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Research Article

Performance Evaluation of the Kırkgözeler Bridge under Combined Vehicle and Seismic Loads in Erzurum, Turkey

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Keywords

Time history analyses, Transportation superstructure, Performance based evolution.

Abstract

Throughout history, transportation structures have played a vital role to ensure cultural and commercial interaction. Today, the continuation of this interaction and the transportation superstructure's ability to safely withstand vehicle and earthquake loads is critical. In the current study, the performance of the Kırkgözeler transportation superstructure, which is located in the Horasan district of Erzurum, Turkey and connects the villages in the region to the district and city center, has been evaluated. The performance of the Kırkgözeler bridge under vehicle and earthquake loads was evaluated using time history analyses. The results indicate that the bridge experiences limited damage under horizontal earthquake loading, but may sustain controllable damage, particularly in the main beams, under vertical earthquake loading. Reinforcement of the main beams is suggested to mitigate potential damage.

1. Introduction

Transportation superstructure systems are important structures that show the social, cultural and economic development of a country [1]. Transportation superstructures are necessary for the continuation of activities such as industry and agriculture in the country [2]. However, the design and construction of new superstructures is a costly undertaking for continued sustainability. Therefore, assessing the functionality of existing transportation superstructures and taking necessary precautions is essential. Therefore, it is necessary to evaluate the performance of transportation superstructures such as bridges, which are made of reinforced concrete, masonry and steel carrier systems. Current design and performance evaluations of these structures are guided by regulations such as AASHTO and AASHTO LRFD [3,4]. However, some transportation superstructures in Turkey have not been adequately engineered and have sustained significant damage, particularly in recent earthquakes [5]. It is crucial to predict potential damage to bridge structures from earthquakes and vehicle loads and to plan necessary strengthening/repair procedures to prevent loss of life and economic losses. Analyzing a typical bridge structure under earthquake and vehicle loads allows for the determination of potential damage to its columns, beams, parapets, and supports [6]. In this context, a number of studies have been conducted in the literature to evaluate the performance of transportation superstructures such as bridges. These studies generally focus on the application of dynamic analyses to bridge structures [7,8]. Dynamic analyses provide values for tensile, compressive, and in-plane shear stresses in bridge load-bearing elements. Additionally, these analyses yield data on the bridge's energy absorption capacity, acceleration variations from supports to the deck, horizontal displacements, and collapse behavior [9]. Such studies have been conducted both before and after earthquakes [10].

After the performance evaluation of the bridge in the literature, a number of strengthening methods have been suggested. These strengthening methods include sheathing and FRP wrapping in the bridge columns, placement of MR liquid dampers in the support areas, high strength mortars reinforced with steel fiber and basalt fiber used for strengthening [11-14]. The effectiveness of these strengthening methods has been verified through finite element analyses and laboratory experiments [15,16].

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This study aims to assess the seismic vulnerability of the Kırkgözeler Bridge, providing valuable insights for infrastructure management and potential retrofitting strategies in the region. The current study focuses on the Kırkgözeler Bridge, located in the Horasan District of Erzurum, Turkey, which connects five villages to the district and city center. According to Turkey's Earthquake Hazard Maps, the bridge is located in a high seismic activity zone with a peak ground acceleration (PGA) greater than 0.5g [17]. Additionally, the bridge is surrounded by several local faults, including the Şenkaya-Narman-Oltu Fault, Erzurum-Pasinler-Köprüköy-Erzurum Fault, Pasinler Fault, Palandöken Fault, and Karayazı Fault [18]. Time-domain analyses were conducted to evaluate the performance of the bridge structure in this high seismic activity region. The time-domain analyses yielded tensile, compressive, and in-plane shear stresses in the bridge structure, which were then compared to limit values. Additionally, acceleration and displacement values were obtained to determine the bridge structure's performance.

2. Material and Method

2.1. Finite element model

The Kırkgözeler Bridge, a reinforced concrete load-bearing system, is 105 m long with 5 spans and was started in 1968 in the Horasan district of Erzurum Province, Turkey (Figure 1).

Figure 1. The structural system of bridge

The Kırkgözeler Bridge connects the Harçlı, Kükürtlü, Buğdaylı, and Emre neighborhoods to the Erzurum city center. It has support lengths of 19.70 m and span distances of 21.35 m, 21.70 m, 21.70 m, and 21.35 m. The bridge has a height of 11.90 m from the ground and a distance of 5.80 m between the support and the upper deck (Figure 2). The deck thickness in the bridge structure is 30 cm, the beam dimensions are 60x60 cm and the column dimensions are 70x120 cm.

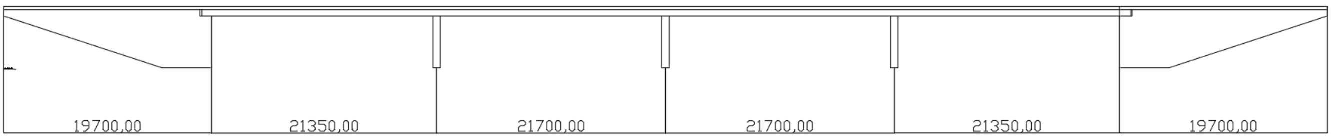


Figure 2. Geometric structure of the bridge

The finite element model of the bridge structure was developed using ANSYS software (Figure 3).The bridge deck was modeled using shell elements, while the beams and columns were modeled with beam elements. At the supports, columns were given sliding boundary conditions to simulate rotation, horizontal displacement and potential collapse [19]. The supports were modeled as fixed [20]. Plastic hinges (P-M2-M3) that can represent axial pressure forces, in-plane and out-of-plane bending moment behavior in the columns and plastic hinges (M3) representing in-plane bending moment in the beams were defined in the element end regions. Plastic joints are defined under axial compression and compound bending since ductile collapse of the clones is desired. In beams, they are designed as simple bending.

