carbonate from thermal springs that gives rise to *travertine* (Fig. 11.7) and *calcareous alabaster*. Evaporites are rocks formed after the chemical process of precipitation of calcium sulfate, sodium chloride, and other salts in lagoon basins characterized by hot and arid climates. Great importance is played by the deposits of calcium sulfate (gypsum and anhydrite) used to produce the gypsum binder. In architecture, carbonate rocks (limestones, dolomites, marly limestones, organogenic limestones, travertine) have been widely used as building materials both as dressed/cut stones, thin slabs for roofing and for the production of lime. In particular, the marly limestones have been widely used in the constructions of north–central Italy (ie, east Liguria, Florentine region) and the calcareous tufa in southern Italy (Sicily, Naples, Salento).

**Figure 11.7** Travertine (whitish blocks) together with volcanic trachyte blocks in Castiglione d'Orcia (Tuscany, Italy).
Photograph: F. Fratini.

#### *11.3.1.5 Metamorphic rocks*

Metamorphic rocks have undergone changes in their mineralogical composition and texture due to increasing temperature and pressure (metamorphism) within the earth's crust. All rocks (magmatic, sedimentary, metamorphic) may be subject to metamorphism.

The typical appearance of the great majority of metamorphic rocks is the schistose texture; schistosity is the tendency of a rock to split into thin slabs according to sub parallel planes. Schistosity is the consequence of the oriented pressure sustained by the rock during the metamorphic process that caused an orientation of the minerals with elongated, fibrous, and lamellar shapes. Typical metamorphic rocks are *slates*, *schists*, and *gneiss*.

The *marbles* are a particular type of metamorphic rock, produced by metamorphism of carbonate rocks composed of calcite or dolomite. Generally, they show a low schistosity.

Metamorphic rocks have been widely used in the architecture of the Alpine countries, in the area of the Pyrenees, in northern Spain, Wales, and in the north of England, especially as thin slabs for roofing but also as dressed/cut stones. Famous is the "Ligurian slate," which, with its gray color, characterizes the roofs of Genoa and of many villages of Liguria (Italy) (Fig. 11.8).

### *11.3.2 Petrographic characteristics and use of rocks as building materials*

The petrographic characteristics of the rock affect the properties of stone construction material. In particular, the mechanical properties, including compressive strength and the stiffness, and the physical properties, such as durability, workability, polishing, and

**Figure 11.8** The Ligurian slate (ardesia) used as tiles for roofs and wall protection (Genoa, Italy).
Photograph: F. Fratini.

sculptability characterize the behavior of stone materials. The mechanical properties of stone blocks affect the global behavior and the bearing capacity of masonry structural elements. Rocks with good compressive strength (eg, granites, marbles, compact limestones) were used for columns, pillars, and cornerstones. Durability (ie, the resistance to decay caused by atmospheric agents) must be taken into account in relation to the intended use of the material. Rocks resistant to abrasion such as sandstones and porphyry were often used for flooring. Workability is better in soft stone (volcanic tuffs and tufa) that are split, sawn, and shaped more easily than sandstone, compact limestones, and granites. Polishing cannot be accomplished in rocks such as sandstones, because of the presence of minerals with very different levels of hardness such as quartz and clay minerals. Polishing is possible in compact and homogeneous rocks (eg, igneous rocks, compact limestones, marbles). Sculptability is favored in homogeneous, compact, and fine-grained rocks, free from veins and minerals that may be altered (pyrite). In fine-grained marbles, these conditions are well satisfied.

The majority of the rocks present in the Earth's surface can provide building stone. Those rocks that are not suitable for construction include the sedimentary rocks in which a strong clay component is present (eg, marls, marly clays, shales). These rocks are poorly coherent, laminated and fissile but, nevertheless, when the clay component is predominant, can be used to produce bricks, tiles, and earthenware in general. Other rocks unsuitable for use are very schistose metamorphic rocks (phyllites) and volcanites rich in a glass component (obsidian, pumice).

Vernacular architecture has the characteristic of using, in most cases, materials available in the immediate vicinity of the buildings. Therefore, these materials determine the character and uniqueness of each site, and technical and stylistic convergences between different territories may occur in instances of availability of similar materials.

The shape of stone blocks in buildings depends on the geological nature of stone; this also influences the type of processing and use. The following typologies can be distinguished: (i) river pebbles (unprocessed), (ii) unworked stones (shapeless or regular blocks), (iii) roughly worked stones (dressed stone), (iv) cut stone (worked on all sides) for special masonries, and (v) slabs for floors, walls, stairs, and roofs.

*River pebbles* may have more or less rounded surfaces as a function of the transport distance and a more or less spherical shape as a function of the textural homogeneity of the mother rock: rocks with homogeneous texture without preferential orientation of the constituent minerals, such as granites, basalts, and some types of limestones, give rise to spherical shapes, while those with preferential orientation, such as the metamorphic rocks and some types of sedimentary rocks, result in flat or elongated shapes.

*Unworked stones* can have an irregular shape if obtained by splitting rocks devoid of fractures and characterized by a homogeneous texture without cracking (eg, granites) or a regular shape when obtained by taking advantage of the presence of cracks (eg, columnar basalts), the thickness of layers (in the case of sedimentary rocks), or the schistosity (metamorphic rocks).

*Dressed stones* are obtained through rough working of hard rocks (using chisels of various shapes) and through cutting with axes, saws, etc. for soft rocks like volcanic tuffs and calcareous tufa.

*Slabs* can be obtained through splitting along planes of sedimentation for sedimentary rocks (limestones, sandstones) or through splitting along the planes of schistosity for metamorphic rocks (slates, schists, gneisses).

### 11.3.3 Mortars

Mortars are artificial materials produced by man since ancient times that are used for different functions including masonries, plasters, to adhere tiles or realize decorations (stuccos, etc.). Mortars with special uses (filling of holes, sealing, pointing of mortar joints etc.) or features (resistant to moisture, pigmented, etc.) also abound.

Mortars are obtained by mixing water and aggregate with different types of binders, capable of hardening the paste. Organic additives (egg yolk, egg white, casein, animal glue, “fig milk”, walnut oil, linseed oil, blood, resins, etc.) and natural fibers (straw, animal hair, iron filings, etc.) can also be added, as well as synthetic fibers and pigments, to impart particular characteristics.

The aggregate is added to the mixture with the aim of reducing the shrinkage and enhancing the strength of the final product. Generally, aggregate is supplied from river beds, but it can also come from beach deposits and from unconsolidated sand outcrops. It can also be obtained through the mechanical crushing of rocks.

