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An Assessment of the Atranos Castle Tower Remains' Seismic Response and Recommendations Towards Its Protection

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Atranos Kalesi Kule Kalıntılarının Sismik Tepkisinin Değerlendirilmesi ve Korunmasına Yönelik Öneriler

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Abstract

Atranos Castle is an early Byzantine heritage founded by the emperor Hadrianus in the second century in Orhaneli, a district south of Bursa with mountainous geography. Two towers of the castle survived in partial to date. About 5m long main wall foundation and two more towers' base were also identified during field study. The survey of the castle remains was done by use of a laser scanner and drone to reveal its disappearing cultural and archeological value. This partially collapsed tower has a partially circular shape in plan. Voids within the masonry body and early findings of the wood remnants in these holes reveal the existence of the bond beams. There were horizontally placed wooden bond beams within the tower walls at several levels in the original construction. The main purpose of these bond beams is to provide in-plane and out-of-plane stabilization of these masonry walls. The voids left after decayed wooden bond beams create weaknesses, such as stress concentration around the holes and a decrease in buckling resistance. A simplified finite element model of one of the partially collapsed towers is prepared and a parametric study is performed. Effects of the voids are examined and filling the voids with a mortar, modulus of elasticity of mortar close to the masonry wall, improved the response of the structure. As a minimum intervention approach to limit further degradation, before any archaeological excavation program starts on the site, mortar fill to the existing bond beam voids is proposed.

Keywords: *Atranos castle; Cultural heritage; Masonry seismic response; Wooden bond-beams in masonry; Masonry strengthening with mortar fill.*

Öz

Atranos Kalesi, Bursa'nın güneyinde dağlık bir coğrafyaya sahip olan Orhaneli ilçesinde ikinci yüzyılda imparator Hadrianus tarafından kurulmuş erken bir Bizans mirasıdır. Kalenin iki kulesi kısmi olarak günümüze ulaşmıştır. Saha çalışması sırasında yaklaşık 5 metre uzunluğunda ana duvar temeli ve iki kule temeli daha tespit edilmiştir. Kale kalıntılarının araştırılması, kaybolmakta olan kültürel ve arkeolojik değerini ortaya çıkarmak için lazer tarayıcı ve drone kullanılarak yapılmıştır. Kısmen yıkılmış olan bu kule, plan olarak kısmen dairesel bir şekle sahiptir. Kâgir gövdedeki boşluklar ve bu deliklerdeki ahşap kalıntılarına ait ilk bulgular, bağ kirişlerinin varlığını ortaya koymaktadır. Orijinal yapıda kule duvarları içinde çeşitli seviyelerde yatay olarak yerleştirilmiş ahşap hatıllar bulunmaktaydı. Bu hatılların temel amacı, yığma duvarların düzlem içi ve düzlem dışı stabilizasyonunu sağlamaktır. Ahşap hatılların çürümesinden sonra kalan boşluklar, deliklerin etrafında gerilme yoğunlaşması ve burkulma direncinde azalma gibi zayıflıklar yaratmaktadır. Kısmen yıkılmış bir kulenin basitleştirilmiş bir sonlu eleman modeli hazırlanmış ve parametrik bir çalışma gerçekleştirilmiştir. Boşlukların etkileri incelenmiş ve boşlukların elastisite modülü yığma duvara yakın bir harçla doldurulmasının yapının tepkisini iyileştirdiği görülmüştür. Daha fazla bozulmayı sınırlandırmak için asgari müdahale yaklaşımı olarak, sahada herhangi bir arkeolojik kazı programı başlamadan önce, mevcut bağ kirişi boşluklarına harç dolgu yapılması önerilmektedir.

Anahtar Kelimeler: *Atranos kalesi; Kültürel miras; Yığma sismik tepki; Yığma ahşap bağ kirişleri; Harç dolgusu ile yığma güçlendirme.*

1. Introduction

Atranos Castle is in one of the four mountainous regions of Orhaneli, Bursa. In ancient times, this area was under the control of feudal landlords during the Byzantine era. However, during the reign of Orhan Beg, the Ottomans took over the Atranos Castle, which had previously belonged to the Eastern Roman Empire. Orhaneli, situated in the southern part of Bursa, was founded by Emperor Hadrianus in the 2nd century under the name Hadrianoi (ad Olympum) (Schwertheim 2014). After the Ottoman conquest, the region became known as Atranos and retained this name until the early days of the Turkish Republic.

