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Characterization of the materials used in the multi-leaf masonry walls of monumental structures in Istanbul, Turkey

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HIGHLIGHTS

- Mechanical characteristics of historical multi-leaf walls in Istanbul are investigated.
- Test results for materials, dry joints, single- and multi-leaf walls are presented.
- Indicative values for strength and deformability characteristics are obtained.
- Test results are compared with the predictions of equations from literature.

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ABSTRACT

Knowledge on the mechanical behavior of materials used in the walls of historical masonry structures has paramount importance for reliable seismic evaluation of heritage buildings. Since the knowledge on the mechanical characteristics of traditional stone masonry walls in Turkey is scarce, this study intends to enlarge the experimental data on the behavior of the Ottoman period multi-leaf walls constructed in Istanbul. For this purpose, results of an experimental campaign, carried out on these multi-leaf walls and their constituents, are provided. In addition, experimental strength and deformability parameters of single- and multi-leaf masonry are compared with the predictions of simple equations available in the literature.

1. Introduction

Istanbul, the economic and cultural heart of modern Turkey, served as capital of the Roman (330–399), the Byzantine (395–1204 and 1261–1453), the Latin (1204–1261), and the Ottoman Empires (1453–1922) for more than sixteen centuries [1]. Several structures constructed during the reigns of these empires (particularly during the latest of them, the Ottoman Empire) still stand and constitute the architectural heritage of the city and continue to contribute to the daily life of the inhabitants. However, the high seismicity of the region, stemming from the activities of the North Anatolian Fault extending along the country in the East–West direction, has always been the major natural source of damage and devastation to the heritage structures in and around the city [2]. Consequently, research efforts that aim to investigate the structural and mechanical characteristics of these masonry structures play a major role for mitigation of damage during future earthquakes.

Multi-leaf walls with ashlar external leaves were widely utilized in the Ottoman period monumental structures in and around the city of Istanbul (Fig. 1a). Due to time and money consuming process required to construct structures with this type of walls, they could only be used in esthetically important structures that were ordered by the imperial family or by the members of the ruling class. In this type of masonry walls, finely cut stone units, laid without use of any mortar (or with a very thin layer of mortar), constitute the ashlar external leaves. As seen in Fig. 1b, the core between the external leaves consists of rubble masonry that was obtained by addition of stone and brick pieces to lime based mortar [3–5]. Stone units of the external leaves extend into the rubble core with roughly shaped faces so that better interlocking between the ashlar leaves and rubble core can be established. Although they were not considered in this study, interlocking stone units and ties

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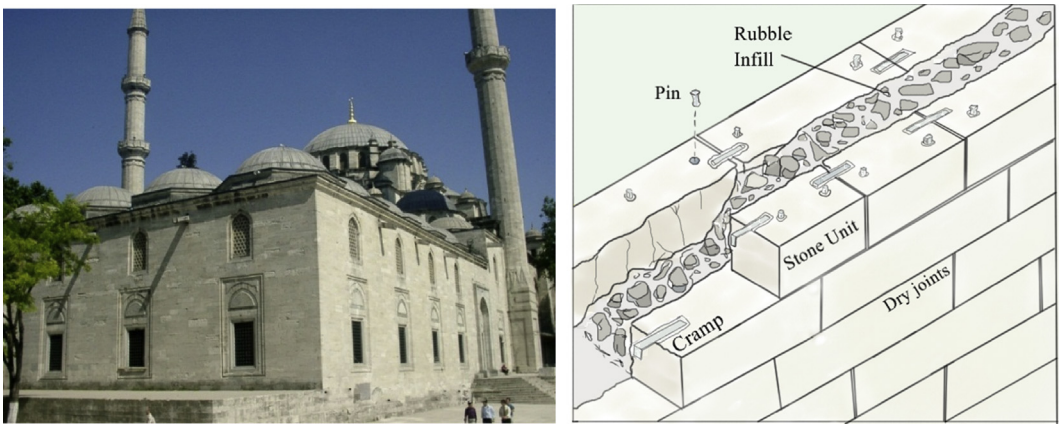

(a) Fatih Mosque (15th century) (b) Schematic view of a multi-leaf wall cross-section

Fig. 1. Multi-leaf stone masonry walls of Ottoman Period monumental structures (illustration modified from [5]).

(timber or iron), connecting the two external leaves, may exist. Depending on the size of the structure, the wall thicknesses generally vary between 0.8 m and 2.5 m. The dimensions of the external leaves' stone units typically have values between 0.5 and 2.0 m for length (generally in the order of 1.0 m), 0.2 and 0.6 m (generally in the order of 0.3 m) for height and 0.2 and 0.4 m for width. In many structures, the length/height ratios of the stone units vary between one and five (mostly in the order of two and three) [4]. The finely cut stone units of the external leaves were mainly produced by using a local limestone also known as Küfeki stone. Since, in the ashlar masonry, the interfaces between the units were formed as dry or thin mortar joints, limestone blocks were generally connected to each other via metal cramps (and in some cases with pins), which were fixed to the stone units with molten lead as also illustrated in Fig. 1b [3–5]. Tanyeli [5] indicates U shaped cramp lengths ranging between 170 and 500 mm and widths between 18 and 50 mm.

