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# The Stone Masonry Contribution in Greek Industrial Buildings' Typology and Construction Durability (Late 19th to Early 20th Century)

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**Abstract.** *Stone masonry is the oldest form of construction in the world until the beginning of the 20th century. The first stone walls were constructed by farmers and primitive people by piling loose field stones into a dry stone wall. Later, mortar and plaster were used, especially in the construction of city walls, castles, and other fortifications before and during the Middle Ages. These stone walls are spread throughout the world in different forms. Stone walls are usually made of local materials varying from limestone and flint to granite and sandstone. However, the quality of building stone varies greatly, both in its endurance to weathering, resistance to water penetration and in its ability to be worked into regular shapes before construction. Also, the majority of buildings in Greece at the end of 19th century up to the use of concrete in constructions are load-bearing stone masonry structures. Moreover, research shows that it is the most widely construction material in industrial buildings, that era. As it is known, stone masonry has high compression strength under vertical loads but has low tensile strength (against twisting or stretching) unless reinforced, while the tensile strength of masonry walls can be increased by thickening the wall. In general, industrial buildings constructed of stone masonry, from late 19th to early 20th century, have particularities in their typology because they were directly dependent on their mechanical equipment and production line. The aim of this study is to investigate the contribution of stone masonry as a construction material in the typology of these industrial buildings concerning their durability.*

**Keywords:** *Stone Masonry, Durability, Stone Masonry Properties, Traditional Constructions, Industrial Buildings' Typology.*

## 1 Introduction

Stone masonry is a traditional form of construction practiced for centuries in the regions where stone is locally available (Khan, Lemmen, 2013). Until the emergence and wide use of steel around the mid-20th century, load-bearing masonry was the only building material up to date in the construction of various works around the world. Exceptions were areas where wood was used exclusively for building. In countries with a tradition in using masonry constructions and where there was no strong seismicity such as Great Britain new buildings up to four floors using bearing masonry techniques are still constructed.

This type of masonry is still found in old historic centres, often in buildings of cultural and historical significance, and in developing countries where it represents affordable and cost-effective housing construction. This construction type is present in earthquake-prone regions of the world, such as Mediterranean Europe and North Africa, the Middle East, India, Nepal, and other parts of Asia.

Houses of this construction type are found both in urban and rural areas. There are broad variations in their shape and the number of storeys. Houses in rural areas are generally smaller in size and have smaller openings since they are typically used by a single family. Buildings in urban areas are often of mixed use, that is, with a commercial ground floor and a multifamily residential area above. Houses in the countryside are built as stand-alone structures, while the neighboring houses in old town centers often share a common wall.

Moreover, research shows that it is the most widely construction material in industrial buildings, after the first Industrial Revolution. Between the end of the 19th and the beginning of the 20th century, industrial buildings constituted a large part of the cities' urban fabric, especially ports, such as Piraeus in Attica, Volos in Thessaly, Syros in the Cyclades etc., constituting an important chapter in the architectural development of each area. Therefore, their typological structures as well as their morphology, in relation to their structural construction system, which is bearing stone masonry and its durability, need special study.

## 2 Stone Masonry: Building Materials and Construction Technology

The main components of stone masonry are simple stones and synthetic mortar. Stones come mainly from sturdy rocks, which after a short or a long process get the proper shape to be suitable for the construction of the project. From a geological point of view, and depending on the way the rocks are formed, the natural stones used in building construction can be classified according to their origin as igneous, sedimentary and metamorphic.

The igneous stone principally used in building is granite, which was formed from the fusion of minerals under great heat below the earth's surface many thousands of years ago. Sedimentary stone was formed gradually over thousands of years from particles of calcium carbonate or sand deposited by settlement in bodies of water. Gradually layer upon layer of particles of lime or sand settled into depression in the earth's surface and in course of time these layers of lime or sand particles became compacted by the water or earth above them. Metamorphic stones have been changed from igneous or sedimentary stone or from earth into metamorphic stone by pressure, or heat, or both in the earth's crust. Examples are: a) marble which was formed from limestone and slate and b) shale formed from clay (Anmol, J.-10: 2019).

