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Vertical Ground Motion Effects on the Seismic Responses of Historical Masonry Structures

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Abstract

In this study, the effects of vertical ground motion on the seismic responses of historical masonry structures are numerically investigated. To this aim, a historical mosque subjected to the 2011 Van Earthquakes and their aftershocks is considered. These seismic actions caused devastating damages to the minaret, the main dome covering the prayer place, and the porch sections of this mosque. The seismic behavior and structural responses of the mosque are evaluated by using linear time-history analyses. The ground motions recorded Van Earthquakes (23 October 2011 (M_W=7.1) and 09 November 2011 (M_W=5.7)) are used. Analyses of the mosque are conducted considering both only horizontal components and all components of the earthquakes. The displacements, absolute accelerations, and tensile stresses are handled as comparison parameters. As a result, it can be clearly seen that the vertical components of 2011 Van Earthquakes significantly modify the seismic behavior and structural responses of the inspected structure.

1.Introduction

Structures are simultaneously exposed to three-dimensional ground motion effects during an earthquake phenomenon because the earthquake motion is multi-axial. In the design and analysis of these structures, two horizontal components of the earthquakes are generally taken into account and their vertical components are ignored. Therefore, it can be clearly seen that the horizontal ground motions have been inclusively investigated by the researchers compared to the vertical ground motions. However, the vertical ground motions recorded in the past earthquakes such as 1994 Northridge in USA, 1995 Kobe in Japan, 2011 Christchurch in New Zealand led to extraordinary structural responses, damages, and failure mechanisms in structures [1-3].

Transferring historical structures to the next generations is among the essential challenges of modern societies, due to their contributions to both cultural and economic developments. Historical structures are exposed to several environmental and operational actions during their service life. Earthquakes are one of the most important of these actions that can lead to historical heritage losses. Historical structures have a high seismic vulnerability due to several reasons such as design philosophy, structural materials characterized by insufficient tensile strength, etc. In recent years, many studies have been conducted to evaluate the seismic behaviors and earthquake-induced damages of historical structures [4-12]. On the other hand, several studies have been performed to investigate the vertical ground motion effects on the seismic performances and responses of historical structures. Casolo (1998); Casolo et al (2017) [13, 14] emphasized significant influences of vertical ground motions for masonry towers. Bayraktar et al. (2018) [15] stated that the vertical components of earthquakes affect the damage distributions on historical masonry minarets. Chieffo et al. (2020) [16] revealed that vertical ground motions remarkably change the seismic behavior of the masonry building.

In this study, the effects of vertical ground motions on the seismic performances and damages of historical masonry structures are handled using linear time-history analysis results. For this aim, the numerical model of a historical masonry mosque damaged in Van Earthquakes (23 October 2011 and 09 November 2011 earthquakes) is constituted in the SAP2000 program [17]. The analyses are performed utilizing the horizontal and vertical ground motions recorded in the 2011 Van Earthquakes. Two different scenarios are considered to reveal the vertical ground motions effects. To determine the seismic response of the inspected structure, analyzes are carried out considering horizontal components in the first scenario, while the second one three components of the earthquakes are simultaneously used.

2. Numerical Application

2.1. Kaya Çelebi Mosque

Kaya Çelebi Mosque is located in the Ortakapı district of Van province, Turkey. Its construction was started by Kaya Çelebizade Koçi Bey in 1660 and it was completed by Cem Dedeoğlu Mehmet Bey in 1663 [18]. The mosque, which consists of two parts as prayer place and porch, has a square plan with 16.20×16.20m. The prayer place is covered by a main dome with a radius of 7.5m. It also has walls with a thickness of 1.8m, and eight arches supporting the main dome. The porch consists of small domes, columns, arches, and stretchers. In the Van Earthquake on 23 October 2011, the cone part of the minaret was collapsed. In the second earthquake on 09 November 2011, devastating damages occurred in the main dome covering the prayer place and in the porch section of the mosque. It was also observed in conditions such as material deformations and environmental deterioration that could affect the structural integrity. A photograph of the restored mosque is given in Fig. 1. Fig. 2 presents a photograph of damages and deteriorations in the mosque due to the 2011 Van Earthquakes.