The bridge structure was modeled using shell elements. Then, the structure was divided into finite elements. The load-bearing elements of the bridge structure were defined in ANSYS as reinforced concrete." "After the bridge structure was divided into finite elements, the loading was applied in a way that the rear and front wheel loads of the vehicles would correspond to the nodal points. After the bridge structure was divided into finite elements, the loading was applied in a way that the rear and front wheel loads of the vehicles would correspond to the nodal points.

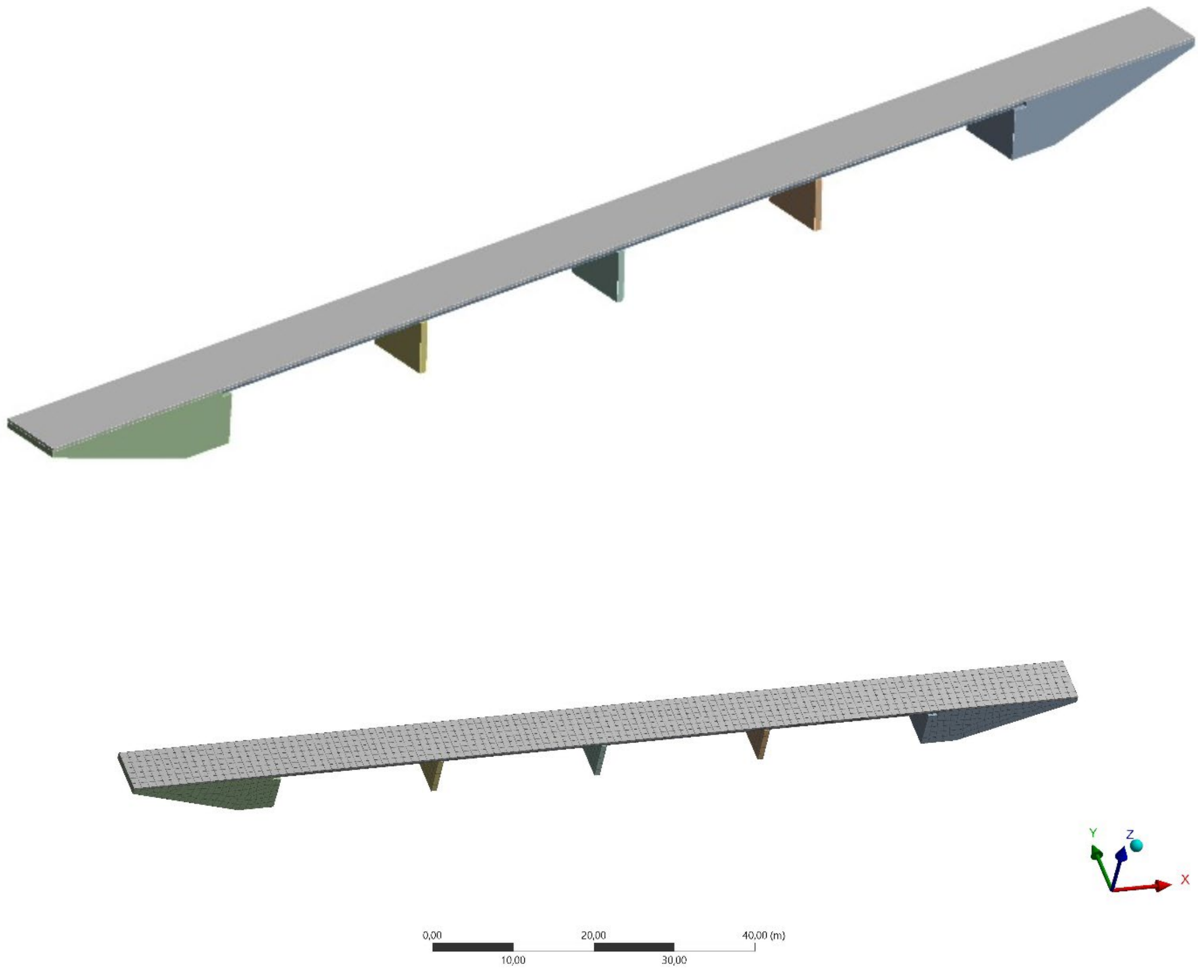


Figure 3. The finite element model of bridge structure

The bridge structure was subjected to live loads (vehicle loads), self-weight, coating loads, and horizontal and vertical earthquake loads. The loads defined for the H30-S24 model are given in Table 1 [19]." --> "Vehicle loads were applied according to the AASHTO 2014 H30-S24 model (Table 1) [19].

Table 1. Equivalent strips loads

Load Type	H30-S24
Total Weight (kN)	540
Front Axis (kN)	60
Middle Axis (kN)	240
Rear Axis (kN)	240
Equivalent Strip Load (kN/m)	15

2.2. Earthquake records

The earthquake loads applied to the Kırkgözeler Bridge were designed as horizontal and vertical earthquake loads in the time domain within the scope of AASHTO and related literature. The local soil class of the bridge structure was selected from the MTA maps as approximately multi-layered clay and loose sand layer [18]. In the study, the data of the Erzincan earthquake (Horizontal EW) and the Elbistan earthquake (Vertical UD) were taken into account for the horizontal earthquake effect. The characteristic features of both earthquakes are given in Table 2.

Table 2. Characteristics of earthquake data

Earthqıake	Date	Latitude	Longitude	Station	Depth (km)	Magnitude (Mw)	PGA (g)
Erzincan	13.03.1992	39.7159	39.6292	Otlukbeli	22,6	6,6	0,488
Elbistan	06.02.2023	38.089	37.239	Göksun	7	7,6	0,504

Scaled and unscaled acceleration time graphs of the earthquakes are given in Figure 4 and scaled and unscaled earthquake spectra are given in Figure 5. The scaling of the earthquake records specific to the structure was made according to the location and geological formation of the structure [20]. Figure 5 shows the spectral acceleration values of the Sae bridge structure. Time history analyses were performed with the highest ground acceleration value of 0.40 g in horizontal and vertical directions.

