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Adopted Material Properties of Historical Masonry Structures for Finite Element Models: Mosques and Bridges

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Abstract

This paper aims to present adopted material properties of masonry elements to historical mosque and bridge structures. The importance of this study is to adopt correct material properties with reliable reference according to material types and structure types.

Keywords: material properties; historical structures; historical mosques; historical bridges.

Sonlu Elemanlar Modelleri için Tarihi Yığma Yapılarda Kullanılan Malzeme Özellikleri: Camiler ve Köprüler

Özet

Bu çalışmada, yığma yapı ile yapılmış camii ve köprülerde kullanılan malzeme özelliklerinin sunulması amaçlanmıştır. Bu çalışmanın önemi, yığma yapılarda kullanılan malzeme özelliklerini güvenilir kaynaklara dayandırarak malzeme çeşidine ve yapı tipine göre sınıflandırarak sunmaktır.

Anahtar Kelimeler: malzeme özellikleri, tarihi yapılar, tarihi camiler, tarihi köprüler

1. Introduction

Historical structures are the most important part of civilization where constructed. Therefore, these cultural heritages of the urban population should be protected through centuries against external extreme loads. Conservation of cultural heritages are commonly considered as suitable restoration. However, with developing numeric analysis tools, it is possible to estimate global behavior of a historical structures available and after restoration situation under severe loads like earthquake. Structural characteristics of a historical monument mostly depend on the availability of local construction materials during construction era [1]. Moreover, it is difficult to determine the engineering properties of materials adopted to the historical structures due to the lack of experimental data and forbidden destructive test by authorities [2]. For this reason, indirect methods are developed to evaluate historical structures to reveal information related to available conditions. These indirect assessment methods are based on visual inspection, geometrical and crack pattern survey, surface decay mapping, radar, geoelectric and ultrasonic testing. Listed indirect methods are not convenient for the assessment of historical masonry structure alone. In addition, these methods cannot be substituted by destructive testing [3]. These are necessary to understand the damages and their causes and carry out a first interpretation of the phenomena [4].

During the analytical modelling, defining incorrect or uncertain material properties causes unavoidable wrong results. For a typical masonry heritage, the most difficult step is defining input parameter to quantify the material properties of masonry and mortar assembly. When developing a (FE) models, especially for historic masonry structure, it is possible to define imprecise input parameters that can result in unrealistic models and erroneous solutions [5]. Indefinite references or insufficient material data force researcher to use wide range of data with lower boundary and upper boundary [6]. The aim of using upper and lower boundary material data is to adapt randomly selected engineering property due to insufficient material data for modelled structure. The reliability of the selected material properties depends mostly on model calibration of the FE model. Basic philosophy of model calibration is to compare dynamic identification test result of investigated structure with FE model of the same structure on the base of natural vibration period and frequencies. The success of model calibration depends not only on selecting the correct comparative quantitative but also in updating the correct quantitative. Thus, if the extreme use of the FE model is to assess damage in historical structures, the engineering properties must be adapted well to represent linearity and nonlinearities. Model calibration includes engineering judgment and self-intuition about selecting calibration parameters. Moreover, the unforeseen dependencies or correlations of parameters possibly arise among the calibrated inputs. If these dependencies or correlations are strong, this will raise the problem of the calibration of one parameter compensating for imprecision in another [5]. Besides, purchasing accelerometer always not possible due to extreme cost of test set up and non-destructive application. For listed reason above, it is very important to define certain and robust material properties for investigated historical structures.

This study presents 14 different study composed of mosques and bridges.