Figure 1. Kaya Çelebi Mosque [19]

Figure 2. Damaged mosque after 2011 Van Earthquakes [19]

2.2. Numerical Modelling of the Mosque

The Finite Element (FE) model of the selected historical masonry mosque is created with the SAP2000 program considering general information, dimensions, structural material characteristics which are determined according to restoration projects and art history reports. The macro-modeling method is adopted during creating the numerical model of the mosque. In this study, the columns, steel stretchers, arches are modeled using beam elements, whereas shell elements with four nodes are preferred to represent domes, peripheral walls. The FE model of the mosque has 29567 nodes, 270 beam elements, and 27123 shell elements. Fig. 3 represents the FE model of the Kaya Çelebi Mosque.

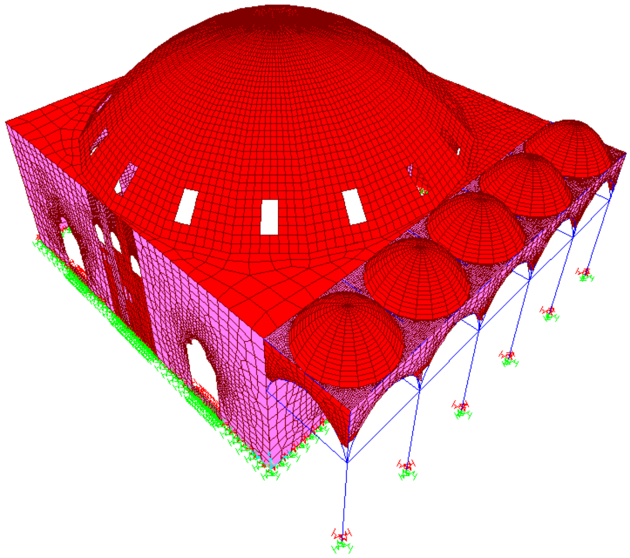


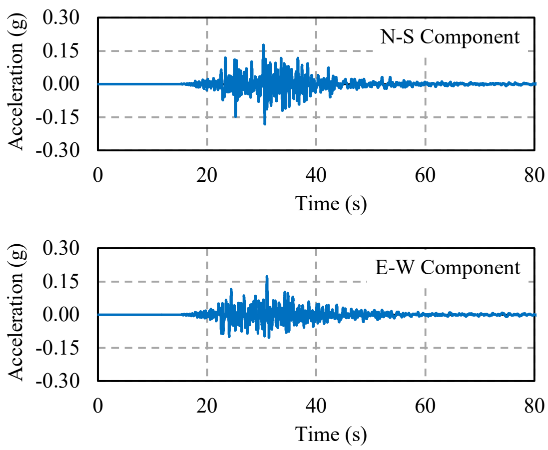
Figure 3. FE model of the Kaya Çelebi Mosque