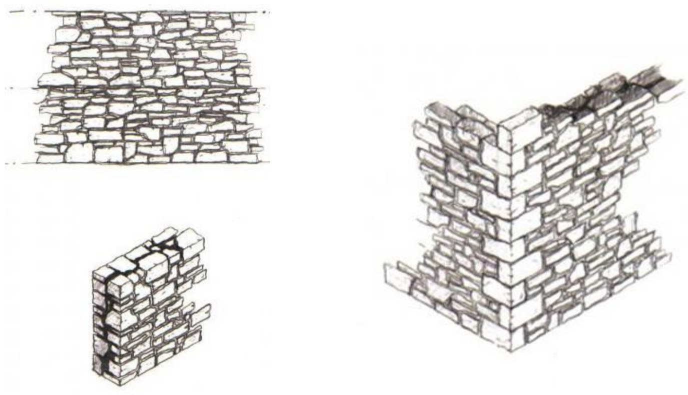


**Figure 1**. Stone masonry constructions.

Stone masonry is the most common type of masonry in Greek traditional architecture due to the abundance of stone in many places in Greece. They can be distinguished in coursed rubble masonry and uncoursed rubble masonry (Fig1.). The coursed rubble masonry walls have more durability due to the better fitting of the stones and homogeneity. However, they require larger and better quality of stones, in order to have quantity and quality material for achieving the best possible fitting. Furthermore, highly skilled craftsmen are required to carve the stones properly. The highest level of coursed rubble and durability, was achieved by the creators of the marble buildings in the Acropolis rock, in Athens. The carved stones were so well fitted together that no mortar was needed and their interconnection was finalized with internal metal fasteners.

On the other hand, uncoursed rubble masonry has the disadvantage of less durability, due to the poor adhesion of the stones and the high proportion of mortar required to fill the gaps. Another factor of less strength is the heterogeneity of the stones, since their irregular shape requires the use of different sizes to fill the gaps. Typical traditional architecture adopts an intermediate state using the coursed rubble stones are in the most sensitive parts of the building (corners, base, crown), and the uncoursed rubble stones in the least sensitive or visible parts of the building. Although brick masonry is very common in lowland areas where stone is scarce, as well as in northern Europe, in areas where the stone is abundant, there are brick masonry constructions, because they have some advantages over stone masonry such as the light weight of the bricks compared to the stones and the standardization of their dimensions (Ravi *et al*., 2014; Francis *et al.*, 1971).

Mortar, the binder material between the stones in masonry, is called the mixture consisting of fine aggregates (maximum aggregate grain diameter 4mm), cements such as binder and treatment water, having a wide variety of compositions and strengths (ASTM C 270-10:1019). Generally, the use of mortars makes the stonewall a comprehensive body, carrying safely the loads it was designed for and remaining also unchanged over time. Mortar's mechanical properties have a catalytic effect on the masonry characteristics. An additional factor of diversity is the construction type or otherwise the "knitting" way of masonry construction, giving to the stone masonry a distinct character and some additional features, such as better bonding and stone durability.

Structural walls are supported either by stone masonry strip footings or not. Floor structures in towns and historic centers are vaulted brick masonry at the ground floor level and timber joists at the upper floor levels. Timber joists are usually placed on walls without any physical connection. The original floor structures in historic buildings have typically been replaced either by a precast joist system or by solid reinforced concrete slabs especially in Italy (WHE Report 28-8:1019) and Slovenia (WHE Report 58-8:1019).

## 3 The Structural Stone Masonry Mechanical Behavior and Durability Under Vertical and Seismic Loads

The mechanical behavior of masonry is characterized by:
-Relatively high compressive strength.
-Extremely low tensile strength.
-Relatively satisfactory shear strength.
-Strongly anisotropic behavior.

The high compression strength of the masonry compared to its other mechanical properties also determined its use as a mainly compressed load bearing component (Stylianidis *et al.*-10:2019). Both the strength and type of failure of compression masonry are strongly influenced by the angle of the compression force as to the direction of horizontal joints (anisotropy).

When a masonry construction is being pressed perpendicularly to the main horizontal joints, usually, fails due to transverse splitting of the stones, due to the development of tensile strength in transverse directions. These tensile strengths are caused by the reconciliation of the large transverse deformations of the mortar joints with the smaller ones of the bricks, which causes corresponding transverse adhesion in the mortar. Thus, under axial compressive loading of the masonry, triaxial strength is developing on the stones and joint mortar. When using the term masonry strength refers to the compressive strength perpendicular to the horizontal joints (Tensing *et al.*, 2013).