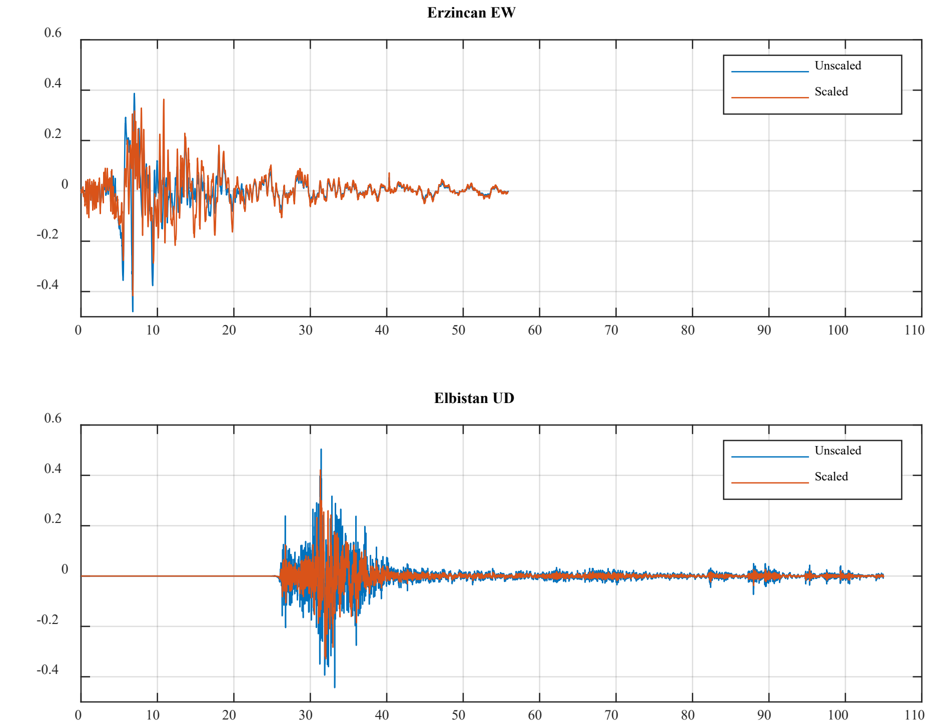


Figure 4. Acceleration time graphs of earthquakes

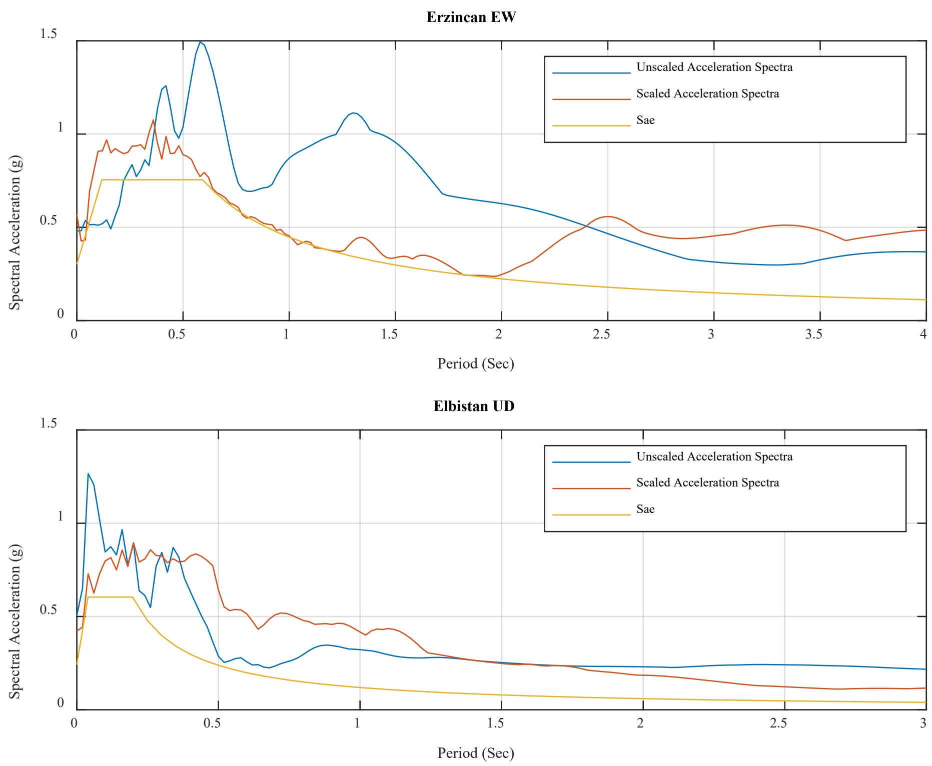


Figure 5. Earthquake spectra

It was planned to obtain tensile, compressive and in-plane shear stresses in time history analyses. It was also aimed to obtain acceleration and displacement values. It was aimed to compare these values obtained in the bridge bearing elements with the limit values defined in AASHTO 2014 and related literature and to make performance evaluation.

3. Analyses results

The time history analyses of the bridge structure were performed under the effect of horizontal and vertical earthquake loads combined with vehicle loads. Figure 6 shows the tensile stresses obtained in the event of the Erzincan earthquake and the relevant vehicle loads acting on the bridge structure. The analysis results showed that the largest tensile stress value was 1.24 MPa in the main beams of the bridge span. It was observed that damages originated from tensile stress occurred in the bending areas of the beams. The maximum tensile stress of 1.24 MPa in the beams suggests that the bridge is operating within the elastic range under horizontal loading. The time history analyses revealed tensile stresses in the bridge structure under horizontal earthquake loads combined with vehicle loads (Figure 6). The maximum tensile stress was 1.24 MPa, located in the main beams of the bridge span [3]. This stress level indicates that the beam is currently performing within its elastic limit. Tensile stresses in the joint and support areas were significantly lower, ranging from 0.2 to 0.3 MPa [4]