The Atranos Castle, situated approximately 2 kilometers north of Orhaneli city center, lies amidst the rugged landscape. Unfortunately, despite its historical significance, the castle has not received adequate conservation efforts or protective measures. In 2014,

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Turkish authorities recognized it as a 3rd-degree archaeological site where new arrangements may be permitted in line with conservation use decisions. However, to this date no substantial work has been undertaken to safeguard castle remnants. Although the region encompassing the Atranos Castle remains was officially designated as a protected area by the Ministry of Culture and the Bursa Regional Board for the Protection of Cultural Heritage, little progress has been made in its preservation. The tower remnants, exposed to the harsh environmental conditions, are rapidly deteriorating. A comparison between the current state of the remains and earlier photographs underscores the ongoing erosion. To address this critical situation, a documentation study was conducted. This pioneering effort aimed to assess the existing tower remnants and establish the foundation line, laying the groundwork for potential archaeological excavations. The study utilized advanced techniques such as laser scanning and drone imaging to capture essential data about the castle's remains. This documentation study represents a crucial step in understanding and preserving the historical legacy of the Atranos Castle.

Atranos Castle, strategically designed to conform to the natural topography, was constructed atop bedrock. The castle's main wall, encircling its perimeter, exhibited signs of damage due to geographical features. Unfortunately, dense vegetation hindered a comprehensive assessment, preventing precise identification and site planning. During initial surveys, the castle's remains were delineated within an isosceles trapezoidal area. The castle spans approximately 150 meters north-south and 110 meters east-west. Notably, two surviving tower remains were documented along the eastern wall, running parallel to the highway. These findings revealed that Atranos Castle featured circular towers positioned at regular intervals along both corners and long wall stretches. To create an accurate castle plan, thorough vegetation clearance is essential. Once the area is cleaned, detailed information about the castle walls can be obtained. Within the scope of this study, documentation unveiled the remains of two prominent towers on the eastern wall, as well as remnants of two tower foundations and partial sections near the body wall foundation. A third of each of the two prominent towers remains, with internal and external diameters of approximately 2.30 meters and 6.80 meters respectively. Interestingly, despite the vegetation growth, a straight line has been recorded at the top of the towers. Calculations based on the gaps of the decayed wooden bond beams suggest that the castle towers probably retained a height close to their original state, estimated at around 7.50-8.00 meters from the lowest point. The castle's fascinating history and architectural remains continue to fascinate researchers and enthusiasts alike.

Orhaneli district is in an earthquake-prone region, its proximity to an active fault line, Orhaneli fault, shown in Figure 1, also underlines the seismic risk in the region. The seismic hazard map presented in Figure 1 shows moderate earthquakes for the last decade in the vicinity of the region. Being in an active earthquake-prone region requires the utmost attention for building stock, lifelines, and historic heritage. Especially, the loss of historic heritage structures is unlikely to compensate. If cultural heritage structures are destroyed or severely damaged in earthquakes, they can be neglected for a long time and cannot be restored for economic reasons, and for some other priorities, and eventually, they vanish. Therefore, damaged heritage structures are prone to complete losses. Environmental factors are escalating the already existing deficiencies in Atranos castle remains and this cultural heritage is becoming more vulnerable to seismic risks.

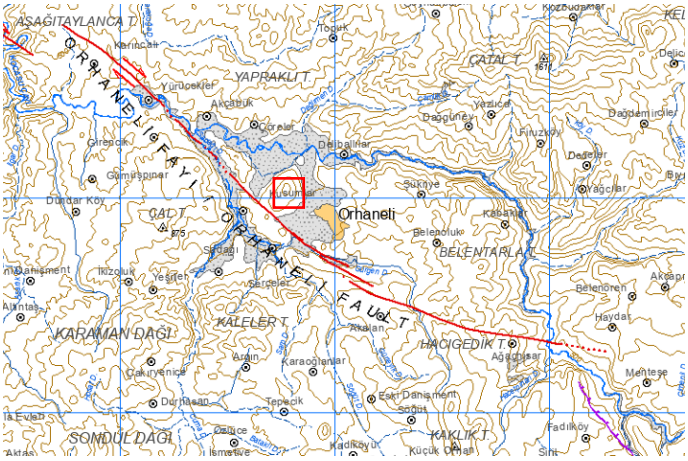


Figure 1. Turkey active fault lines for the vicinity of Orhaneli and Atranos castle location https://www.mta.gov.tr/v3.0/sayfalar/hizmetler/doc/diri_fay_haritalari/kutahya.pdf]