Although a number of studies exist for compressive behavior of multi-leaf stone masonry walls and their retrofitting [6–10], they mainly involve the local construction techniques and materials where the study has been carried out. To the best knowledge of the authors, no comprehensive experimental study exists for mechanical behavior of Ottoman period multi-leaf masonry walls encountered in the heritage structures of Istanbul area. The present study aims to contribute filling of this gap, firstly, by presenting the results of laboratory tests performed on representative constituent materials of Ottoman period multi-leaf walls of monumental structures in Istanbul. This stage includes a series of mechanical, metallurgical and chemical tests carried out on Küfeki local limestone, mortar, rubble masonry and iron materials. In addition to that, the shear behavior of dry joints in between the stone units of external ashlar leaves is also investigated. Then, the compressive behavior of 1/3 scale ashlar masonry prisms that represent the external leaves of the multi-leaf masonry is studied through uniaxial compression tests. Besides, considering the test results of this study and other studies in the literature, the applicability of a rock mechanics based approach for prediction of dry- and thin-joint masonry compressive strength and elasticity modulus is examined. Finally, uniaxial compression test results of 1/3 scale three-leaf masonry prisms that represent the main characteristics of investigated type of walls are presented and performances of available equations for prediction of the compressive strength of multi-leaf masonry are evaluated.

2. Tests on constituent materials

The first phase of the experimental campaign aimed to investigate the fundamental mechanical characteristics of the components of multi-leaf stone masonry walls observed in Ottoman period structures of Istanbul. Thus, this stage included compression tests performed on stone units and rubble masonry, three-point bending tests on limestone samples, splitting tests on rubble masonry, metallurgical and chemical investigations on original cramps from a historical structure and tension tests on steel material used for production of cramps of tested masonry prisms. Moreover, initial shear tests that aim to investigate the friction phenomenon that takes place in the dry joints of the ashlar external leaves were carried out for two different surface textures of the ashlar units: Machine sawn and roughened.

2.1. Mechanical characteristics of stone units

In the past, Küfeki stone was preferred due to the availability of the stone quarries in the vicinity of Istanbul and due to the advantages such as being lightweight and easily workable. In addition to these advantages, the mechanical and physical properties continue to develop due to carbonation process after Küfeki is quarried and transported to the construction site [11,12]. Consequently, the stone is rather easily treated soon after the quarry process and continues to develop strength even after the construction of the structure is completed.

Küfeki is an Upper Miocene age fossiliterous hollow cryptocrystalline limestone that was obtained from the quarries in today's Bakırköy, Sefaköy, Halkalı, Hadımköy-Sazlıbosna provinces of Istanbul. However, most of these quarries are not active currently [12]. Matrix of Küfeki limestone mainly consists of $CaCO_3$ (93–100%) surrounding the mactra, melanopsis, helix and crinoid fragments. This composite material can be found in nature in massive and intact forms and do not contain any rifts [13,14]. The lower layers of the limestone formation are fine grained, very fractured with many fossil shells and the upper level of the formation is clayey and sandy. Especially the lower layers of this type of limestone were used as building materials [15].

Uniaxial compressive and three point bending tests aimed to define the complete compressive stress-strain behavior and tensile strength of lime stone units. The stone blocks, sawn in required dimensions, were obtained from the Küfeki stone quarries in Hadımköy-Sazlıbosna area of Istanbul. A total of 40 compression and 10 modulus of rupture tests were conducted on stone units that were randomly chosen among the available stone blocks.

As also mentioned above, the mechanical and physical properties of the Küfeki stone continue to develop due to carbonation process after it is quarried. In order to have similar physical and mechanical characteristics during all tests that were going to be performed at different times, the fresh units were kept in the laboratory for approximately 4 months after the quarry process. To ensure that the stone specimens have reached their natural water contents, the unit weights of the specimens were measured at three successive days until weight change was stabilized. The average unit weight was obtained as 20.5 kN/m^3. All tests of this study were performed with natural water contents of the stone units.

Cross-section dimensions of the compression test specimens were either 100 × 100 mm or 100 × 130 mm and height to width ratios were between 1.1 and 1.6 (mainly 1.3). All specimens were extracted from larger quarried stone masses by using a large diameter rotating saw available in the quarry. View of a stone unit specimen before and after the compression test can be seen in Fig. 2.