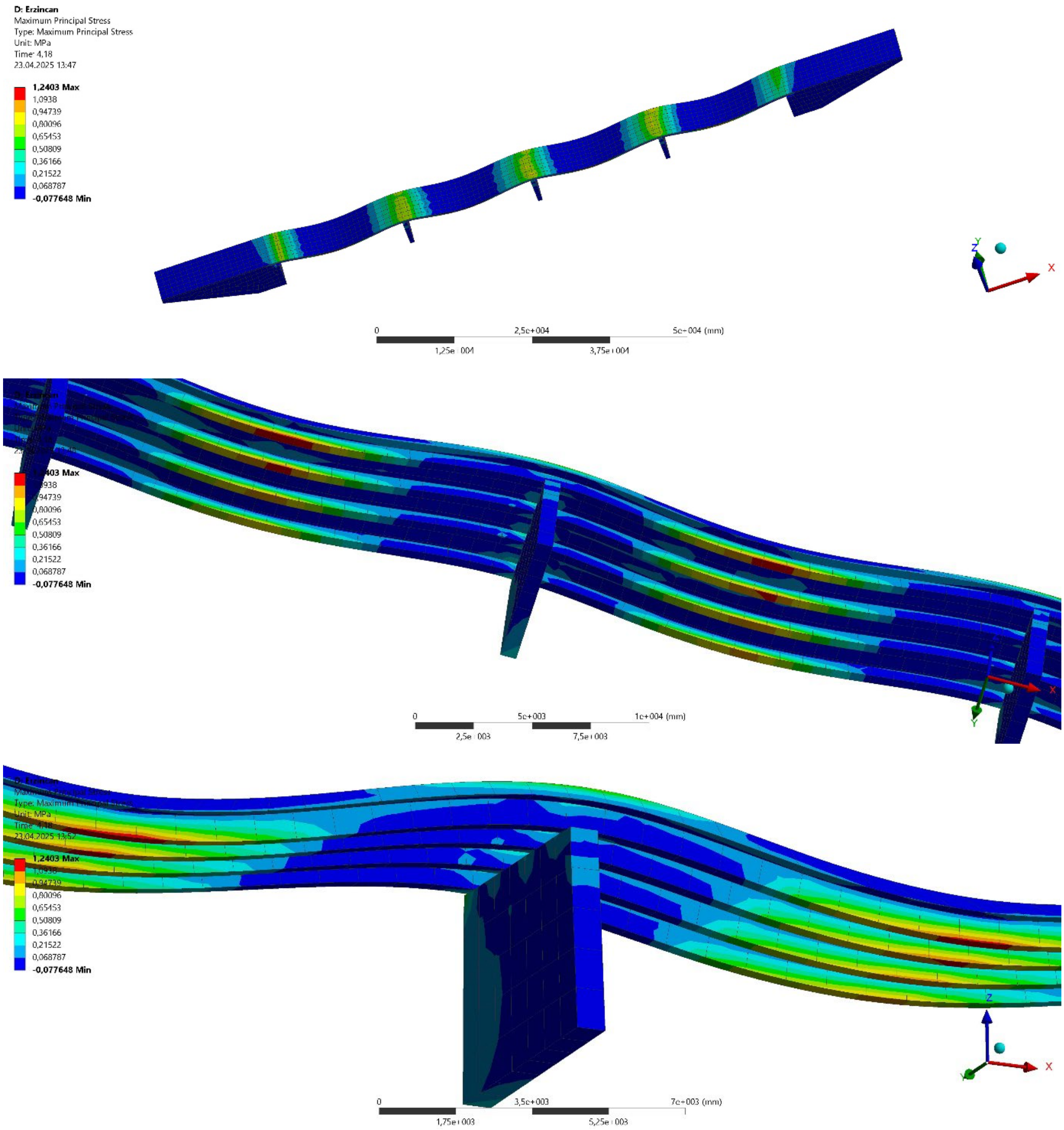


Figure 6. Tensile stress distributions under the influence of horizontal earthquake and vehicle load.

The distribution of compressive stresses in the bridge structure under the influence of horizontal earthquake load and vehicle load is given in Figure 7. It was observed that the compressive stresses were concentrated in the bridge decks and the edge and middle columns. It was calculated that the maximum compressive stress in the middle columns of the bridge structure was approximately 4 MPa. Since this value remained significantly below the compressive strength of the concrete, the bridge structure showed that it safely transferred the compressive stresses horizontally.