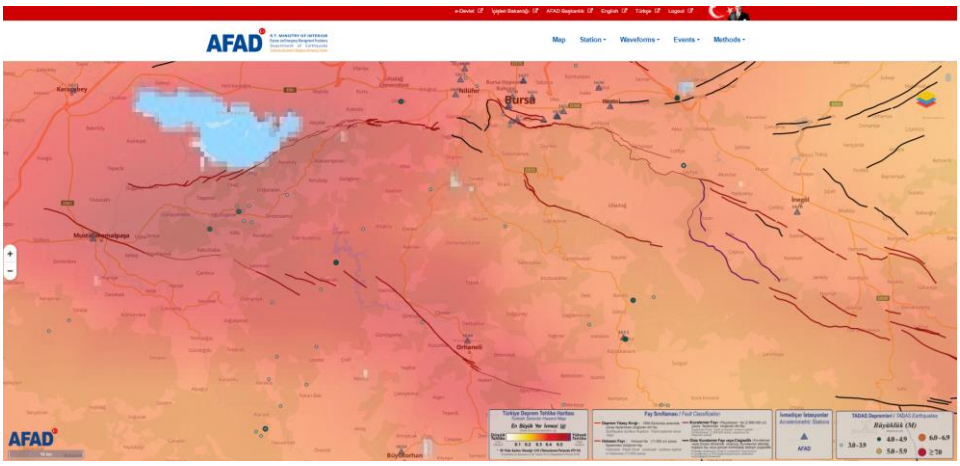


Figure 2. Turkey seismic hazard map for the vicinity of Orhaneli [1]

The use of embedded wooden bond beams or tie beams in masonry walls was a common practice to increase the seismic performance of historic structures, traditional structures, and ancient monuments (Turer 2013, Al Qablan *et al.* 2019, Vintzileou 2008, Rababeh *et al.* 2014, Ersoy *et al.* 2022). Tie beams were usually used to strengthen the arches and vaults of historic structures to partially overcome thrust, whereas embedded bond beams were used to help with in-plane and out-of-plane response of masonry walls. The use of embedded bond beams in main masonry walls, and towers for castles was common practice too (Vitruvius 1914), as an example Byzantine land walls from the 5th century and Kilitbahir castle from the 15th century (Turer 2013, Ersoy *et al.*).

Traditional masonry houses throughout Turkey without proper bonding between layers in plan and cross-sections between alike layers suffered from earthquakes (Göçer 2020). By use of bond beams in traditional masonry houses, thick masonry was prevented from out-of-plane movement and also the walls in orthogonal directions were connected, and possible detrimental cracks were better managed and forced to happen at bond beam locations instead of critical locations on the structure (Göçer 2020, Karaman and Zeren 2010, Ökten ve Yüce 2023, Uşma 2021, Zengin 2022). Researchers conducted studies from the structural engineering point of view and the studies revealed the positive effect of bond beam use in terms of seismic performance, preserving the beams will strengthen the structure against seismic forces (Vintzileou 2008, Rababeh *et al.* 2014). The use of wooden bond beams embedded within the masonry walls is one of the main focuses of this study. In Atranos Castle already existing voids within the masonry reveal that wooden bond beams were also utilized for Atranos castle from the second century by embedding them in the original masonry construction. The wood remnants were identified by some researchers in 2003 (Giros 2003), however, the current study conducted on-site in 2021 showed that even the wood remnants were completely diminished. As stated in many studies, one of the very common seismic mitigation methods for the existing cracks in masonry walls is grout injection and it improves the overall response of structures. The bond beam holes within masonry walls can also be reconstructed, however, this type of intervention is prone to jeopardize the originality of the heritage. The current study focuses on the seismic response of the structure due to the voids of the decayed bond beams embedded within the masonry walls, by employing a parametric study, the effects of the voids are examined. The seismic response of the tower with proposed mortar fills into the existing voids is studied. Before possible archaeological excavation on the site starts, it is necessary to avoid further erosion of the structure and to enhance its seismic response so that the structure can be intact.

2. Materials and Methods

Documentation study for Atranos Castle is performed with the help of a laser scanner and a drone. The survey of the castle remains, and vicinity is done by RIEGL VZ-400i three-dimensional laser scanner system and a drone, and the data is processed by RiSCAN Pro software, the orthophotos are prepared from the laser scanning data. Figure 3 shows both the plan and elevation orthophotos of the castle remains. The two towers are delineated in the photos and the circular plan of the towers is depicted from the figures. Analysis of the orthophotos and investigations on site helped to produce the material analysis and the damage analysis. Atranos Castle was visited in 2019 and structural deterioration was observed in the surviving towers. During the documentation study, it is observed that the deteriorations are escalating and Figure 4 shows the picture taken in 2019 and the orthophoto from the documentation study supports this argument.