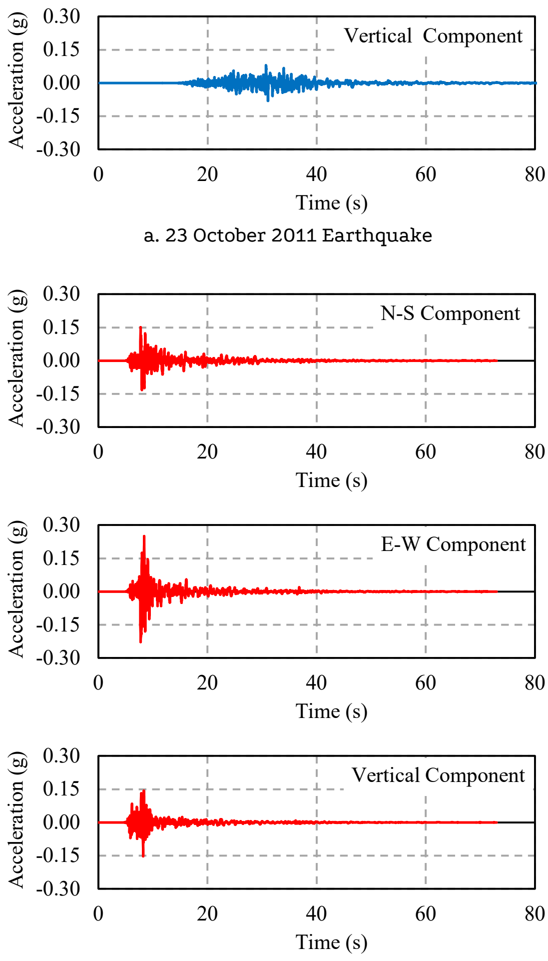
The seismic responses and behavior of the Kaya Çelebi Mosque are evaluated using linear time-history analysis results. Therefore, linear material properties are considered. The selected material properties elasticity modulus (E), Poisson ratio (υ), density (γ) are briefed in Table 1 [19-22].

Table 1. Material properties

Structural Part	Material	E (MPa)	υ (−)	γ (kg/m^3)
Main Dome	Brick	1.20×10^3	0.200	2400
Arches	Cut Stone	1.60×10^3	0.200	2000
Walls	Artless Stone	4.50×10^2	0.200	2400
Domes	Cut Stone	1.60×10^3	0.200	2000
Columns	Marble	3.50×10^4	0.316	2690
Stretchers	Steel	2.00×10^5	0.300	7850

The dynamic analyses of the mosque are performed using horizontal and vertical components of the 2011 Van Earthquakes. The acceleration time-history graphs of Van Earthquakes are plotted in Fig. 4. In the analyses, the damping ratio is considered as %5. In order to accurately predict the dynamic behavior of the mosque, the first 150 modes are also considered.





a. 23 October 2011 Earthquake

b. 09 November 2011 Earthquake

Figure 4. The acceleration time-history graphs of Van Earthquakes

3. Results and discussions

In this section, structural responses are comparatively investigated. Displacements and absolute accelerations are obtained using earthquake loads, whereas stresses are calculated by combining dead loads and earthquake loads. Since the mosque has a square plan, similar structural responses are obtained in both orthogonal directions. Therefore, graphs and comparisons are presented for a single horizontal direction in addition to the vertical direction.

3.1. Displacements

As a result of the linear time-history analyses of the mosque, time-histories of displacements at the dome center and displacement contour diagrams are presented in Figs. 5-7. The displacements in the orthogonal direction which are estimated using only horizontal component and combined horizontal and vertical components are 8.059mm and 8.055mm for the first earthquake and 9.740mm and 9.795mm for the second earthquake, respectively. In the vertical direction, these displacements obtained with and without vertical components of earthquakes are determined as 0.145mm and 1.233mm for the first earthquake and 0.124mm and 2.236mm for the second earthquake, respectively (Fig. 5).