Among the binders used to make the mortar, the following categories can be distinguished: (i) clay binders, (ii) gypsum binders, and (iii) lime-based binders. *Clay-based binders* are probably the earliest binders used by man, who realized how the dried clay develops a remarkable cohesion and is able to bind together elements of masonry. Mixtures of earthy clay are normally used as bedding mortars for masonry in mud brick (adobe) and for plastering the same earthen walls, in this case often combined with plant fibers. To make the clay paste more resistant to moisture, the addition of lime is also documented. Lime is able both to form a calcitic binder and to react with the clay minerals, thereby inhibiting the absorption of water in the crystal lattice of these minerals (Gamrani et al., 2011).

With respect to *gypsum binders*, use probably began in Middle East, where large outcrops of sulfatic rocks are present, and spread, especially in Egypt at the time of the ancient dynasties. The binder is obtained by burning evaporitic rocks of sulfatic composition at relatively low temperatures. At 130°C, these rocks undergo a chemical transformation, due to partial dehydration, giving rise to hemihydrate calcium sulfate called fast-setting plaster or plaster of Paris. Kneading with water quickly rehydrates and hardens the mixture. By burning the gypsum stone at 160–180°C, "gypsum for plasterers" or anhydrous gypsum is obtained, which on very fine grinding, is suitable for bas-reliefs, statues, etc., realized through molds or shaping in paste.

Gypsum binder has been widely used in historic buildings, especially for its capability to set and harden quickly. It can be used without aggregate because during setting it does not undergo shrinkage. Nevertheless, knowledge of its actual use in historical architecture has been forgotten because the gypsum mortars produced at present, obtained from the hemihydrate gypsum or from anhydrous gypsum, are hygroscopic, absorb a lot of water, and tend to pulverize. Therefore, today, gypsum binders are used mainly indoors to realize plasters, stuccos and decorations, as well as in the form of a fluid paste injected into masonry for consolidation operations. In some regions of Europe rich in sulfate rocks, like the Paris basin, some parts of Germany, and eastern Spain, gypsum mortars have been used extensively, with good results of durability, for exterior plasters, bedding mortar and even for realization of floors (Vegas et al., 2010; La Spina et al., 2013; Sanz and Villanueva, 2004). The good behavior of these mortars is particularly evident when sulfatic rocks, rich in carbonate and clay impurities, have been used as a raw material. In fact, traditional burning in furnaces where the temperature is not controlled causes the formation of calcium oxide and calcium silicates that give to the gypsum binder its particular resistance to decay.

Among the *lime binders*, *air-hardening calcic lime* is obtained by burning of pure limestones at a temperature of 850–900°C. At first, quicklime (calcium oxide) is obtained that, mixed with water, gives rise to slaked lime or lime putty (calcium hydroxide). The lime putty mixed with aggregate, without the necessity of adding water, hardens through the process of setting (evaporation of water and fixation of carbon dioxide [carbonation]) with the consequent transformation of the calcium hydroxide into calcium carbonate (Fig. 11.9).

From the burning of dolomite or dolomitic limestones, *air-hardening magnesian lime* is obtained that, on setting, produces mortars with mechanical properties higher than those from the air-hardening calcic lime. Regarding these two types of limes, and in particular for the calcic lime, experience has taught that the quality of the lime putty (plasticity, workability, carbonation, mechanical characteristics of the finished product) improves with aging, that is, with storage in an anaerobic environment (under a layer of water, covered with moist sand or in airtight containers) for as long as possible. In this regard, the recommendations of Pliny the Elder (1952)

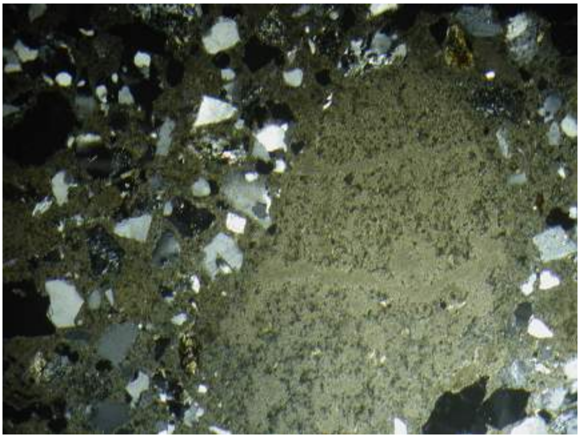

**Figure 11.9** Air hardening calcic lime mortar from a Florentine building of the XIXth century observed in thin section under transmitted light at the optical microscope. In the center an underburnt fragment of the limestone used to produce the lime.
Photograph: F. Fratini.

in "Naturalis Historia" are well known, suggesting a prolonged maturation. Early Roman provisions required curing in water for at least 3 years before use. The reasons that the curing improves the quality of the lime putty have been investigated by some scholars (Rodriguez Navarro et al., 1998; Hansen et al., 1999), who found that with aging, the crystals of calcium hydroxide undergo major changes in shape (from prismatic to tabular) and in size (from micron to submicron). These changes induce a significant improvement in the physical properties of putty, which becomes more plastic.

Nevertheless, there is a traditional technique of slaking and use of lime called "dry slaked lime." This technique does not require curing and it is used in the production of "hot lime mortars."

It is a technique common especially in Northern Europe, reported in treatises (Kraus et al., 1989), and represented in paintings. It was used both to produce bedding mortars and to fill the cores of masonry construction. In Northern Europe, this technology is still used (British Standard Code of Practice, 1951), in particular for restoration and as a traditional building technology, thanks to its good workability, durability, affordability of the final product, and suitability for winter use.

Usually, the mortars made with this technology are characterized by (i) a high amount of binder (ratios binder:aggregate 1:1 to 1:2), (ii) presence of numerous whitish inclusions consisting of lime not well mixed in the paste (dusty lumps, lumps of putty, remnants of under burnt lime fragments) (Kraus et al., 1989; Middendorf and Knöfel, 1991; Forster, 2004), and (iii) excellent mechanical properties with good adhesion to masonry and high resistance to frost.

There are various methods of making these mortars (Doglioni et al., 1986, Foster, 2004), but in summary we can say that fragments of quick lime are covered with sand, wet several times, and mixed before use. Doglioni et al. (1986) reports that in the case of use as bedding mortar, the mixture was sieved while, when used to fill the core of masonries, once cast with stone chips and pressed, was sprayed with water from above. It is this procedure, washing away the lime, that resulted in the precipitation of calcite concretions in the areas below.

With regard to the excellent mechanical properties and high durability of the "hot lime mortars," the heat developed in the mixture during slaking can have a positive effect in improving the binding between lime and aggregate because a basic attack on the surface of the silicatic aggregate is favored, making the granules rougher and more reactive (Jedrzejewska, 1967; Gibbons, 1993). Additionally, the steam that is produced can aid the formation of large pores, making the mortar more resistant to frost action.