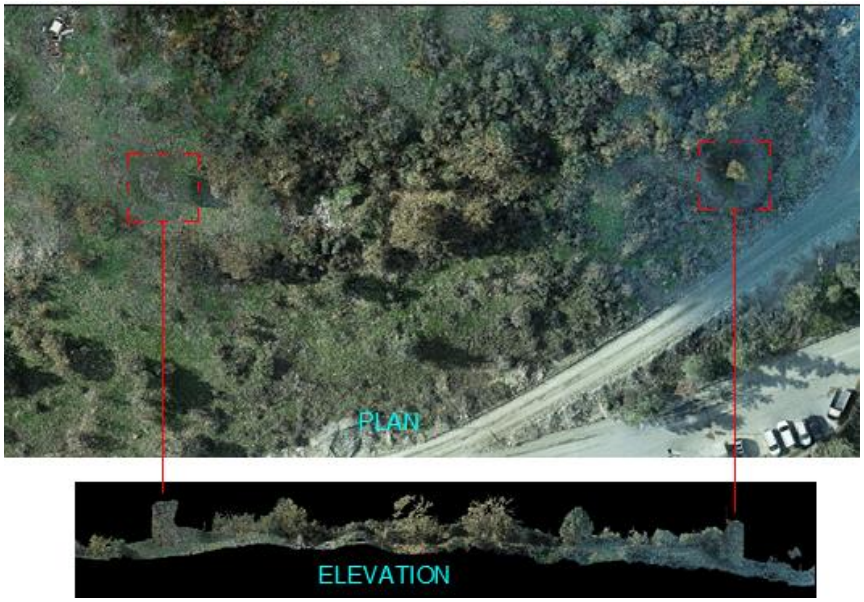


Figure 3. Plan and elevation orthophoto images of Atranos Castle (Istanbul University scientific research project no. FBA2021-38062 archieve)



Figure 4. Comparison of two images from 2019 and 2021(Istanbul University scientific research project no. FBA2021-38062 archive)

2.1 Material and damage analysis of Atranos castle tower remains

The remains of Atranos Castle exhibit both structural deterioration and material deterioration. Structural deterioration manifests as cracks and section loss in the tower walls, posing a significant threat to the castle's stability. Additionally, wooden beam remnants identified by researchers in 2003 have not endured to the present day. Regarding material deterioration, several issues were identified: Surface losses in the stone material, voids in the original masonry of interior and exterior façade sections, deficiencies in stone, brick, and wood materials, surface pollution, including carbon accumulation and black crust formation, overgrowth of herbaceous and woody vegetation, and non-original additions. The detailed material and damage analysis are performed, and they are presented in Figure 5 and Figure 6. Despite the need for preservation, reconstruction recommendations were avoided during damage assessments. Instead, emphasis was placed on reinforcing the tower remains to ensure their survival until detailed investigations commence. Atranos Castle holds significant cultural and archaeological value, yet it faces gradual disappearance. Efforts to reveal its current condition and raise awareness are crucial. By doing so, it is aimed to pique curiosity among academics and locals, attract tourism, and foster economic growth through local tourism initiatives.

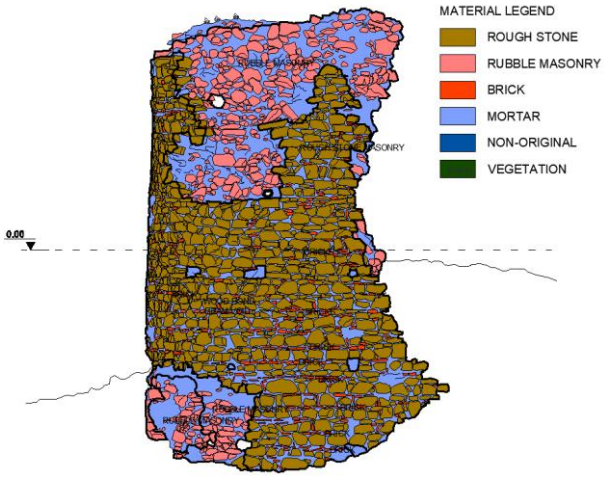


Figure 5. Material analysis for one of the two towers (Istanbul University scientific research project no. FBA2021-38062 archieve)