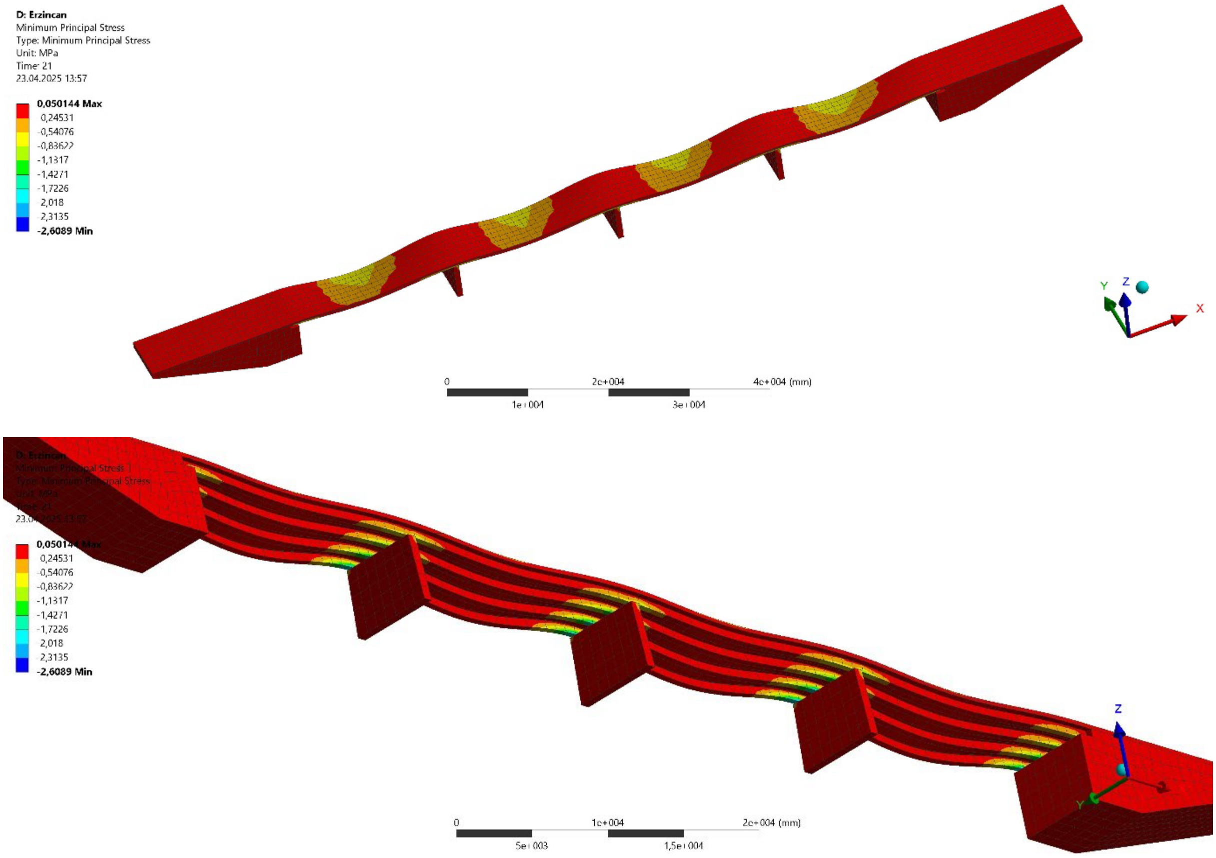
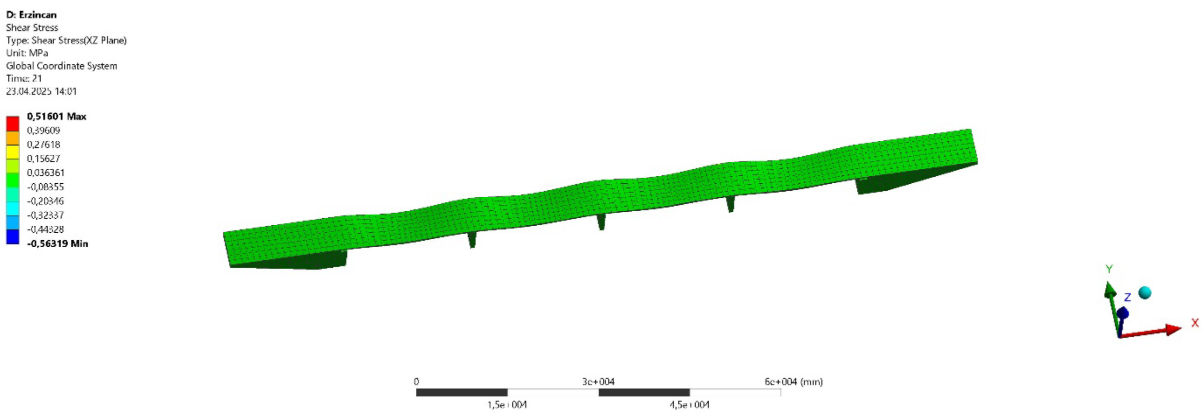


Figure 7. Compressive stress distributions under the influence of horizontal earthquake and vehicle load.

It was determined that in-plane shear stresses occurred in the middle span region of the bridge at the outermost deck and middle column joints (Figure 8). The shear stress strength for the bridge structure was calculated as 3.25 MPa according to AASHTO 2014. The maximum in-plane shear stress value in the middle support regions of the bridge structure was approximately 1.27 MPa. In side column regions, the maximum shear stress was approximately 0.60 MPa. In this case, it was determined that the in-plane shear stresses were safely withstood by the bridge structure.



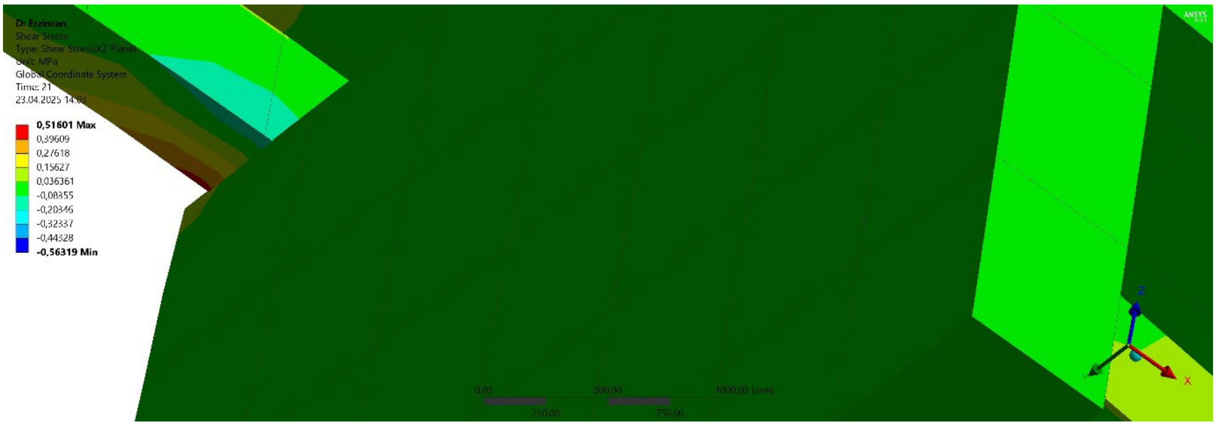


Figure 8. In-plane shear stress distributions under the effect of horizontal earthquake and vehicle load.

The acceleration distributions resulting from the horizontal earthquake (Erzincan earthquake) are given in Figure 9 and the displacement distributions in Figure 10. It was determined that the horizontal response accelerations occurring in the bridge structure increased when the upper decks were reached from the support areas. Since the acceleration values are expected to increase when the elevation difference increases under normal conditions, it was thought that the response acceleration values occurring in the bridge were at a level that would not cause any damage to the bridge. It was determined that the maximum acceleration values occurring in the bridge structure occurred at the top edge deck at a value of 0.69g.