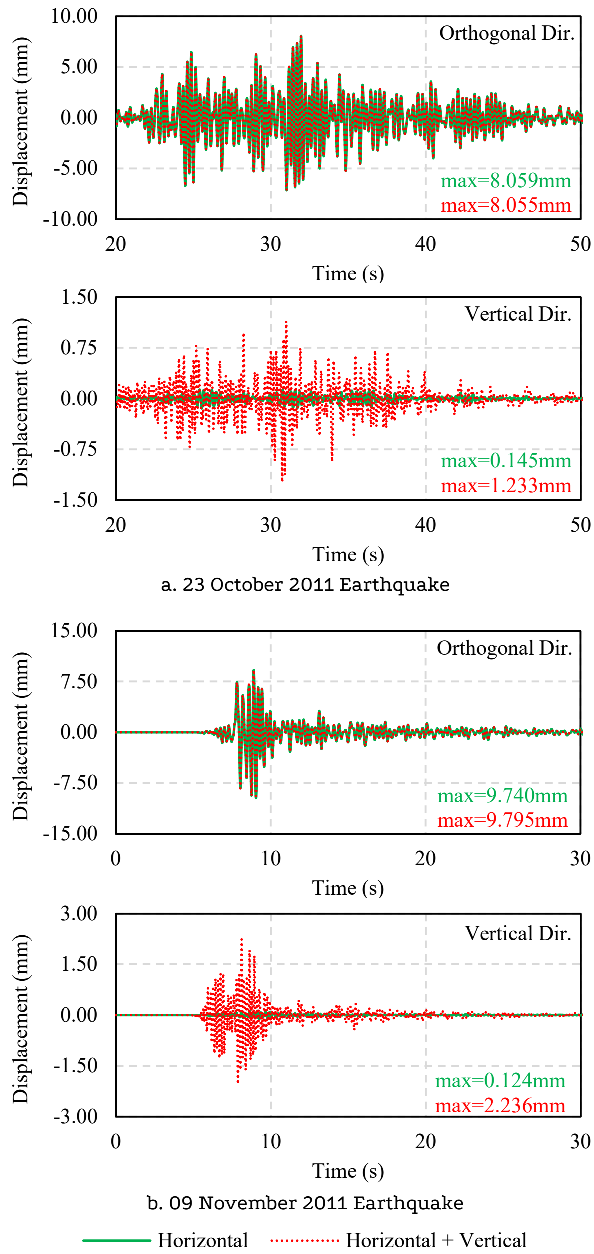
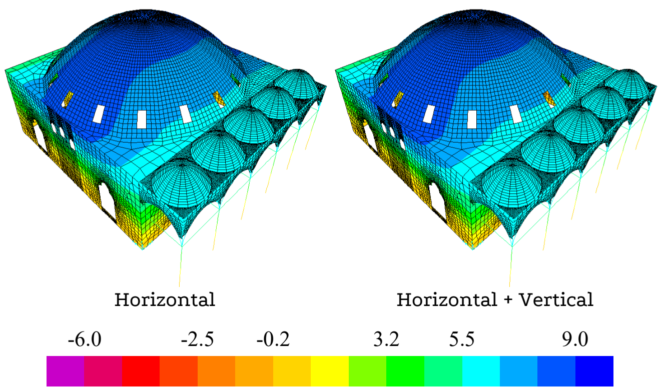
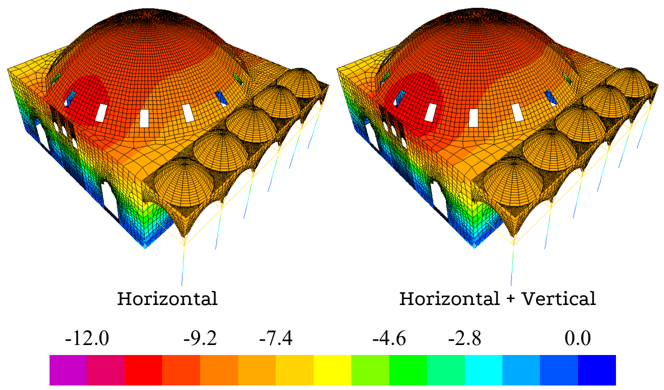


Figure 5. The time-history of dome displacements for orthogonal and vertical directions of mosque

