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Assessing the impact of retrofitting on structural safety in historical buildings via ambient vibration tests

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HIGHLIGHTS

- FE models of a historical masonry is developed for before/after retrofitting states.
- FE models are updated via ambient vibration tests.
- Earthquake behavior analyses are conducted by a real earthquake data recording.
- The stiffness has increased 3 times after the retrofitting.
- OMA is capable of validating the impact of the retrofitting procedure.

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ABSTRACT

Historical structures are generally vulnerable to damages under earthquakes over the course of their life and are subject to be retrofitted to preserve the heritage against any possible extreme loads, particularly earthquakes. This process is handled via analysis by taking into account existing condition of the buildings, however, there are few studies focusing on the effectiveness of the applied retrofitting solutions. Therefore, there is a growing need to understand and compare the earthquake behavior of historical structures before and after retrofitting states. This paper aims at investigating the structural behavior of a historical timber/masonry building for conditions both before and after the retrofitting of the building. To enable a comparison for conditions, firstly theoretical finite element models were developed and then experimental operational modal analyses of the historical building were performed. Secondly, the experimental data regarding the dynamic response of the structure was obtained by ambient vibration tests and finite element models were updated. Two final updated models representing before and after the retrofitting states were developed. The final models selections were based on the convergence between the experimental and analytical natural frequencies, and the mode shapes. The updated final models enable to assess the earthquake behavior of the structure for both before and after retrofitting states. Furthermore, updated finite element models of the building for both before and after the retrofitting states were analyzed by a recorded earthquake in Turkey. Dynamic responses of the structure including principal stresses and displacements before and after retrofitting were compared and the impact of retrofitting is evaluated. The results show that the stiffness of the retrofitted structure has increased 3 times compared to its initial condition. The finding of this study will be beneficial to develop FEM models for a wide range of possible future retrofitting solutions.

1. Introduction

Historical structures have great importance in cultural heritage and there is a big stock of historical structures worldwide as well as in Turkey. These heritages are exposed to damage due to several reasons including earthquakes, degradation of materials by time, dilapidation and changes in the building's functionalities Therefore, safety assessment and retrofitting are necessary to preserve the historical structures. Due to their construction method and materials, these unique structures have sophisticated and very complex structural and geometrical layouts. Traditional structural safety calculation methods do not provide sufficient accuracy since they are empirical methods. On the other hand, numerical methods such as Finite Element Method (FEM) are widely used for the analysis of masonry structures, however; they are stated to be complex

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because these models lack insight to understand the complicated behavior of units, mortar/adobe, joints and masonry as a composite material [1,2]. In addition, the accuracy of numerical methods depend on proper identification of the material properties and the boundary conditions. However, the determination of material properties as well as boundary conditions in historical structures is challenging. It can be concluded that analyzing and defining proper retrofitting strategies for these structures by traditional calculation methods or numerical methods might not be reliable. Over the past few decades, the advances in computing to solve large matrices have led to the development of numerical models for structures. One of those numerical methods is FEM which provides tools that can simulate and predict the response of the - structures. However, the FE models might have physical and numerical uncertainties [3]. The physical uncertainties could be due to the boundary conditions and material properties (i.e. modulus of elasticity, yield stress) whereas numerical uncertainties could occur due to lack of data of the physical process and the characteristics of the structure such as element type, mesh density and dimension of the [4].

Recently, Operational Modal Analyzes (OMA), which is a non-destructive technique, has attracted attention among researchers as an alternative way for generating realistic finite element (FE) models and obtaining acceptable accuracies in the structural analyses of structures. OMA provides general information about the whole structure via modal parameters. In addition, OMA can be used to validate FEM models and to identify earthquake response of the structures. There are several studies, which utilize FEM and OMA for analyzing historical structures including churches, towers, bridges and aqueducts [5–17]. Diaferio et al. [18] determined the non-destructive characterization and the identification of the modal parameters of an old masonry tower. Pintucchi et al. [19] investigated nonlinear seismic response of slender masonry towers by pushover and time history analyses methods. Cakir et al. [20] investigated seismic behavior of Erzurum Clock Tower under the acceleration records of two different level earthquakes that occurred in, Erzurum Turkey in 1983 and 1992. Foti et al. [21] investigated a slender historical bell tower in Bari to obtain the accurate FE model. Then, the accurate FEM model was developed by conducting environmental vibration tests and comparing first five modes. Preciado et al. [22] suggested a procedure for the seismic vulnerability evaluation of all types of towers and slender masonry structures such as light houses and minarets. Preciado et al. (2016) proposed an approach for the seismic vulnerability reduction of masonry towers via with external prestressing devices. Ramos et al. [6] carried out OMA by using the results of an ambient vibration test in the historical masonry of the Clock Tower of Mogadouro and the Church of Jeronimos Monastery in Portugal. The results show that the proposed methodology is beneficial for damage identification and is applicable to complex historical masonry structures. The authors concluded that OMA is a reliable method for damage detection. Ramos et al. [12] investigated long term dynamic parameters of the Saint Torcato Church in Portugal, which has soil settlement. Long term observations showed that the dynamic characteristics may change by time, and, thus, the authors recommended conducting FEM model updating by using OMA.