The firing of marly limestones (with a percentage of clay from 5% to 20%) results in *hydraulic lime*. The slaking of this lime is done by sprinkling the clods of quicklime with water until they disaggregate to powder. This powder must then be stored in dry conditions; otherwise, it hardens and can no longer be used. Unlike air-hardening lime, the setting of hydraulic lime can take place in very humid environments and, indeed, under water. In the past, hydraulic lime was realized by adding to the lime putty additives such as pyroclastic material (volcanic ash, pumice) and ground earthenware. These substances, rich in active silica and alumina, react with the lime-forming calcium silicates and aluminates, which make the mortar capable to set in very humid conditions. Therefore, these types of mortars were often used for flooring and as tank and aqueduct coatings.

Organic additives are all those organic substances (milk, egg, beeswax, oils, starches, natural resins or acrylic, etc.) that, when mixed with lime, form binders with particular characteristics (adhesion, water repellence, etc.) (Arcolao, 2001). Some of these binders can be called mastics and be used for bonding, to fill cracks or fissures, or to form protective layers for floors, balconies, etc. Generally, the mixtures of lime, brick dust, and linseed oil or litharge were most frequently reported in the texts of the eighteenth and nineteenth centuries, while those based on pitch date to more ancient times. Pitch, defined by sources as colophony, is a natural resin produced in the form of secretion from some resinous plants. Recipes with pitch-based binders are numerous and testify to its widespread use, especially for its protective, adhesive, and waterproof properties. Often, the pitch-based compound was added with oil, animal fat, or wood ash to increase the workability and water resistance and with ox blood, wax, or to increase toughness, to accelerate the setting, reduce shrinkage, and to create less-viscous mixtures able to better penetrate the masonry.

In the first half of the nineteenth century, a new type of binder was developed, *Portland cement*, obtained by burning at very high temperature (1450°C) marly limestone or mixtures of limestone and clay. This revolutionary material was an important turning point in the history of architecture and resulted in the gradual abandoning of traditional mortars. Portland cement, compared to traditional binders, is characterized by a quick set and higher mechanical strength, allowing a wider use in the structural field. Cement mortars, however, have demonstrated poor durability in many applications, demonstrating the continued value of traditional binders.

## 11.4 Masonry constructions

The use of stone blocks assembled by mortar has characterized the architecture of all periods, creating a wide repertoire of technological and typological forms, which differ based on the specific characteristics of the stone and the construction techniques used. Different levels of performance and mechanical behavior correspond to different levels of development of the construction techniques used. These result from the quarrying capacity and processing of the stone and the technological methods adopted in the construction phase. Masonry buildings are continuous, consisting of bearing walls rather than framed structures. When subject to vertical loads, the walls demonstrate good mechanical behavior and typically have excellent resistance to sustained (creep) or accidental loads. In fact, in masonry buildings, all walls play a structural function, the transverse dimensions are consistent, and applied compressive stresses are typically low.

In the case of horizontal actions, such as those induced by the earthquakes, masonry structures exhibit an intrinsic weakness due to the low tensile strength of the material. Masonry consisting of stone elements assembled with or without mortar have poor adhesion between the stone blocks. In constructions without mortar, only gravity and friction resist tension forces, whereas in mortared construction, adhesion contributes to the capacity. Dangerous crack patterns or catastrophic collapses demonstrate the vulnerability of masonry construction to seismic action; this is mostly attributed to the lack of tensile strength of the walls. In particular, crack patterns highlight the separation between orthogonal walls, damages due to shear actions in the plain of the walls, and the initiation of wall overturning (Fig. 11.10).

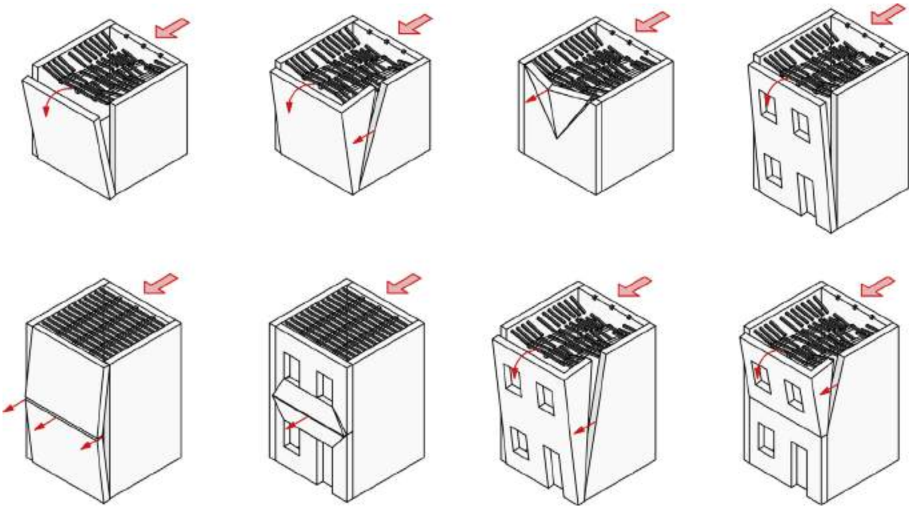

**Figure 11.10** Collapse mechanisms of masonry walls subjected to horizontally thrust. Drawings: D. Omar Sidik.

To evaluate the mechanical efficiency of a masonry building in the event of horizontal actions, the main factors to consider are the ability of the building to behave like a box and the degree of monolithic behavior of the walls. The box behavior depends on the efficiency of the connections between orthogonal walls and between walls and floors; in the case of good connections, the seismic action is absorbed by the walls with greater stiffness, the overturning of the individual walls is mitigated, and only shear fracture in transversal walls appears.

The degree of monolithic behavior of a masonry wall made up of separate blocks is different than the theoretical model of wall consisting of a single block, which responds to the vertical loads with homogeneous stress and resists the seismic actions with rocking behavior. A wall consisting of small and irregular pieces, assembled in a chaotic way, cannot behave as a monolith and, when affected by the earthquake, disintegrates during low values of the seismic action. Only if the wall has a certain degree of compactness does the rocking mechanism engage, allowing greater resistance to horizontal loads.

### 11.4.1 The box behavior

Masonry buildings have a box behavior when the interlocking between orthogonal walls is effective. Construction techniques have resulted in different approaches for the realization of interlocking. The most common technique uses "cornerstones," stones of a larger size than those used in the walls and typically of regular shape. In this manner, an effective coupling of orthogonal directions through the thickness of the walls is possible.

Efficient systems of restraining (hooping) building walls to maintain the box were made with wooden or iron chaining. The use of wood for hooping is widespread in countries in which the earthquake risk is high and wood is abundant. Very interesting are examples in the Balkans, Anatolia, and sub-Himalayan regions (Dipasquale et al., 2014a,b). An evolution of wooden hooping is the iron chaining that begins to be used in the thirteenth century, developing along with the techniques of iron working, first in France and then across all the northern Mediterranean basin.