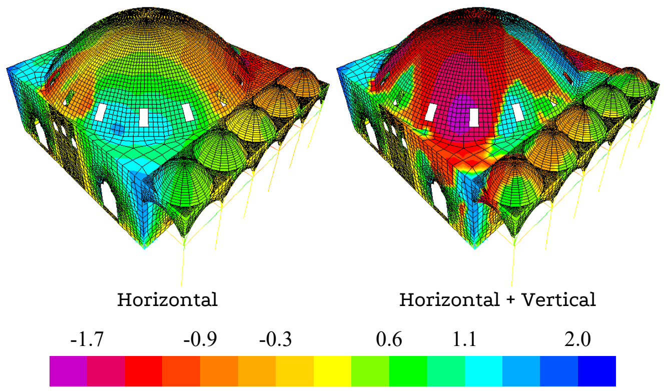


a. 23 October 2011 Earthquake

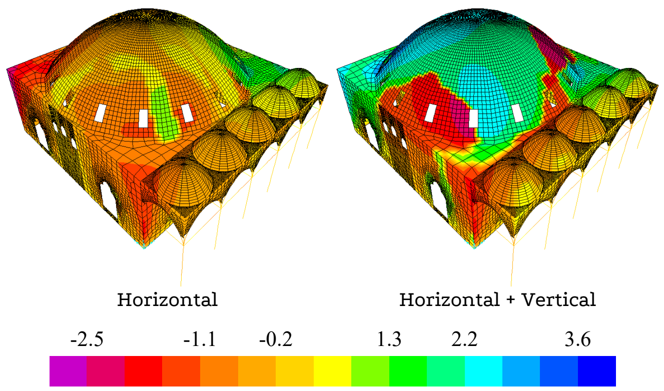


b. 09 November 2011 Earthquake

Figure 6. The displacement contour diagrams in the orthogonal direction of the mosque (units in mm)



a. 23 October 2011 Earthquake



b. 09 November 2011 Earthquake

Figure 7. The displacement contour diagrams in the vertical direction of the mosque (units in mm)

As can be clearly seen in Fig. 5-7, the displacements in the vertical directions of the inspected mosque are significantly influenced although these values in orthogonal direction are constrictedly affected by vertical ground motions.

3.2. Accelerations

The absolute acceleration is a significant parameter in terms of earthquake forces applied to structural and non-structural elements. These accelerations at the main dome center, where the highest structural responses are generally obtained, are examined. The maximum absolute accelerations are given in Fig. 8. The maximum accelerations in the orthogonal direction which are determined using only horizontal component and combined horizontal and vertical components are 4.473m/s^2 and 4.491m/s^2 for the first earthquake and 5.489m/s^2 and 5.810m/s^2 for the second earthquake. In the vertical direction, these accelerations obtained with and without vertical components of earthquakes are determined as 0.126m/s^2 and 1.933m/s^2 for the first earthquake and 0.333m/s^2 and 3.563m/s^2 for the second earthquake, respectively (Fig. 8). It can be observed that vertical ground motions increase the absolute accelerations of the main dome.

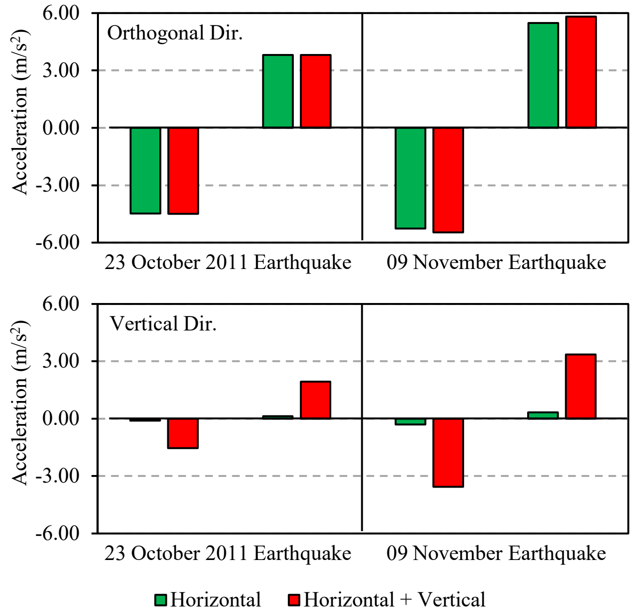
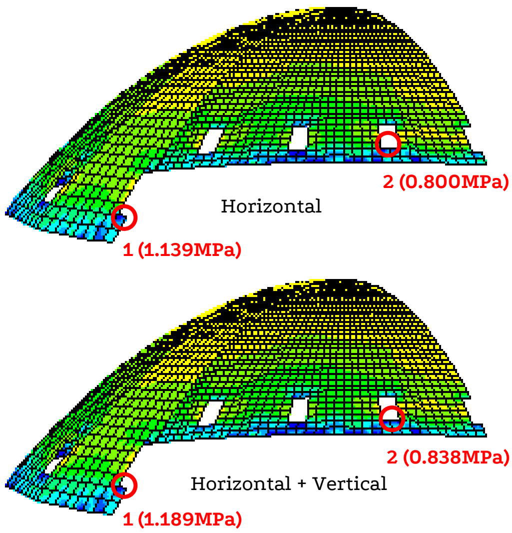