The compressive strength of the masonry depends on:

1. The properties of stones, such as their strength, type and geometry.
2. The characteristics of the mortar such as its durability and composition.
3. The prevailing conditions in masonry i.e. the manner of engagement of masonry.
4. The material and the thickness of the joint.
5. How to apply and effect concentrated loads.
6. The quality of construction.

On the other hand, features of weaknesses in masonry are due to the behavior of the contact interface, mainly, along the repeated horizontal joints that have been characterized as "weak levels of masonry". The tensile strength of the masonry is clearly much lower than the compression, varying and depending on the angle of the tensile strength in the horizontal joints. In particular, the tensile strength of the bearing masonry is low, being perpendicularly to the horizontal joints and greater when is parallel to them. In case there is tensile strength on the joints, the mortar will be detached. Usually, the tensile strength being parallel to the joints is greater the tensile strength is greater, because of the resistance to sliding mortar or stone, as well as, the tensile strength of masonry.

Factors affecting tensile strength of masonry:

A. Joint resistance to detachment
B. Tensile strength mortar.
C. Mortar coherence.

Masonry’s behavior in shear compression is more satisfactory, as the incurred structure passes through various stages, until reach the crash stage. Pressing under vertical loads is clearly defined, but it is not the same in case of seismic pressing. Even after the simplification of the earthquake action in the two main directions of the building, the size and distribution of the seismic intersection (also between the vertical load-bearing elements of each floor) depending on the geometric and dynamic mechanical characteristics of the bearing organism, remains unpredictable (Kaaki, 2013).

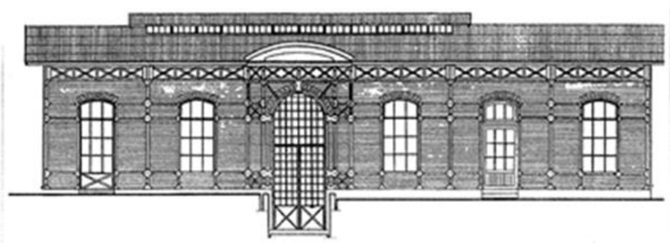
The most important factors affecting the seismic performance of these type of buildings are the strength of the stone and mortar, the quality of construction and the density, distribution of structural walls and wall intersections and floor/roof-wall connections (Costa *et al.*, 2011).

Stone masonry construction generally shows very poor seismic performance. Poor quality of mortar is the main reason for the low tensile strength of rubble stone masonry. Timber floor and roof structures are usually not heavy and therefore do not induce large seismic forces. However, typical timber floor structures are made of timber joists that are not properly connected to structural walls. These structures are rather flexible and are not able to act as rigid diaphragms. Due to their large thickness, stone masonry walls are rather heavy and induce significant seismic forces.

Typical damage patterns for built rubble stone masonry are delamination and disintegration, infilling in weak mud mortar with many air voids. Out-of-plane failure can occur when the connections between the exterior and interior walls are inadequate. When the connections between the perpendicular walls are strong, the wall shear capacity can be exhausted, thus causing typical shear cracks can be developed.

**Figure 2.** Dracopoulos Textile House, Athens, Greece (1882). **Figure 3.** Politis Factory, Piraeus, Greece (1882).

**Figures 4, 5, 6**. Power Plant in Karditsa, Greece (1909).



**Figures 7, 8**. Water Pumping Station building, Thessaloniki, Greece (1890-1892).

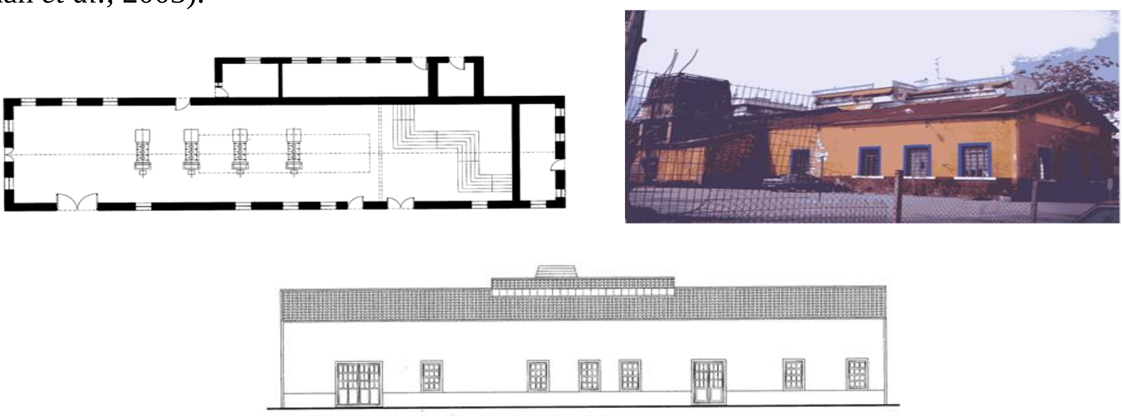
## 4 Typological and Material Characterization of Stone Masonry Durability in Industrial Buildings