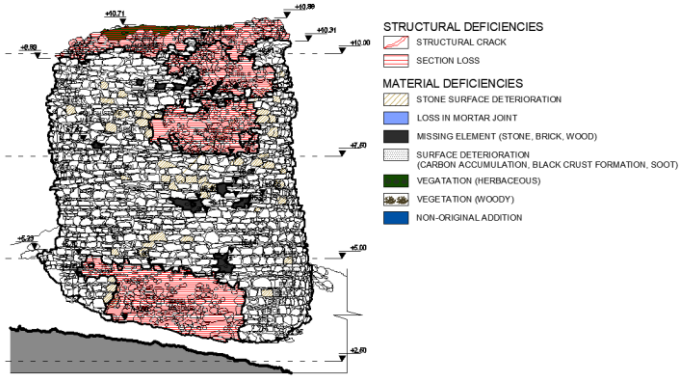


Figure 6. Damage analysis of one of the two towers (Istanbul University scientific research project no. FBA2021-38062 archieve)

2.2 Finite element analysis of the Atranos castle tower remains

Several analytical and experimental types of research were conducted for similar types of masonry structures with various modeling techniques in the past. Micro-modeling, simplified micro-modeling, and macro-modeling approaches are often used in the Finite Element (FE) Models (Chácara *et al.* 2017, Kamal *et al.* 2014, Valente *et al.* 2017, Valente and Milani 2018). Advances in point cloud data collection and its integration with highly improved computation techniques made it possible to make very realistic FE models (Providakis *et al.* 2023, Di Re *et al.* 2021, Pirchio *et al.* 2021, Castellazi et al. 2022, Chen et al. 2025, Cui et al. 2023), FE models by cloud data can be realistic for the facades, however, inner sections are still a challenge. Texture for the masonry of Atranos Castle façades and cross-section is shown in Figure 7, it is noticed that texture is completely irregular without a regular pattern, on the cross-section, in the middle part between the façades different texture is even more irregular compared to the facades is obvious. For simplification and the desired level of accuracy, the material behavior of the masonry is assumed as the combined composite behavior of all elements with irregular stone and brick pattern, and mortar, therefore, the macro-modeling approach is adopted in this study (Valente and Milani 2019a, Valente and Milani 2019b, Bernardeschi *et al.* 2004). A finite element model of one of the two partial towers remains is prepared by general purpose structural analysis software SAP2000. The tower is 7.5m-8.0m tall and has a circular shape in plan, with an inner diameter of 2.3m and an outer diameter of 6.8m. Examination of the tower section showed that the interior and exterior faces are formed by rough masonry units with scattered brick layers. On the other hand, in between the inner and outer façades, ruble masonry is used. The model is formed by eight-node solid elements with three translational degrees of freedom at each joint, for facade solid elements and inner solid elements different material properties are used to depict the characteristics of facades and rubble masonry.

Material properties for the analytical model for parametric study is a challenge since the masonry is a composite thoroughly irregular unit. In this parametric study since the effect of the voids and the mortar fill inside the holes are the main concern therefore the

modulus of elasticity of the material is obtained from the literature and the manuals. Table 1 shows the material properties used in the analysis. Compressive strength and flexural tensile strength properties are adopted from Federal Emergency Management Agency 356 (FEMA, 2000). In the original construction of the towers, common practice was to utilize wooden bond beams, to provide in-plane and out-of-plane stabilization of the tower. Over time bond beams decayed and disappeared eventually leaving the gaps within the body of the tower. 4 levels of bond beam voids are implemented on the model as shown in Figure 8. A close-up picture shown in Figure 9 underlines that the wooden tie beams were placed as rotating chords. A parametric study is carried out, the first model includes the voids as in the existing condition of the tower, is analyzed. Another FE model is formed by defining the bond beam void locations as solid elements, the material properties of mortar-filled bond beam voids are varied for this model to be able to see the effect of the material when the voids are filled with mortar of varied modulus of elasticity. 3D view, section view, and the plan of the finite element model are shown in Figure 10.



Figure 7. Atranos castle tower masonry texture

Table 1. Material properties

Material	Element type	Unit weight (kN/m³)	Modulus of Elasticity (MPa)	Compressive Strength (FEMA, 2000) (MPa)	Flexural tensile strength (FEMA, 2000) (kPa)
Outer Fascade	SOLID	20	1000	1,83	137
Rubble Masonry	SOLID	20	500	0,92	137
Inner Fascade	SOLID	20	1000	1,83	137
Mortar for Bond Beam Voids	SOLID	20	500	0,92	137
			1000	1,83	137
			5000	9,20	137
			10000	18,30	137