### 11.4.2 The masonry wall

The primary factors affecting the mechanical quality of a masonry wall are the shape and size of the stone blocks, the quality of the mortar, and the masonry texture (Dipasquale and Volpi, 2010). With regard to the size of blocks, a wall shows good performances if larger elements represent the majority of the section or if the size of the elements is homogeneous. The mortar makes the contact and friction between the stone elements relatively uniform in order to avoid concentrations of load when the surfaces are not regular. In the case of walls built with elements of small dimension, in which the meshing of the stones is not sufficient to ensure the monolithic behavior of the wall, the mortar should compensate providing transverse interlocking. The low tensile strength of the mortar, however, prevents it from completely fulfilling this task. Nevertheless, when the laying of stones is well organized, the cohesion of the mortar is less important: even a poor mortar accomplishes the function of making the contact uniform.

In terms of wall texture, a good mechanical solution must prevent any vertical separation of the wall into leafs exhibiting independent behavior. However, since the size of the stone blocks is typically smaller than the wall thickness, it is inevitable that the wall tends to behave as two vertical elements. For this reason, connections are needed between the external and internal wall elements to ensure a monolithic behavior, particularly when subject to seismic loads. This connection is obtained through the meshing of overlapping stones, which are crossing stones that bind the two opposite leafs. The resistance of the wall is ensured when the meshing between stones is sufficient to provide an equilibrium path for the transmission of loads through contacts between stone blocks.

Additionally, horizontally oriented "bonding courses," realized through the use of small stones, stone flakes, or brick layers, are useful to improve the mechanical behavior of the wall (Fig. 11.11) (Dipasquale and Volpi, 2010; Rovero and Fratini, 2013). The horizontal courses allow the formation of linear hinges in the event of horizontal loads. These trigger a reversible tipping mechanism and eventual self-righting stability of the wall, when the horizontal excitation ceases. In the instance of irregular masonry courses, the rotation triggered by an earthquake would result in irregular portions of the masonry and large variations in contact loads between the stones. When the rotation initiates, the combined action of the weight of the wall and the horizontal force (which should be dissipated along the edge of the wall) runs obliquely along the thickness of the wall, affecting the transverse monolithic

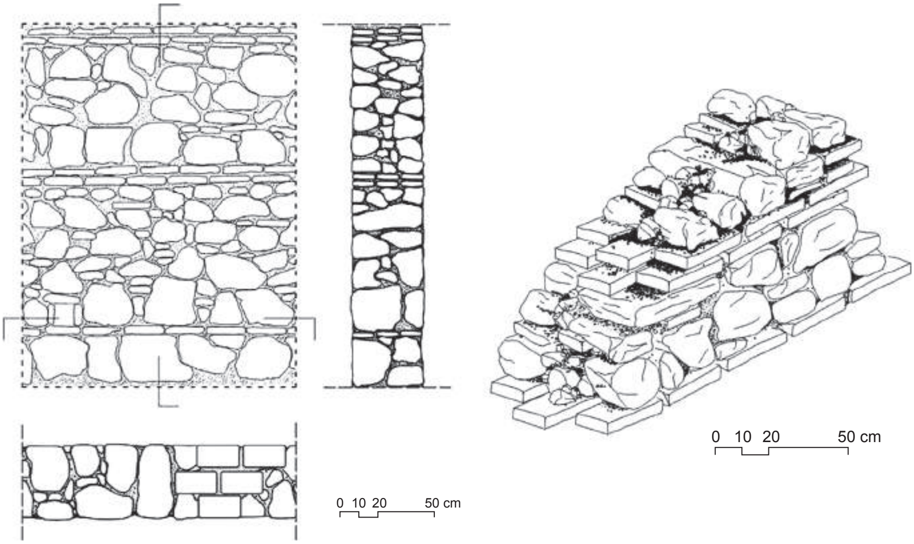

**Figure 11.11** Representation of masonry walls of good quality, with bricks to improve the horizontality of the laying planes and diatones to connect the opposite leafs of the wall. Surveyed in Chefchaouen, Morocco.
Drawings: L. Dipasquale & V. Volpi.

character of the wall and potentially resulting in failure of the wall. Bonding courses help to make these forces more uniform through the wall thickness.

### 11.4.3 Masonry wall types

According to the shape of the stone elements and their assembly, different types of masonry walls can be distinguished.

#### 11.4.3.1 Dry stone walls

Dry stone walls are composed of blocks of stones that are laid down without any mortar to bind them together. The structural integrity of dry stone walls arises from compression forces and the interlocking of the stones. The wall thickness depends on the nature and size of the stones and boulders available; these often come from nearby fields during preparation for agriculture.

The tools used for cutting and roughing of the stones are elementary: hammer, pick-axe, and shovel for soil preparation and the mallet and chisel to make a flat surface. The walls are built up by course, and at intervals, large tie-stones are placed that span both faces of the wall and increase the strength and integrity of the wall. In many cases, the last row is realized by placing larger pieces, that span the entire width of the wall, to connect the two leafs and close the wall.

Such walls have been traditionally used in building field boundaries and retaining walls for terracing, but dry stone buildings, bridges, and other structures also exist. In Europe, dry stone structures can be found mostly in regions having natural rock outcrops or large stones exist in quantity in the soil; they are abundant in the upland areas of Britain and Ireland (particularly Connemara) and throughout the Mediterranean, mostly in southern Italy (Apulia and Sicily) (Fig. 11.12(a–c)), France, Greece, and Spain.

#### 11.4.3.2 Rubble masonry

Rubble masonry has been extensively used for vernacular building worldwide where a local source of stone is readily available. This type of masonry consists of blocks of undressed or rough stones placed with mortar. Depending on the characteristics of the local rocks, the dimension of the stones, and their arrangement in the wall, a large variety of subtypes can be distinguished: *Random rubble masonry* consists of not-squared-off stones of different sizes and shapes arranged in courses of equal (*coursed random rubble masonry*) or different height (*uncoursed random rubble masonry*) (Fig. 11.13(a) and (b)). In both cases, the larger stones are laid down first and the spaces between them are filled up with chips of stone. The more regular the courses, the better the mechanical performance of the wall will be. When the rock is very compact and hard, generally the blocks of stone are irregular in shape and dimension. For this reason, the organization of the blocks for the stability of the wall requires a considerable amount of binding mortar, capable of ensuring the assembly of the various elements, as well as the success of the masonry which depends on the strength of the mortar itself (Fig. 11.13(c)). *Squared rubble masonry* consists of face stones that