Although there are several studies that prove the applicability of OMA to update FEM models and analyze existing/initial conditions (i.e. before retrofitting/restoration), there are few studies that compare the results for before and after retrofitting/restoration conditions. Among these studies, Zanardo et al. [23] applied a similar technique to assess the stiffness of a bridge before and after strengthening. The results show that the upgrading works resulted in a 5% increase in the first modal frequency whereas the change appears to be more significant for higher experimental torsional mode frequencies up to 10%. Similarly, after the model updating, in the updated analytical model of the structure after strengthening, the fundamental frequencies increased by 4.7–10.6%. This change in the frequency values indicates the increase in the structural stiffness. Osmancıklı et al. [7] investigated the dynamic parameters of the masonry bell-tower of Hagia Sophia church in Trabzon, for before and after the restoration conditions via OMA. The results showed that the first 5 modes of the structure did not change significantly whereas the average modal damping ratios of the structure decreased by 2.69%–0.6% after the restoration. In conclusion, the authors suggested that the restoration projects must be designed by taking into account the dynamic behavior, which can be determined by using OMA. Çalık et al. [15] investigated the dynamic parameters of the Küçük Fatih Mosque by using OMA for before and after retrofitting and restoration conditions. It should be noted that the retrofitting and restoration included only repairing the cracks under the plastered mortar. The results showed that the frequency of the structure increases significantly after retrofitting. Although these studies present the benefits of using OMA and prove the reliability of its results, there is still a lack of research that analyzes updated finite element models of the building for both before and after the retrofitting states by an earthquake record. This kind of analyses would be of paramount importance to determine dynamic responses of the structure including principal stresses and displacements for before and after retrofitting states, which in turn would be an indicator for assessing the impact of the retrofitting.

This study aims at investigating the impact of retrofitting in a historical building via two different methods: (i) developing the FE model and updating the FE model by OMA; (ii) conducting earthquake performance analyses by using the data of 1999 Kocaeli, Turkey earthquake. Then, the findings of the methods were conducted with respect to before and after retrofitting states. The paper is organized as follows: (i) Introduction, (ii) Description of the building and retrofitting procedure; (iii) Methodology; (iv) Findings; (v) Discussion and conclusion.

2. Description of the building and retrofitting procedure

Bornova, Izmir became a popular village among European/ Levantine merchants and foreigners in the early 1860 s. Therefore, rich foreign representatives decided to move to the village, in which they built their own mansions. The ‘‘Grand House” was one the most famous houses owned by Whittall family of merchants. Kuyulu Ev which was also known as ‘‘English Club” is located in the gardens of the ‘‘Grand House”. The Grand House and Kuyulu Ev, which were known to be built during the early 1860’s, are owned by Ege University since 1966. Kuyulu Ev is accommodating the research center of ‘‘Women’s Studies” of Ege University [24].

2.1. Seismic behavior of the region

The main cause of the building’s damage is the numerous earthquakes that have affected the structure over its lifetime. Izmir is stated to be in the first earthquake fault zone. A total of 17 earthquakes, which have magnitudes over 5, occurred after the building was erected. Eight of the earthquakes have strong ground motion that has a magnitude over 6.5. The strongest earthquake occurred in 1955 with a magnitude of 6.8.

2.2. Structural properties of the building

The building is a two-story building with a small basement and an attic. The structural system mainly consists of stone masonry