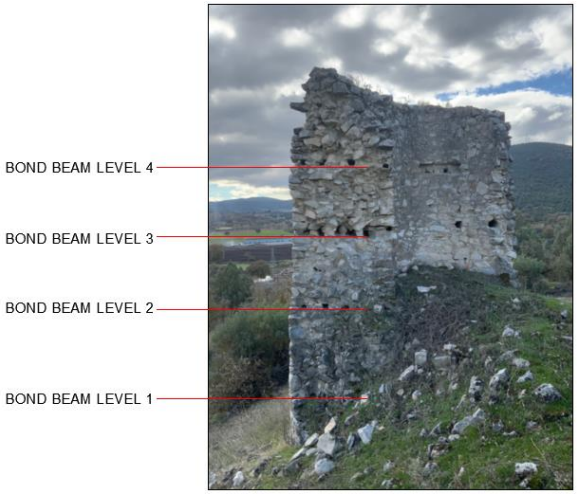


Figure 8. Atranos castle tower current bond beam voids level

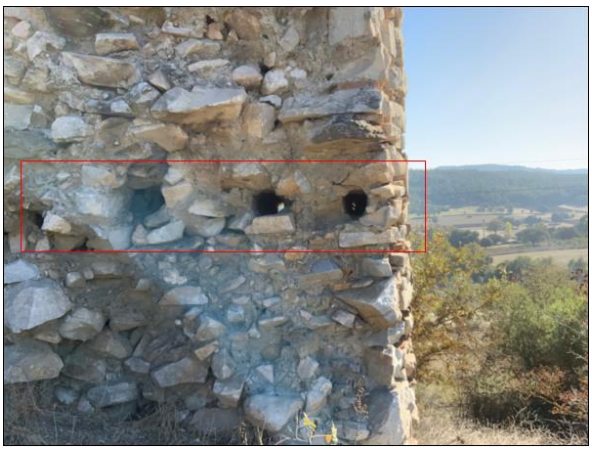


Figure 9. Close-up view of bond beam voids

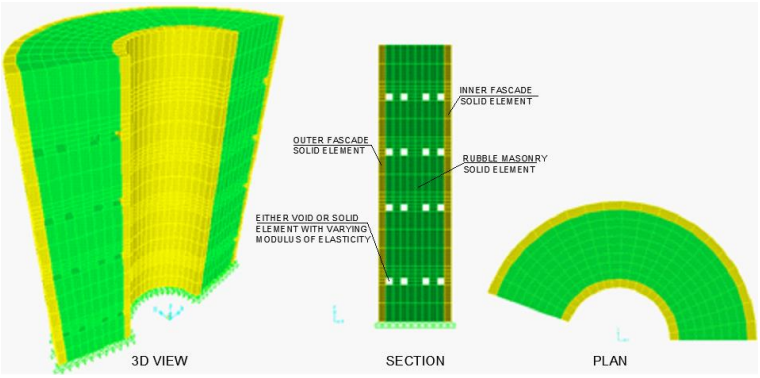


Figure 10. FE model – 3D view, cross-section – and plan

Linear dynamic analysis with the mode superposition method is performed on the model. The elastic response spectrum for two different seismic levels, namely seismic level 1 (DD1) and seismic level 2 (DD2) is obtained from the interactive seismic maps of Turkey (Int. Ref.-1). DD2 corresponds to a 10% probability of exceedance in 50 years (Return period, T=475 years), and DD3 corresponds to a 50% probability of exceedance in 50 years (Int. Ref.-2). The response spectrum used in the analysis for DD1 and DD2 levels is shown in Figure 11 (Int. Ref.-1).

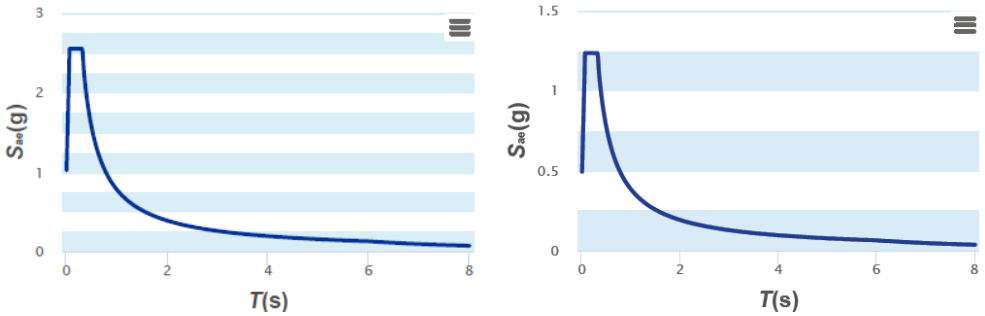


Figure 11. Elastic response spectrum for the site for seismic level DD-1 and seismic level DD-2

3. Results and Discussions

The results of one of the analyses for S11 stresses on the 3D FE model are shown in Figure 12 as an example. For the two orthogonal horizontal directions, the maximum stresses namely S11 and S22 are shown at 4 different bond beam levels. As it is observed from Figure 13 and Figure 14 highest stresses occur at the first level, which is closer to the base. It has been verified that the voids cause stress concentrations as expected.