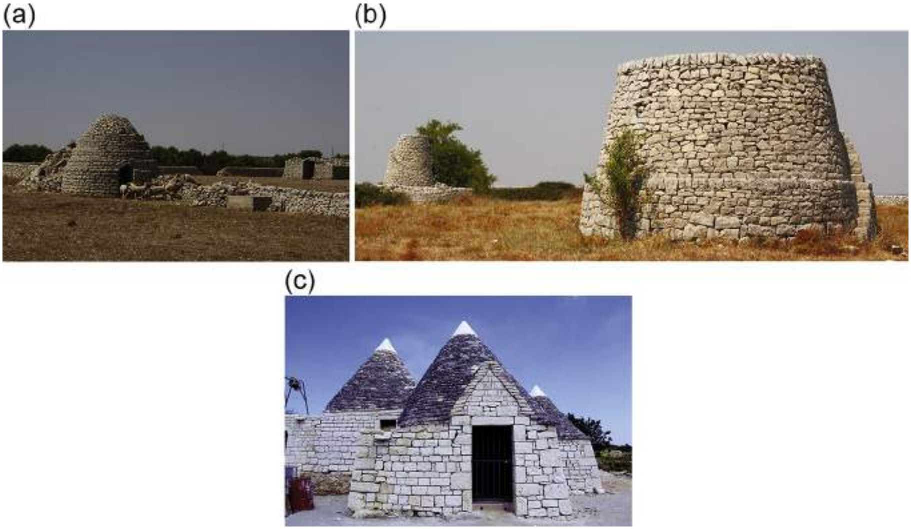

**Figure 11.12** (a, b) Dry stone construction near Ragusa (Sicily, Italy). *(Photograph: L. Dipasquale.)* (c) Dry stone construction in a "trullo" of Alberobello (Apulia, Italy) *(Photograph: L. Dipasquale.)*

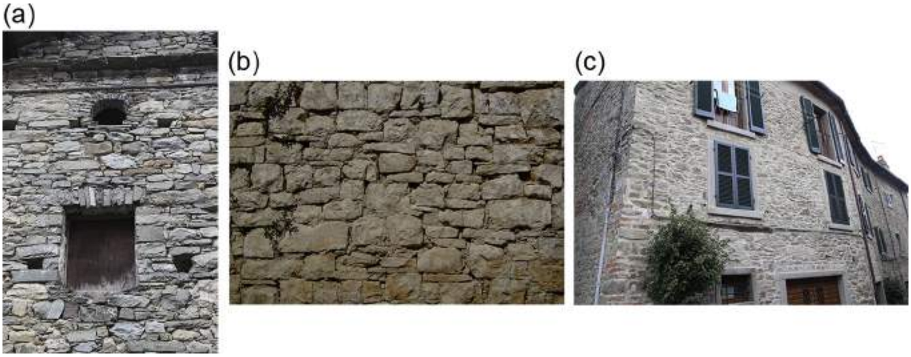

**Figure 11.13** (a) Random rubble masonry with a little amount of bedding mortar in Lunigiana (Tuscany, Italy). *(Photograph: L. Dipasquale.)* (b) Random rubble masonry in Alberobello (Apulia, Italy). *(Photograph: L. Dipasquale.)* (c) Random rubble masonry with a lot of bedding mortar in Cortona (Tuscany, Italy). *(Photograph: L. Rovero.)*

are squared and brought to hammer-dressed or straight cut finish before being laid. Stones can to be laid in courses of equal layers with uniform joints (*coursed square rubble masonry*) (Fig. 11.14(a)) or can be arranged in several irregular patterns or courses of different size (*uncoursed square rubble masonry)* (Fig. 11.14(b) and (c)).

Together with quarried stone, river stone (pebbles) were sometimes employed in the construction of rubble walls. Such alluvial soil provides high amounts of such material in suitable sizes. In addition to the blocks, stone flakes can be used, together with

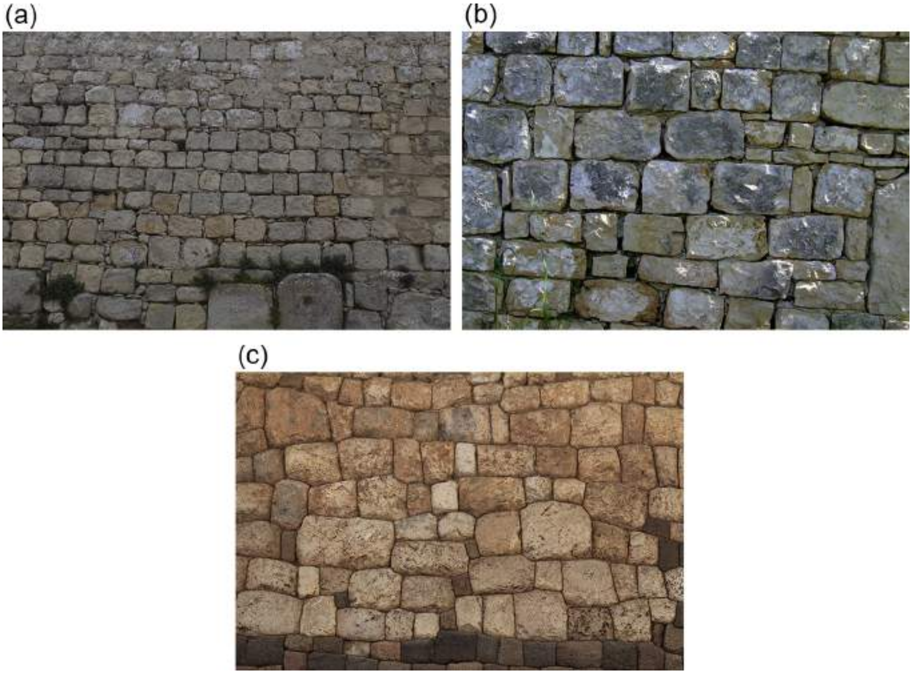

**Figure 11.14** (a) Coursed square rubble masonry in Ragusa (Sicily, Italy). *(Photograph: L. Dipasquale.)* (b) Uncoursed square rubble masonry in Apulia, Italy. *(Photograph: L. Dipasquale.)* (c) Uncoursed square rubble masonry in Cusco, Perù. *(Photograph: L. Rovero.)*

pieces of brick and roof tiles, in order to fill the uneven gaps remaining among the stones and to obtain a kind of uniformity. Generally, large stones are employed at quoins and jambs to increase the strength of the masonry. Bricks can be also used with the aim of creating horizontal layers so as to improve effectiveness in the irregular stone work (such as in the Roman *opus listatum* shown in Fig. 11.15).

The evaluation of the quality of the rubble masonry structure depends also on the disposition of large stones, or through stones used as internal cross-connections, whose dimensions exceed half the thickness of the wall. In the absence of large stone blocks connecting the outer leafs of the wall, the masonry arrangement needs a high use of mortar in order to allow the transfer of loads and to ensure the integrity of the whole, although this alone cannot guarantee a monolithic behavior and resistance against out of plane actions. Rubble masonry is often covered by a plaster, which plays the role of protection and counteracts the dangerous phenomenon of washing out due to rain.