Basic properties of stones for stone masonry are strength and durability, while economy and appearance are additional values. The main considerations for durability are the lasting qualities of stone itself and the locality where it is going to be used. Porous stones are unsuitable for areas prone to heavy rainfall and frost. Stones, e.g. marbles having low porosity and low coefficients of expansion and contraction should be used in areas subjected to large variations in rainfall and temperatures. Generally, lime and cement mortars are used for stone masonry, providing a workable matrix and ultimately a hard building material, which renders masonry into a monolithic unit.

As a matter of fact, the typology of traditional industrial buildings has been characterized by the elongated rectangular shape of the ground plan (Fig 8,9.), which contained the mechanical equipment for the production of the products. These elongated rectangular industrial buildings must have very thick walls (from 0,50 to approximately 1,00 meter, depending on the building's size: height and length) in order masonry durability to be increased. Also, this building's shape proves that the layout of the machines was not random, but was arranged in a linear layout to facilitate the production line. Using the perimetric bearing stone masonry, which was the structural construction system until the early 20th century, it was possible to construct most of the rectangular elongated buildings, or even having a square ground plan (Cheirchanteri, 2014).

The entrance of this type of buildings was most often located in the center of the narrow or longitudinal side, in such a way, that the production line was not interrupted. In this construction building system, although the openings were large, symmetrical, repetitive and sometimes arched, interior lighting was not sufficient in the middle of the building. As a result, elevated skylights were installed along the roof in order to enhance lighting (Fig 7,10,11.), (Cheirchanteri, 2014).

Masonry advantages, usually, include thermal insulation, fire safety, durability, ecological recycling materials of the building at the end of its lifetime and the elegant façade appearance. Among the disadvantages is the diversity of the stones, which makes its mechanical behavior unpredictable, contributing in the great difficulty of standardizing materials and methods (Phan *et al.*, 2003).



**Figures 9, 10, 11**. Power Plant building in Larisa, Greece (1913).

### 4.1 Stone Masonry Greek Industrial Buildings' Typology and Construction Durability

Until World War I, the typology of industrial buildings in Greece was the same as in Europe. The architectural volumes of these buildings were adapted to the shape and size of the mechanical equipment, as well as to the needs of the production cycle, unlike to other private and public buildings of that era, in which the shape, size, and layout were following strictly by the stereotypes, dictated by neoclassicism.

The basic type of these industrial buildings was the elongated rectangular shape, while the facilities were formed by the layout of many similar units. The machines were positioned across the production area, due to the motion transmission way and the side windows location, which were the only source of natural light for the workforce. Most of them were constructed using traditional techniques. It should be noted that industrial buildings were morphologically influenced by neoclassicism. According to their characteristics they were classified into three categories: the traditional industrial buildings, the monumental and the ragged in shape.

The industrial ground floor buildings constructed until 1900, were usually using in masonries stones cut and dressed to proper shapes, as well as, double incline roofed contractions, with small rectangular repeated openings. The stone masonry of these buildings was load-bearing, made of traditional materials such as wood, stone, tiles, and in many cases cast iron and steel. But their dominant feature was the incorporation of local architectural elements, achieved using traditional materials and construction methods. Concerning construction durability, bearing walls used to be very thick, about 1,00 meter, because of their very big height and length, which were demanded for their mechanical equipment.

A typical example of a traditional industrial ground floor building, built in 1882 in Athens, is the Drakopoulos Textile House (Fig 2.). It was one of the rare occasions among the first factories that the building was outstanding (variety of apertures, classic pediment on the façades, elaborate details, characteristic patterns), as opposed to the simple form of other factories in Greece. Also, the Politis factory in Piraeus (Fig3.), built between 1907 and 1916, had the same treatment as the first ground floor industrial buildings. The arched openings were dominant, while the consecutive double incline roofs had jagged architraves, with double skylights windows in the center, forming small, rectangular openings (Cheirchanteri, 2014).