Filling the voids with mortar with a modulus of elasticity value close to the modulus of elasticity of the masonry does decrease the stresses in the masonry. However, the use of mortar with a comparatively higher modulus of elasticity causes even higher stresses compared to the case with the voids. The use of mortar with the similar modulus of elasticity of the masonry will enhance the seismic behavior of this structure.

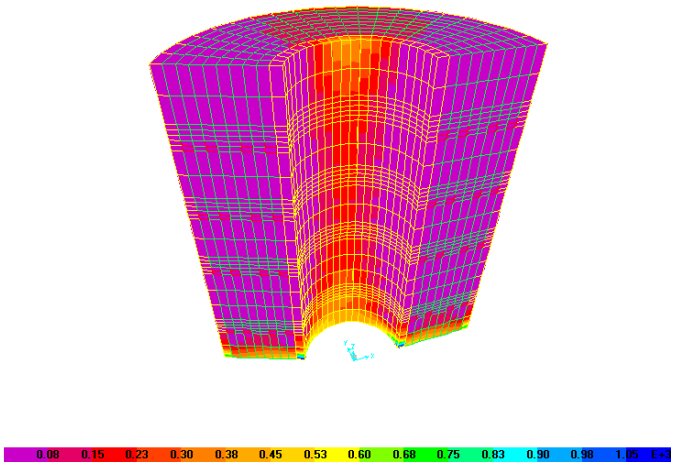


Figure 12. Example of S11 stresses of the 3D model

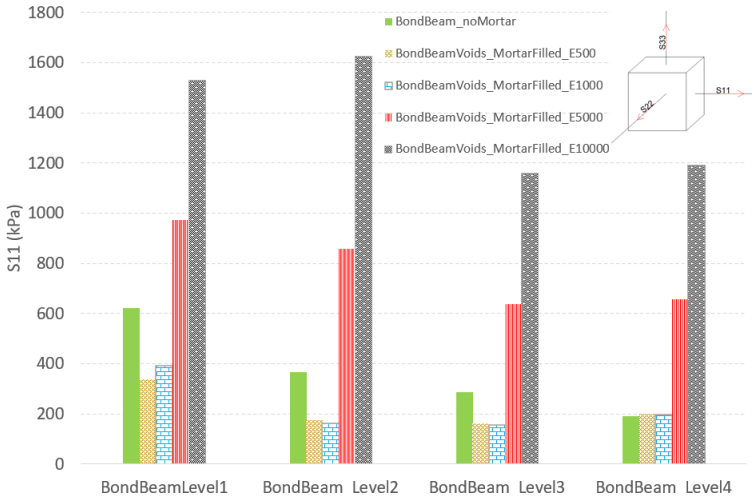


Figure 13. Comparison of stresses S11 at different levels of bond beams with and without mortar intervention

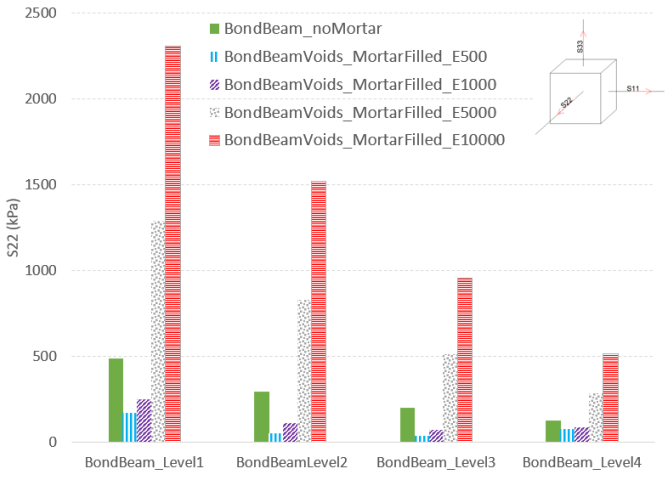


Figure 14. Comparison of stresses S22 at different levels of bond beams with and without mortar intervention