2. Structure Types

2.1. Mosques

Mosques are one of the most prominent religious structures in the history. Nearly all dominated sultans let to construct mosque to shown power. Many of the available mosques are still in use. For this reason, response of their behavior against external loads needs to be assessed. Koçak and Köksal (2010) investigated seismic behavior of Little Hagia Sophia with FE modelling. Adopted material properties were suited with destructive and non-destructive methods [7] and addressed to Aköz and Yüzer (1995) [8]. Teomete and Aktaş (2010) implemented destructive tests on historical masonry and brick elements of an historical Urla Kamanlı mosque in İzmir Turkey [9]. Demir and İlki (2014) studied on material properties and characterization of single layer and multi-layer Küfeki stone in other words limestone which is commonly used to construct mosques [10]. Demir and İlki (2014) characterized the multi layered Küfeki stone in other words limestone according to sample dimensions 40x30 cm, 40x26 cm and 40x20 cm respectively [10]. Altunışık et al. (2015) assessed the performance of Kaya Çelebi Mosque in Turkey. For this purpose, dynamic modal analysis and seismic spectral analysis were performed on model [11]. Material properties were adopted by Altunışık et al. (2015) addressed to Can et al. (2012) [12], Dal-Cin and Russo (2014) [2014] and Saloustros (2015) [14]. Cakir et al. (2015) modelled and analyzed Erzurum Lala Pasha Mosque. For this purpose, firstly material characterization was implemented and then FE model was prepared. Compressive strength and tensile strength of materials were obtained from experimental characterization. However, elasticity modulus and density adapted from literature [15]. Nohutcu et al. (2015) studied Hafsa Sultan Mosque in Turkey. In their study, ultrasonic pulse velocity was used to obtain mechanical properties of granite and stone. Homogenization approach was used to determine mechanical properties of FE model [16]. Nohutcu et al. (2015) obtained mechanical properties by using ultrasonic pulse velocity test and then these values evaluated as bigger to adapt complete model of masonry elements [16]. Güllü and Karabekmez (2016) investigated seismic behavior of 125 years old Gaziantep Kurtuluş mosque. Material properties were adopted from literature [17]. Elasticity modulus, poisson ratio and compressive strength values were obtained from predicting with genetic algorithm by Baykasoğlu et al. (2008) [18]. Tensile strength value is adopted like 1/fc. İlerisoy and Soyluk (2012) studied on Şehzade Mehmet mosque to assess seismic performance [19]. Adopted material properties was addressed to similar studies by Kaya et al. (1998) [20]. Addressed reference contains a numeric study related to Süleymaniye mosque. Altunışık et al. (2016) studied on seismic safety of Kaya Çelebi mosque [21]. Material properties were adopted from Can et al. (2012) [12], Dan Cin and Russo (2014) [13] and Saloustros et al. (2015) [14]. Mangia et al. (2016) assessed seismic performance of Eltihatun Mosque located in Tunceli province.

Adopted material properties obtained from literature on the base of medium hard masonry elements [22]. These properties can be seen in Table 1. There are eight mosques and experimental studies related to mosque. Material properties of these investigated mosques can be seen in Table 1.

Table 1. Adopted material properties to mosques

Author(s)	**Age and Material Properties**				
	Age	***Density (kg/m^3)***	***Young's Modulus (MPa)***	***Compressive Strength (MPa)***	***Tensile Strength (MPa)***
Koçak and Köksal (2010)	536	NA	10000	10	1
Teomete and Aktaş (2010)	14th century	1700	2700	4.25	0.425
Demir and İlki (2014)	15th century	2050	2615	7.91	1.6
Altunışık et al. (2015)	1660	2000	1600	0.3	NA
Cakir et al. (2015)	1562	1900	350	17.49	2.69
Nohutcu et al. (2015)	16th century	2200	1500 (1210)	7.42	0.74
Güllü and Karabekmez (2016)	1892	2500	25000	40	4
İlerisoy and Soyluk (2012)	1548	2190 (Arch), 2000 (Dome)	8500 (Arch), 3000 (Dome)	NA	NA
Altunışık et al (2016)	1663	2400	1200	NA	NA
Mangia et al. (2016)	1252	2200	1500	3	0.15