### *11.4.3.3 Ashlar masonry*

Ashlar masonry is composed of regularly shaped stone blocks, with a dressed exposed face, which may feature a variety of treatments: tooled, smoothly polished, or rendered with another material for decorative effect. All the faces of the block are adjacent to those of other blocks, and joints can be very thin. The height of each course is kept

**Figure 11.15** Random rubble masonry with horizontal layers of bricks in Lamezia (Calabria, Italy).
Photo: L. Dipasquale.

uniform, and all the joints are uniform (Fig. 11.16(a) and (b)). As the dressing of stones requires heavy labor and wastage of material, soft rocks are generally used. It is common, therefore, to find dressed stones used only as a facing (while the backing is rubble or brickwork) or just in the most important parts of the building (angle quoins, lintels, beams, arches, etc.), except in works of great importance and solidity. Ashlar masonry has been used by many ancient cultures (early examples can be found in the Knossos palace in Crete, in the step pyramid of Djosar in Egypt, and in Macchu Picchu in Peru) and is used worldwide for public or high-quality historical buildings.

Ashlar blocks were also used to create domed or arched structures in vernacular buildings (Fig. 11.17(a)). The superposition of successively smaller rings of ashlar stone was used also to construct beehive-shaped domes, used, for example, in the corbelled tombs, known as *tholoi*, which are commonly found throughout ruins of ancient civilizations in the Mediterranean and also in the vernacular architecture of the same region

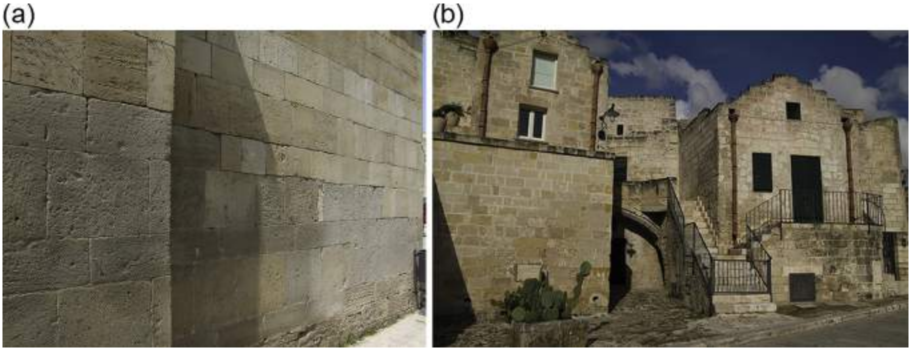

**Figure 11.16** (a) Ashlar masonry in Baku, Azerbaijan *(Photograph: L. Dipasquale.)* (b) Ashlar masonry in Matera (Italy). *(Photograph: L. Rovero.)*

**Figure 11.17** (a) Ashlar masonry used in a barrel vault in Ragusa (Sicily, Italy). *(Photograph: L. Dipasquale.)* (b) Corbelled domes in Alberobello (Apulia, Italy) *(Photograph: L. Dipasquale.)*

(talayots and ponts in Balearic islands, cabanes in Provence, pagghjari in Corse, mitati in Crete, chozos-barracas-pozos-bombos in Spain, nuraghi and pinnéttas in Sardinia, trulli-furneddi, specchie in Apulia) (Fig. 11.17(b)) (Dipasquale and Jorquera, 2009).

### 11.4.3.4 Masonry with wood reinforcing

Masonry with wood reinforcing is a very common in seismic-prone areas. The tensile strength of wood offers reinforcement against horizontal loads and enables the dissipation of substantial amounts of energy in the case of earthquakes. Moreover, timber elements divide the structure into sections, preventing the spread of cracks occurring in portions of the masonry. Two main categories of wood reinforcement can be identified: the hooping and frame systems. Hooping arranges the wooden beams horizontally within the load-bearing masonry during the construction process. The empty spaces between the beams are filled with fragments of brick or stone. The resulting ring beams can be inserted at the floor levels, at openings and lintels, or regularly distributed along the height of the construction. This system can be found in seismic regions of the Mediterranean from the Balkans to Turkey, Maghreb, Greece, and Italy (Dipasquale et al., 2014a,b) (Fig. 11.18).

The second category includes wooden-frame systems, which are articulated in round or square section beams and pillars, and frequently include diagonal bracing elements. The empty spaces defined by the frame are filled with locally available materials (earth, stone, or brick). One of the most ancient examples in Italy of timber-frame buildings techniques is the *opus craticium* by Vitruvius, today visible in some of the surviving houses of the archeological sites of Herculaneum and Pompeii (Fig. 13.19). In the Mediterranean area, relevant traditional examples of timber-frame structures together with masonry can be found in Turkey, Greece, and parts of Eastern Europe. In these countries, common traditional buildings techniques are based on the use of masonry-laced bearing wall constructions on the ground floor level and lighter infill-frames for the upper floors. The ground floor masonry walls are often laced with horizontal timbers; these elements can be thin timber boards laid into the wall so that they overlap at the corners or squared wooden beams.

**Figure 11.18** Masonry with hooping wood reinforcement in Elbasan (Albania).
Photograph: L. Rovero.

**Figure 11.19** *Opus craticium* in Pompei, Regio I Insula XII.
Photograph: L. Giacopelli.

## 11.5 Mechanical performance

### 11.5.1 Assessment of the safety

The problem of safety assessment of existing masonry buildings is very complex because the wall structures, unlike those made of steel or reinforced concrete, do not allow the definition of a single mechanical model capable of realistically modeling any situation. Masonry buildings, in fact, show a great variability in both materials and construction techniques, being the result of local cultures and traditions. Many studies have been devoted to understanding the structural behavior of masonry solids — from the elastic theory to limit analysis approaches, from micromechanical modeling to distinct elements analysis. The approaches are differentiated by purpose, level of approximation, and field of application.

The Italian Technical Standards (NTC, 2008) is a leading code with performance-based approaches for the safety assessment of existing masonry buildings, subject to seismic actions. According to NTC (2008), safety is evaluated using a limit states approach with reference to the ultimate limit states carrying out global analyses and checks against local mechanisms. The standards requires that the structural analysis considers displacement demands and that is carried out assuming that the structure can deform beyond its elastic limit through the opening of fractures, that dissipate energy but do not compromise the bearing capacity for vertical loads. This approach allows imparting upon masonry structures (although consisting essentially of brittle materials (stones, bricks, and mortar)), a “pseudo ductile” structural behavior with considerable capacity beyond the elastic phase, a behavior critical to sound seismic behavior.

To assess global behavior, it is necessary to conduct nonlinear analyses considering the building in its entirety. Masonry buildings are conventionally modeled using a geometrically equivalent frame whose pillars and beams represent the walls. The application of nonlinear static analysis to historic buildings is not always possible and has many unconvincing aspects. The representation of the structure as an equivalent frame is possible only for isolated regular structures (both in plan and in elevation) with aligned windows. Moreover, typically, the mechanical model provides that the interlocking between the walls and between walls and floors is perfect. Essentially, the procedure of calculation assumes that the building to be verified exhibits box-like behavior with effective interlocking, a condition that is unlikely in many historic structures. The resulting analyses are likely to overestimate the in situ structural capacity.