The maximum absolute displacements are calculated at the top of the tower for each case with voids and voids filled with various modulus of elasticity mortar. As the modulus of elasticity of the mortar used gets higher, the structure becomes stiffer, therefore resulting in a decrease in displacement. There is about a 10% decrease in displacement. The following Structural Performance Levels are defined in the Guidelines for Seismic Risk Management of Historic Structures under a given earthquake effect (Int. Ref.-3):

a. Immediate Occupancy (IO) Performance Level: This level corresponds to the damage level where limited

damage (limited nonlinear behavior) occurs in the structural elements of the building.

b. Life Safety (LD) Performance Level: This level corresponds to the level of controlled damage to the structural elements of the building, which is mostly repairable.

c. Collapse Prevention (CP) Performance Level: This level corresponds to a situation where severe damage to the structural elements of the building occurs, the building is close to partial or total collapse, but collapse is prevented.

The drift ratio is calculated, and it is shown in Figure 15. For the seismic level DD1, for all the cases the drift ratio is above the controlled damage level (life safety performance level) of 0.7% as per the guidelines. However, the drift ratios for the seismic level DD2 as shown in Figure 16 are in between the limited damage and the controlled damage.

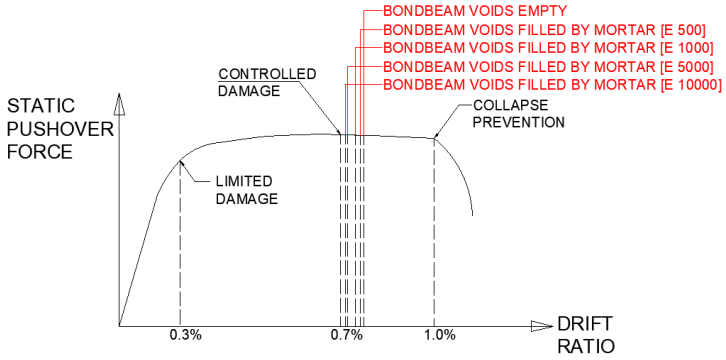


Figure 15. Static push-over limit conditions and drift ratio for DD1 seismic level for various cases

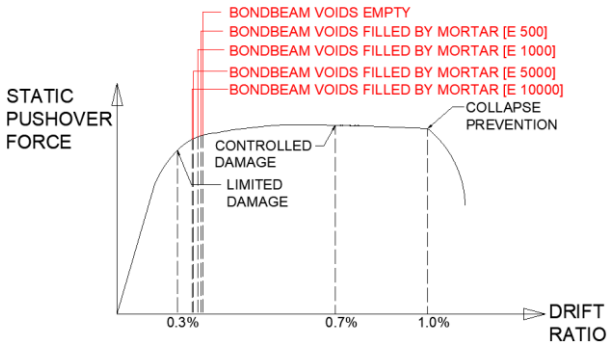


Figure 16. Static push-over limit conditions and drift ratio for DD2 seismic level for various cases

4. Conclusions

Turkey is located in one of the most active earthquake-prone regions in the world and it has been devastated by major earthquakes several times. Damages to the buildings, infrastructure, and historic heritage impose a big overburden on the economy. The recent earthquake events of February 6, 2023, of Kahramanmaraş and the aftermath revealed the seismic fragility of Turkey once more. Rebuilding needs to be done cautiously to revitalize the earthquake-affected region and strengthen it for future events and generations. Aftermath also revealed the devastating effect of the earthquake on historic heritage in the earthquake-affected area and underlined the need for retrofit for many historic heritage structures in terms of their response to the earthquakes in advance.

This study aims to strengthen the remains of a historic heritage, Atranos Castle, before its already escalating erosion due to environmental effects. To reduce the risk of losing it in case of a seismic event, an intervention is required. In this study, the seismic response of Atranos Castle due to the voids of the wooden bond beams is investigated for Atranos castle. Since the minimum intervention approach is adapted as a guide, before any major restoration, minor restoration work is suggested to take place to enhance the seismic behavior of this structure. This will be very crucial until an archaeological excavation starts on site. This study showed that the leftover voids from the wooden bond beams are causing stress concentrations in the vicinity of the voids and they can be eliminated by filling them with grout with a modulus of elasticity in the range of the modulus of

elasticity of the masonry walls in place. Securing the tower will pave the way for further work for this historic heritage and in case of an archaeological excavation, further steps will be taken for a more detailed study and towards the conservation attempts of this structure.

Declaration of Ethical Standards

The author declares that he complies with all ethical standards.

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, methodology and software, Validation, Formal analysis, Investigation, Resources, Data curation visualization and writing

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Datasets are available on request. The raw data supporting the conclusions of this article will be made available by the author, without undue reservation.

Acknowledgement

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