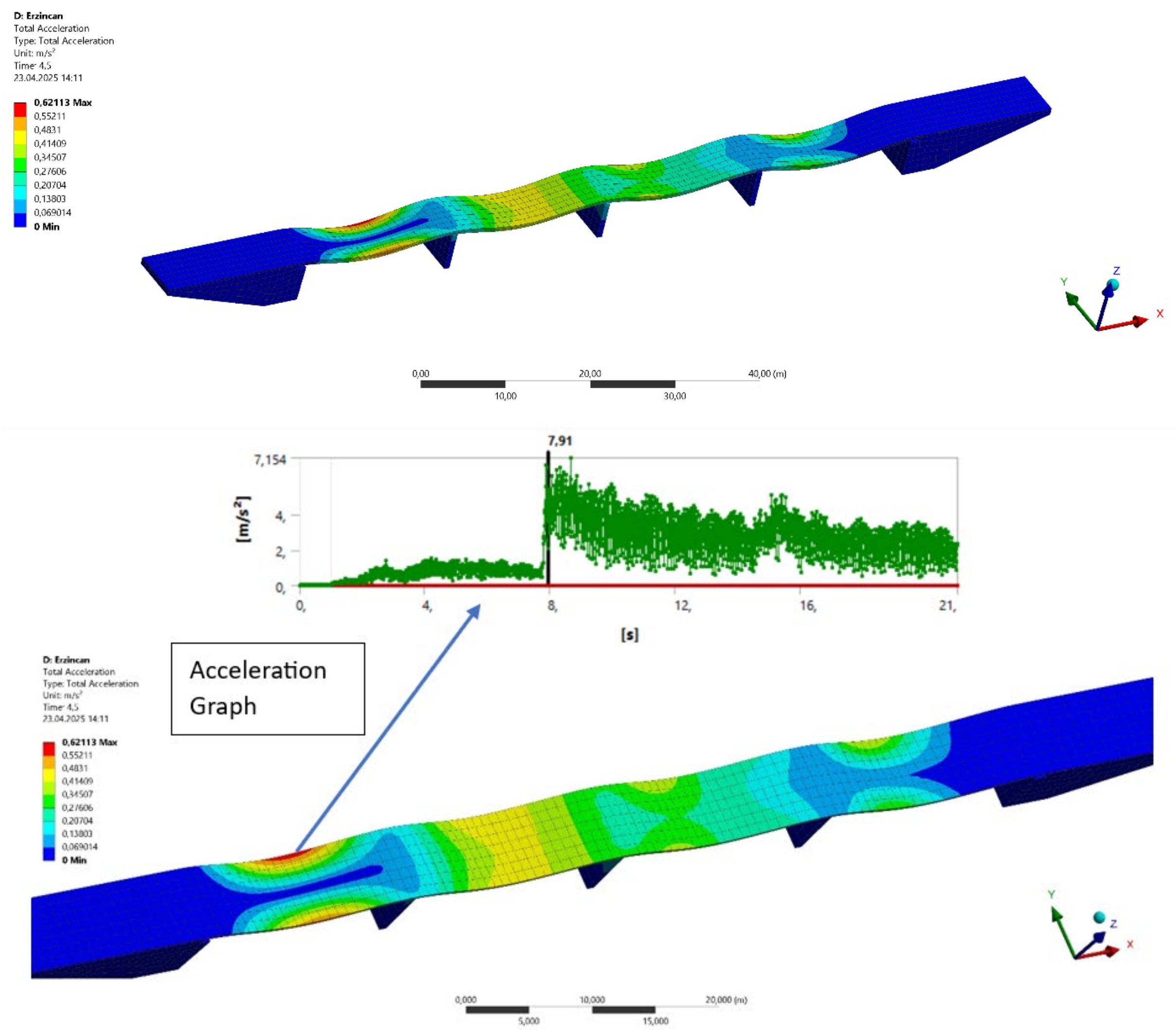


Figure 9. Horizontal response acceleration distributions of the bridge

It was determined that the horizontal displacement values of the bridge were very small. These values were shown to be well below the allowable relative drift values according to AASHTO 2014.

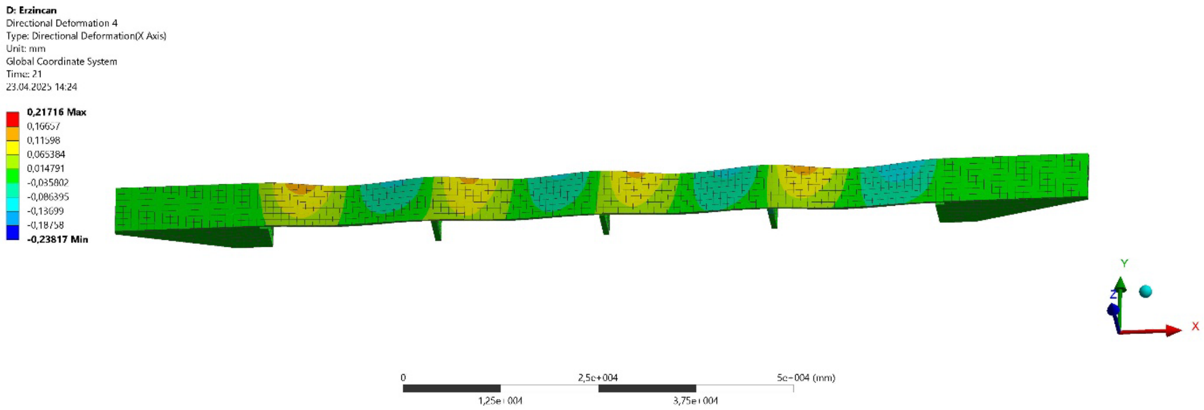


Figure 10. Horizontal displacement distributions

It is predicted that a controllable damage level will occur in case of an earthquake in the horizontal direction in addition to the vehicle loads on the bridge structure. The tensile stress distribution that may occur due to the vertical earthquake (Elbistan earthquake) in addition to the vehicle load is given in Figure 11. It was determined that the tensile stresses occurred in the middle regions of the beams in the mid-span. It was thought that the collapse mechanism would occur in the bending region as expected. It was observed that the maximum tensile stresses in the column and support regions of the structure in question were 1 MPa and approximately 11 MPa in the mid-span beams. Flexural damage is anticipated in the beams. The compressive stress distributions resulting from vertical earthquakes are given in Figure 12. It was observed that the maximum compressive stresses occurred in the middle columns and the deck. It was determined that the compressive stresses could be safely withstood by the bridge structure.