The numbers in bracket demonstrates calibrated parameters

2.2. Bridges

There are many historical bridges either restored or non-restored in our country. A few of these bridges were studied by researchers. Hacıefendioğlu et al. (2015) assessed seismic behavior of masonry arch Kurt bridge in Turkey against blast induced ground motion [23]. Material properties of bridge adopted from Sevim et al. (2011) [24]. Güllü and Jaf (2016) modelled a historical arch bridge with two different boundary condition approach. One of them is soil structure interaction and other of them is with fixed base boundary condition [25]. Material properties were adopted from similar study by Ural and Doğangün (2007) [2]. However, Ural and Doğangün estimated material properties on the base of their experiences for the same arch bridge. Altunışık et al. (2015) modelled a historical arch bridge called as Göderni bridge. Adopted material properties were obtained from laboratory test results. Sayın (2016) performed nonlinear dynamic analysis on a historical masonry arch bridge called as Nadir bridge [27]. The source of adopted material parameters is addressed to literature. Sevim et al. (2011) presented earthquake response of historical masonry arch bridge [24]. Adopted material properties were referenced to similar studies by Frunzio et al. (2001) [28], Toker and Unay (2001) [29] and Brencich and Sabia (2008) [30].

Table 2. Adopted material properties to bridge

Author(s)	**Age and Material Properties**				
	Age	***Density (kg/m^3)***	***Young's Modulus (MPa)***	***Compressive Strength (MPa)***	***Tensile Strength (MPa)***
Hacıefendioğlu et al. (2015)	13th century	2140.7	3000	NA	NA
Güllü and Jaf (2016)	18th century	2354, 2353, 1961	3000, 2500, 1000	NA (Arch), NA (Spandrel), NA (Parapet)	NA
Altunışık et al. (2015)	19th	2000	5000 (Arch),	NA	NA

Author(s)	**Age and Material Properties**				
	Age	***Density (kg/m³)***	***Young's Modulus (MPa)***	***Compressive Strength (MPa)***	***Tensile Strength (MPa)***
	century		3000 (Abutment)		
Sayın (2016)	1569	2300, 2200	2500 (Arch), 2000 (Spandrel)	NA	0.5, 0.4
Sevim et al. (2011)	19th century	1600, 1400	3000 (Arch), 2500 (Side Wall)	NA	NA

3. Statistical Analysis

This section contains statistical evaluation and correlation of Young's modulus and compressive strength of historical masonry material. The most common and used masonry materials are limestone and brick. Statistical evaluations are performed on these materials to easily obtain missing parameters with a known parameter.

3.1. Limestone

Limestone is of the most used material among historical masonry structures. Even if material properties are more abundant while compared with other materials, abrasion factor and environmental interference change the material properties of this material based on local conditions.

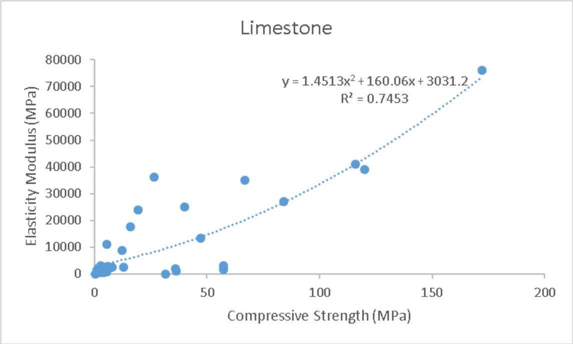

Figure 1. Young's modulus versus compressive strength of Limestone

As seen from the Figure 1, correlation between the Young's modulus and compressive strength is polynomial. This correlation can be defined with an equation indicated in the figure above. The confidence percent is 74.53%. This equation is proposed to determine unknown parameter with known one.

3.2. Brick

Brick is one another abundant material after stone masonry. One of the most important property of brick is more consistent than stone masonry. Because, while plotting the data and fitting the best curve to this material type, none of the data was ignored.