Greater criticism can be made of modeling aggregates of buildings for which standards introduce the concept of structural units that are analyzed separately taking into account the actions that result from contiguous structural units.

In addition to global behavior, safety assessment of masonry buildings subjected to seismic action must be conducted considering the possible local collapse mechanisms. This requirement more realistically accounts for the mechanical behavior of masonry structures characterized by the absence of effective linkages between orthogonal walls and between walls and floors and therefore characterized by high vulnerability to out-of-plane actions (as postseismic scenarios have unfortunately highlighted). The local mechanism approach is based both on the pioneering studies of Giuffré (1991, 1993) concerning the behavior of walls and their damage mechanisms and on the theories of Heyman (1995, 1996) that extended the application of limit analyses to masonry buildings. The method is based on assuming that the masonry behaves like a rigid material, having no tension strength but infinite compressive strength. Therefore, the more “macroscopic” characteristics of the masonry are considered and this fact allows one to carry out the assessment within the conditions of the limit analysis, without the need to identify elastic material properties, whose definition, in the case of heterogeneous materials such as masonry, is not easy. The walls are represented as rigid blocks subject to their own weight, to possible loads transmitted from floors, and to horizontal loads defined, through a multiplier, as function of vertical ones. Based on the observation of post-seismic damage and on the specific local building conditions, a kinematically congruent mechanism can be assumed through the introduction of plastic hinges. Using the kinematic theorem of limit analysis makes it possible to identify the upper limit of the actual multiplier for the horizontal loads at collapse, from the lowest of all multipliers determined for the hypothesized mechanisms. The identification of mechanisms is facilitated by a survey of similar buildings already damaged by seismic activity. From this, the fracture patterns can guide the selection of the macroelements involved in the mechanism and the subsequent selection of the position of the hinges.

The assessment procedure based on local mechanisms provides a very simple tool, capable of capturing the essence of the behavior of masonry buildings and highlighting the most vulnerable parts. The "simplification" taken may lead to an underestimation of the mechanical behavior under earthquake, especially when using the linear kinematics; nevertheless, the approach allows one to obtain the limiting value of the seismic action that can be withstood.

The detailed study of the building, considering the type of the masonry walls and efficiency of the interlocking, allows an enrichment of the approach based on local mechanisms, thus being an improved approximation of behavior. It is possible, for instance, to introduce resistive forces produced by the friction between the blocks and/or the cohesion produced by the mortar. If the walls are made without an adequate cross-connection, taking the form of two essentially separate leafs, the reduced ability to withstand out-of-plane actions should be considered. In such cases, mechanisms that enforce the presence of two leafs and the possible cohesive capacity or interaction between them must be considered.

### 11.5.2 Estimation of mechanical parameters

To perform an assessment of global behavior, it is necessary to make an analysis of the whole building, specifying the actual mechanical properties of the different materials constituting the masonry. The identification of mechanical parameters of masonry structures is complex. In fact, strengths and stiffness of masonries depend on many factors, such as strengths of component blocks and mortar, blocks shape, volumetric ratio between components, and wall texture. Taking into account the complexity resulting from the great number of variables, a fair assessment of the load-carrying capacity of masonry can be made only by in situ test, as highlighted in Binda et al. (2000).

In situ tests with semidestructive methods may not always be performed. In these cases, an assessment of the compressive strength of masonry walls can be carried out on the basis of a qualitative criteria evaluation, as proposed in Borri and De Maria (2009). The method, the Masonry Quality Index (MQI), consists of the evaluation of the presence, the partial presence, or the absence of certain parameters that define the "rule of the art," namely a set of construction techniques that, if executed during the construction of a wall, provide a good mechanical behavior and ensure the compactness and monolithic nature of the structure. A synthetic evaluation of the wall quality is obtained through three overall scores, the MQIs, that define the quality of masonry in relation to three actions: vertical actions, out-of-plane actions, and in-plane actions. An estimation of the mechanical parameters (compressive strength, shear strength, and Young's modulus) of masonry can be obtained through correlation curves, obtained from experimental data (Borri and De Maria, 2009).

## 11.6 Applications in modern architecture and innovative uses

While in traditional architecture stone plays a dominantly structural role, with the emergence of industrial techniques in the building sector and the structural use of reinforced concrete and steel, the use of stone has become mostly limited to veneers and claddings, becoming the skin of the building only. In modern architecture, stone is first reinterpreted by the Modern Movement, which puts aside the structural function of the material and gives it a new role, more related to its texture. Examples of this trend can be seen in the works of Ludwig Mies van der Rohe and Frank Lloyd Wright in the United States and, in Italy, in the buildings of Giuseppe Terragni, Adalberto Libera, and Giovanni Michelucci. In Late Modernism, stone is used on façades with the innovative system of "ventilated walls," which uses thin industrial processed slabs detached from the main structure by means of a metallic shelf, leaving an air chamber between the slab and structure. This gap provides an important function in regulating the interior thermal environment. During mid 1980s, some architects, such as Arata Isozaki, Aldo Rossi, James Stirling, and others, used stones with different colors and textures to emphasize the aesthetics of the surfaces.

The use of bearing masonry in modern and contemporary architecture is rather limited. It should be highlighted that the work of Antoni Gaudi (Crypt of the Guell colony, Barcelona, 1898–1917), that at the time seemed simply a reminder of the building traditions of the past and today seems paradoxically innovative. In recent years, there are some interesting examples from international architects who have enhanced stone in their projects, using different language and renewing its stereotomic conception: from Jorn Utzon (Can Lis House in Maiorca, 1973) to Aldo Grassi (Alessi House in Lago Maggiore, 1989) to Kengo Kuma (Stone Museum in Tochigi, 2000).

Many cases of contemporary architecture use reinforced masonry. Stone is reinforced with concrete, for example, in the St. John the Baptiste Church (Florence, 1960) of Giovanni Michelucci or in the Therme Vals (1991) of Peter Zumthor (Fig. 11.20). In both cases, walls are made by two stone exterior layers used as formwork for the subsequent casting of reinforced concrete.

The modernization of the production cycle of quarries by means of computer numerical control (CNC) machine tools has led to innovative technologies for reinforced stone. As examples, both the Expo pavilion in Seville (1992) of Peter Rice and the Liturgical Hall "Padre Pio" in San Giovanni Rotondo of Renzo Piano (2008) (Fig. 11.21) are based on the assembly of blocks of stone, individually designed, cut with high precision with use of the CNC machine, and stacked using posttensioned metallic cables to realize loading arches (Salerno et al., 2010).

**Figure 11.20** Therme Vals wall structure of Peter Zumthor, Vals, Graubünden (Switzerland) (cc by 2.5).

**Figure 11.21** Liturgical Hall "Padre Pio" of Renzo Piano in San Giovanni Rotondo (Apulia, Italy).
Photograph: F. Fratini.