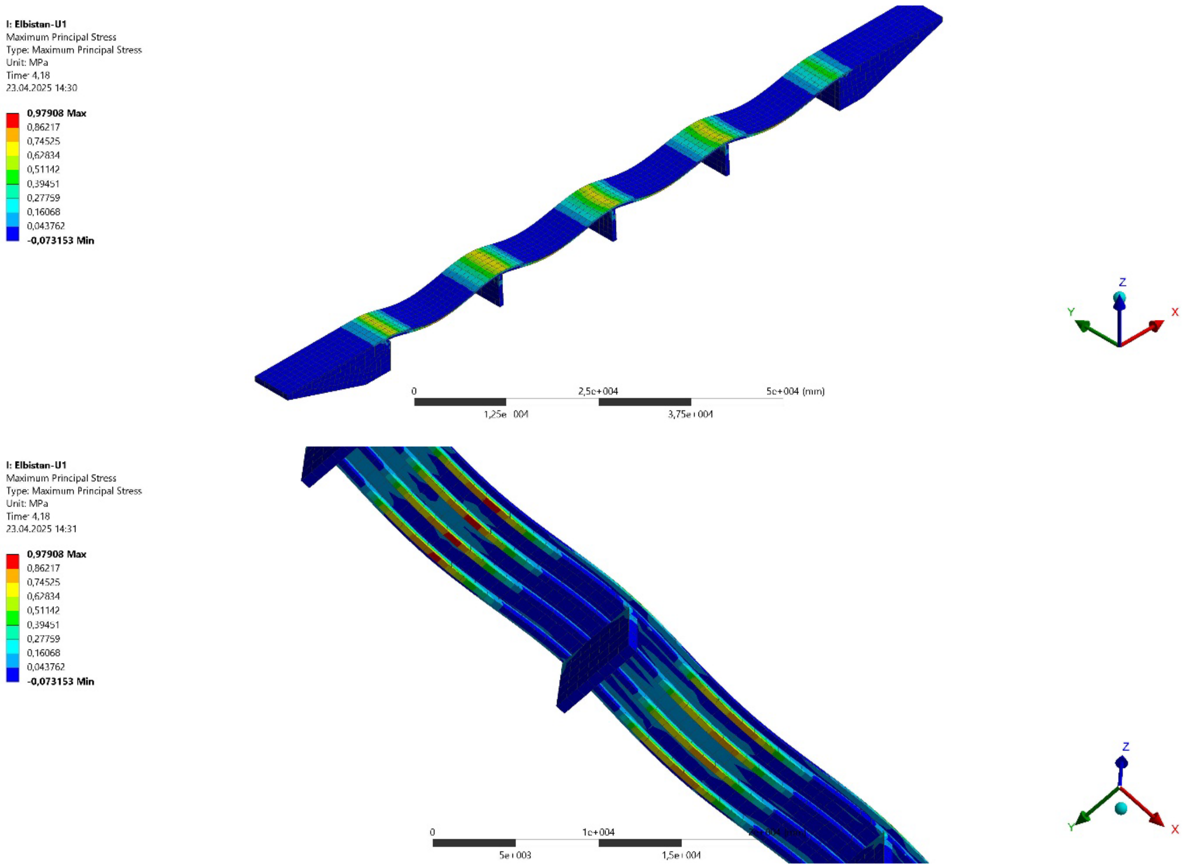


Figure 11. Tensile stresses due to vertical earthquake loading

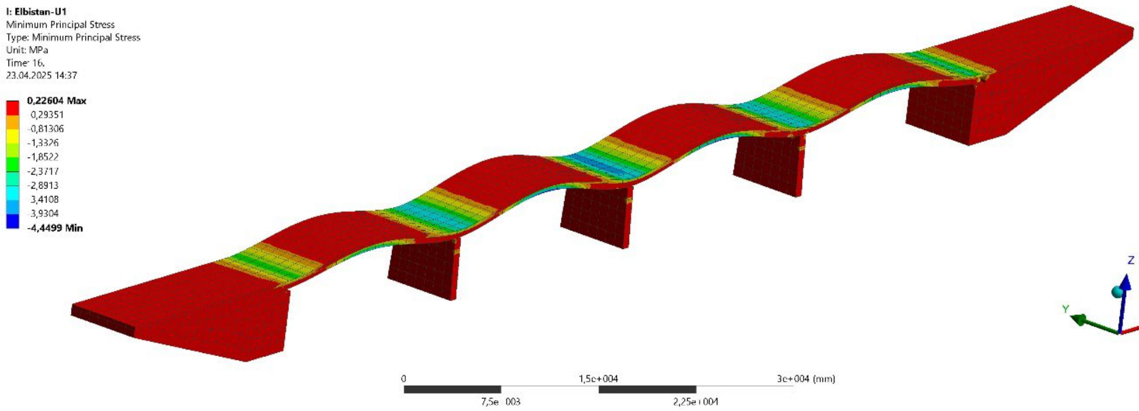


Figure 12. Compressive stress distribution due to vertical earthquake loading.

The in-plane shear stress distributions resulting from vertical earthquake loading are given in Figure 13. It was observed that in-plane shear stresses became evident in the column and deck joint areas. The maximum in-plane shear stress value occurring in the joint areas of the bridge structure is 1.78 MPa. AASHTO 2014 and literature have shown that this value is well below the allowable values.