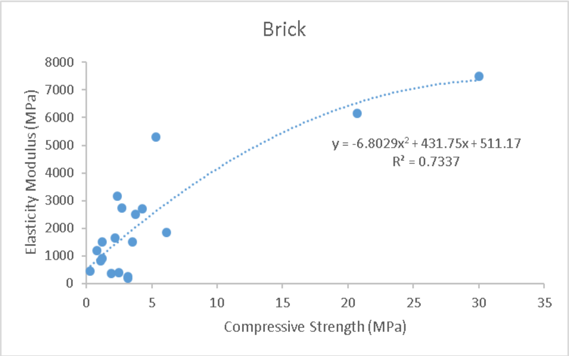

Figure 2. Young's modulus versus compressive strength of Brick

The best fitted curve between the Young's modulus and compressive strength is polynomial as seen in Figure 2. Confidence percent is 73.37%.

4. Discussion

After the FE modelling procedure, one of the most important key point is to define correct parameter of historical heritage. Many researchers are missing a few important parameters like poison ratio, compressive strength or tensile strength. However, each parameter has own importance. Ural and Doğangün (2007) [2] investigated changing mechanical properties of infill and arch material parameters on the seismic performance of historical masonry arch bridge. However, Ural and Doğangün adopted material properties on the base of their experiences and considered intervention of material by external natural events. Güllü and Jaf (2016) [25] modelled a historical masonry arch bridge with soil structure interaction (SSI) and without SSI and then addressed Ural and Doğangün related to material properties of Mataracı bridge located at Trabzon. But, Ural and Doğangün performed sensitivity analysis on the base of masonry arch and infill material properties. Moreover, Ural and Doğangün considered natural intervention on mechanical properties of material [2]. Güllü and Karabekmez (2016) obtained material properties of investigated mosque by prediction with genetic algorithm on the base of in-situ testing [17]. Mangia et al. (2016) obtained material properties from literature referenced to medium strong masonry elements. Indeed, this assumption does not reflect actual behavior of the historical mosque [22]. Sayın (2016) implemented a numeric study on a historical Nadir bridge to assess seismic performance of the bridge [27]. Sayın indicated material properties of historical bridge to reliable references in the mentioned study. One another example is randomly selected material properties on the base of self-experience like Ramos et al. (2010) performed model calibration on historical masonry tower before starting structural analysis [31]. However, randomly 1000 MPa elasticity modulus was selected for FE model of the historical tower. This random selection was implemented on the base of self-experience and high confidence of dynamic identification. However, due to high instrumentation cost, dynamic identification is always not possible for researcher.

5. Conclusions

The purpose of this paper is to present material properties of historical structures. Mosques and bridges were considered for this study. Moreover, this study limited with national historical structures. Recently, there are numerous study revealed by investigators that seek for performance evaluation of historical structures. However, reliability of these investigations depends completely on the adopted material properties of the investigated structure. External intervention is nearly impossible on historical monuments in order not to disturb available property of value. For this purpose, reliable references are required especially for numeric model of the investigated monument. Correct material properties that adapted to numeric model is indispensable to implement risk assessment of any type of historical structure. This study collected all material properties of investigated historical structures either with destructive or non-destructive testing evaluation. Moreover, this study includes experimental tests to determine engineering properties of the historical element or structure. This paper has contributions to the literature on the base of listed aspects;

1. Before performing a numerical assessment of a historical structure, precise material properties should be adopted to the structure with the same material and the structural type.
2. In an investigated structure, material properties of all element type cannot be the same properties. Vault, arch and wall element of the same model may contain different material properties even if these element type composed of the same material.
3. Adopted material properties can be calculated by different approaches like homogenization. This calculated property reflects overall behavior of brick and mortar unit. While calculating these parameters, selected material properties of the unit and mortar should

be selected on the base of individual characterized elements.

4. Adopted material properties should simulate structural intervention and restoration well.

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