The use of stone in massive form reappears in recent years in the works of the French architect Gilles Perraudin, who, for 15 years, has been designing contemporary buildings in which the supporting walls are made entirely of blocks of stone (Fig. 11.22). Blocks of local calcareous stone of large dimension have been used to build wine cellars (including the cellar of Vauvert in the Gard region, 1998) and buildings for cultural activities (Center for Training and Apprenticeship in Marguerittes, 1998, Wine Museum in Patrimonio, Corsica, 2011). Recently, stone construction was efficiently used in a social housing project (Cornebarrieu, suburb of Toulouse). The use of stone responded to a test of its feasibility with respect to very high requirements in terms of energy, environmental impact, and cost—having been constructed on a budget of about 1000 euros per square meter. The technique used by G. Perraudin in this project was based on placing one piece on the other and holding the large blocks

**Figure 11.22** Chai viticole Vauvert by Gilles Perraudin.
Credits: Perraudin architectes.

in place by their sheer mass, without the use of cement or binding elements. A lime mortar mixed with stone sawdust from the quarry was used to prevent wind blowing through the joints. Despite the traditional building site, new technology and machinery allowed the building to be constructed in just few months, despite the weight of the stone blocks.

Another innovative use of stone in contemporary architecture can be seen in gabion walls. This technique consists of cages—generally made of galvanized steel wire or mesh—filled with rocks without mortar. The technique has been employed from the late nineteenth century to build retaining walls, and stabilize shorelines, stream banks, or slopes against erosion. In recent years, gabion walls have also been used in contemporary buildings, since many architects have recognized the effectiveness of such structures: gabions can be made using local stone, including small pieces of (otherwise waste) quarry material, the construction process is simple and low cost. Gabions are modular, can be constructed off site and stacked in various shapes; they are also resistant to being washed away by moving water. Ian Ritchie Architects used gabion structures to build the cultural Centre of Terrasson, France, while Herzong & de Meuron explored the environmental potential of this technique in the Dominus Winery in Napa Valley, California (Fig. 11.23). Here, the gabions are used to moderate the extreme temperatures of the Napa Valley, forming a *brise soleil* and thereby reducing thermal gain during the day, while during the night the mass of the stone acts as a thermal insulator (Dernie, 2003).

## 11.7 Role of masonry in sustainable construction

Stone as a building material demonstrates a number of important inherent qualities, which are well known to those whose work focuses on conservation in historic buildings. These same qualities can and should be leveraged in innovative construction methods and applications for contemporary architecture.

**Figure 11.23** Dominus Winery by Herzog & de Meuron realized with gabions.

Masonry constructions have contributed to define the cultural identity of many areas worldwide, and they still are, thanks to their great durability, the principal constituent part of the current architectural heritage, despite the changing environment of cities and environmental context in which they reside. Great durability and low maintenance requirements of masonry construction mean important benefits also for contemporary buildings, in terms of sustainability from both environmental and socio-economic respects. Of course, certain environmental conditions—such as temperature, precipitation, wind, water, and air pollution—can cause of degradation of stone materials and influence the physical aspect of the building surfaces and their durability (Fig. 11.24). Moreover, factors such as poor design of details, poorly executed repairs, and inadequate maintenance of the building can accelerate the processes of decay to both stone and the building in general. The reaction to exposure to their environment

**Figure 11.24** Degradation of a calcareous masonry in Ragusa (Italy).
Photograph: L. Dipasquale.

varies from stone to stone, which is the reason why durability testing is required in modern construction. Such testing provides product performance over its lifetime and helps the designer to choose the appropriate type of stone depending on its use. Internationally recognized standards for assessing the environmental durability of stone products are promulgated by ASTM International and in Europe by the Construction Products Regulation 305/2011. In European Union countries, durability testing on building stone are required to obtain the CE marking, which is the manufacturer's Declaration of Conformity affixed to a product to indicate that it conforms to certain safety requirements, during both initial type testing and factory production (Dipasquale, 2012).

Today, stone materials can gain an advantageous position compared to other building materials, if they demonstrate their competitive qualities. Among these qualities, reduced environmental impact is a key strength. In terms of embodied energy and embodied carbon—such as many studies comparing natural stone with other building materials have demonstrated—the total energy inputs consumed throughout a stone construction life cycle and the carbon footprints of the entire process are lower than those of other building materials, such as concrete, bricks, and concrete block (Table 11.1) (Crishnaa et al., 2011; Garzonio et al., 2010; Morela et al., 2001; Urquhart, 2008; Stone Federation Great Britain, 2011). Although energy used for the extraction of indigenous natural stone, transportation to the factory, processing, and manufacturing bypass the initial carbon impact associated with the production of materials such as concrete, steel, and brick, the transportation of stone over vast distances around the world is a negative

**Table 11.1** **Embodied carbon of common construction materials**

| Building materials | kg $CO_2$/ton |
|---|---|
| Sandstone | 64 |
| Granite | 93 |
| Marble | 112 |
| General concrete | 130 |
| General clay bricks | 220 |
| Slate | 232 |
| Timber | 450 |
| Facing bricks | 520 |
| General building cement | 830 |
| Steel: bar and rod | 1710 |
| Steel: galvanized sheet | 2820 |

Data for granite, sandstone, and slate are from Stone Federation Great Britain, 2011. Natural Stone the Oldest Sustainable Material, SFGB; the others are from University of Bath (Inventory of Carbon & Energy).

factor in terms of environmental impact. For this reason, the most sustainable approach to rock selection will be when it is sourced from a local quarry or reclaimed from demolished buildings (a practice that has gone on for millennia). Once the masonry is installed, recurring embodied energy, represented by the energy used to maintain, replace, and recycle materials and components of a building throughout its life, is lower than that of other materials (Hammond and Jones, 2006).

Further, stone is an abundant and practically inexhaustible resource. Because of its longevity, stone blocks can be either reused in the original structure or repurposed for use in another structure built with compatible material. Even if stone cannot be reused, it can be crushed for use as aggregate.

In terms of energy efficiency, stone masonry can play an important role by virtue of its high thermal inertia, which is the property that enables building materials to slowly absorb, store, and later release significant amounts of heat, contributing to indoor temperature stabilization against outdoor variations. The most energy is saved in summer, in geographical zones in which significant reversals in heat flow occur within a wall between night and day: the heat absorbed during the day by the mass of the wall can be cooled by natural ventilation during the night.

Masonry buildings are a green and a healthy solution also because they are not harmful. There are no toxic materials used in processing, nor are there direct greenhouse gas emissions during processing. Masonry building materials do not contain chemical additives or involve risks to health.

In conclusion, stone masonry can continue to be regarded as a holistic construction technique. The scientific community must invest a deeper knowledge of the material towards a progressive enhancement of its potential performance, by the considering and learning from practices well established over the centuries. Innovation in terms of sustainability is only now becoming sufficiently understood.

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