Figure 8. The maximum absolute accelerations obtained from main dome for orthogonal and vertical directions

3.3. Stresses

The tensile stress diagrams of the main dome collapsed during the 2011 Van Earthquakes are plotted in Fig. 9. Measuring points are chosen to compare the tensile stresses in the dome. The tensile stresses of the measuring points which are estimated using only horizontal components are 1.139MPa and 0.800MPa for the first earthquake and 1.527MPa and 0.796MPa for the second earthquake. These values calculated using three earthquake components are determined as 1.189MPa and 0.838MPa for the first earthquake and 1.726MPa and 0.924MPa for the second earthquake.



a. 23 October 2011 Earthquake

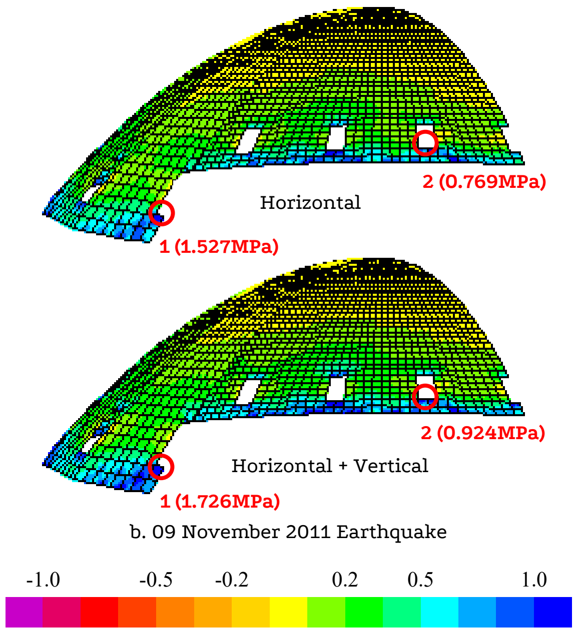


Figure 9. The tensile stresses of the main dome (units in MPa)

4. Conclusion

In this study, the seismic performance of a damaged historical masonry mosque is evaluated to determine vertical ground motion effects on the seismic responses. For this purpose, the linear time-history analyses are performed using the SAP2000 program. Analyzes are carried out considering horizontal components in the first scenario, while the second one three components of the earthquakes are simultaneously used. The displacements, absolute accelerations, tensile stresses are used as comparison parameters.

It can be seen from the results that the vertical components of the selected earthquakes affect the structural responses of the inspected structure. Historical masonry structures have high seismic vulnerability due to structural materials characterized by insufficient tensile strength. Therefore, these increases in structural responses, especially tensile stresses, caused by vertical ground motions may be vital for the seismic assessment and restoration process of such structures. This situation points out that vertical ground motions should be considered in the design and analysis of the historical masonry structures.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. We have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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