The Turbine House of the Larissa's Power Plant in Thessaly (1913, Fig 9,10,11.), was a building with an oblong rectangular ground plan and a double incline tiled roof elevated on its central part, completing natural lighting and ventilation of the building. On the other hand, the Power Plant in Karditsa city, also in Thessaly area (1909, Fig 4,5,6.) was an industrial complex of two buildings, one and two-storey, correspondingly. Additionally, noteworthy is the monumental Water Pumping Station building in Thessaloniki (Fig 7,8.), built by Belgian engineers in 1890–1892. The metal elements in combination with the bricks in the prominent masonry of the building formed a radical façade appearance (Cheirchanteri, 2014).

## 5 Conclusions

- Stone masonry as the oldest traditional form construction in the world was also the most popular construction material in industrial buildings, after the first Industrial Revolution. The typology of industrial buildings in Greece was the same as in Europe, where the architectural volumes of these buildings were adapted to the shape and size of their mechanical equipment and production needs.

- The typology of traditional industrial buildings in Greece was characterized by the elongated rectangular shape of the ground plan, which depended on the stone masonry load-bearing construction system and the mechanical production equipment.
- Stone masonry has high compressive strength under vertical loads, but has low tensile strength (against twisting or stretching) unless reinforced, while the tensile strength of masonry walls can be increased by thickening the wall.
- Concluding, the stone masonry contribution in Greek industrial buildings' typology and construction durability has been proved by the elongated rectangular shape ground plan, which includes the arranged linear machines layout, in order to facilitate the product line. Concerning the industrial buildings construction durability, it was achieved by the big thickness of bearing walls, despite their length and height. In many occasions they were big enough due to the requirements of the mechanical equipment, which was located inside the buildings.

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**References**

Anmol, J. (2019). Stone masonry, https://www.scribd.com/document/137931876/Lecture-No-11-Stone-Masonry (attached 15-10-2019)

ASTM C270, Specification of Mortars and Masonry Units.

Cheirchanteri, G. (2014). *Power plants' first buildings during the period 1889-1940/50: Founding Factors and Planning* (in Greek), PhD Thesis in NTUA, Athens.

Costa, C., Costa, P., Arêde, A. and Costa,A. (2011). Detailed FEM modelling of stone masonry arch bridges under road traffic moving loads, in: M. Papadrakakis, M. Fragiadakis, V. Plevris (Eds.), *3rd ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering* - COMPDYN 2011, Corfu, Greece

Francis, A.J., Horman, C.B. and Jerems, L.E. (1971). The effect of Joint Thickness and other factors on ths Compressive Strength of Brickwork, *Proc. of the 2nd Inter. Brick – Masonry Conf*., G. Britain, pp 31-37.

Kaaki,T. (2013). *Behaviour and Strength of Masonry Prisms Loaded in Compression*, Dalhousie University

Khan, A. and Lemmen, C. (2013). Bricks and urbanism in the Indus valley, rise and decline, available at: https://arxiv.org/pdf/1303.1426.pdf (attached 20-10-2019)

Phan, L.T. and Carino, N.J. (2003). Code provisions for high strength concrete strength-temperature relationship at elevated temperatures, *Materials and Structures, Vol. 36, No. 2*, pp. 91-98, 2003

Ravi, S., Viswanathan, S., Nagarajan, T., Srinivas,V. and Narayanan, P. (2014). Experimental and Numerical Investigations on Material Behaviour of Brick Masonry, *2nd International Conference on Research in Science, Engineering and Technology*, Dubai, UAE, March 21-22-2014.

Stylianidis, K. and Ignadakis, C. (2019). Masonry load bearing constructions, Technical Chamber of Greece, Central Makedonia Sector, http://www.kxcivileng.gr/archive/technical/Katskeues_ferousas_toixopoiias.pdf (attached 15-10-2019)

Tensing, D., Freeda, C.C. and Mercy, S.R. (2013). Experimental study on axial compressive strength and elastic modulus of the clay and fly ash brick masonry, *Journal of Civil Engineering and Construction Technology, Vol. 4, No. 4,* pp. 134-141

World Housing Encyclopedia, Italy WHE Report 28 (attached 20-8-2019)

World Housing Encyclopedia, Slovenia WHE Report 58 (attached 20-8-2019)