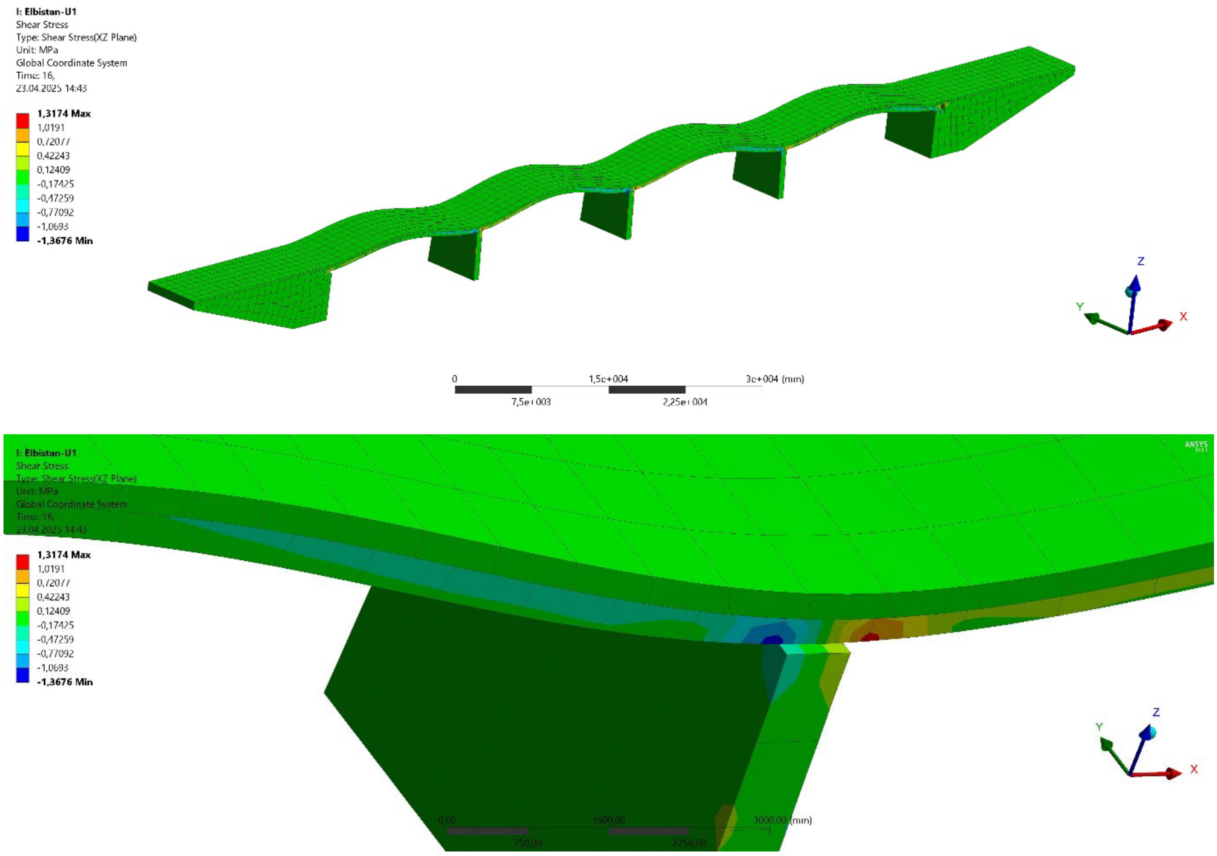


Figure 13. In-plane shear stresses due to vertical earthquake loading

According to AASHTO (2014), it is recommended that the ratio of the bridge center span deflection to the span should be less than 1/800 for bridges outside the city and less than 1/1000 for bridges located in the city center. In addition, it is accepted that the ratio of the deflection to the span should be less than 1/500 during the transfer and that the final deflection should be below 1/500 [3]. The permissible limit value for the ratio of the deflection to the span for the bridge structure was calculated as 2 mm. It was observed that maximum deflection values occurred in the edge span region during vertical earthquake loading (Figure 14). It was determined that the maximum deflection value occurred in the bridge structure was 16.58 mm and the ratio of this deflection value to the span (21 m) was 0.78 mm. In this case, it was concluded that the bridge structure met the deflection value caused by the vertical earthquake.

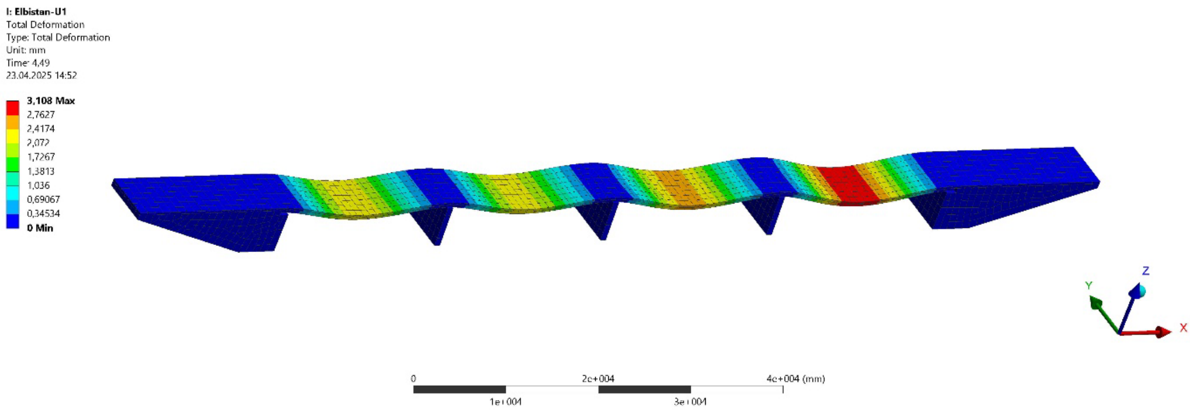


Figure 14. Deflection distributions in the bridge structure

The acceleration distributions resulting from vertical earthquakes are given in Figure 15. As in the deflection distributions, the highest acceleration values occurred at the edge of the opening. The highest peak acceleration value resulting from the vertical earthquake was determined to be 1.81g. It was observed that the acceleration values increased from the lowest support to the upper deck. It was determined that the bridge structure also created a reasonable level of response acceleration value that could withstand the effects of the earthquake in the vertical.

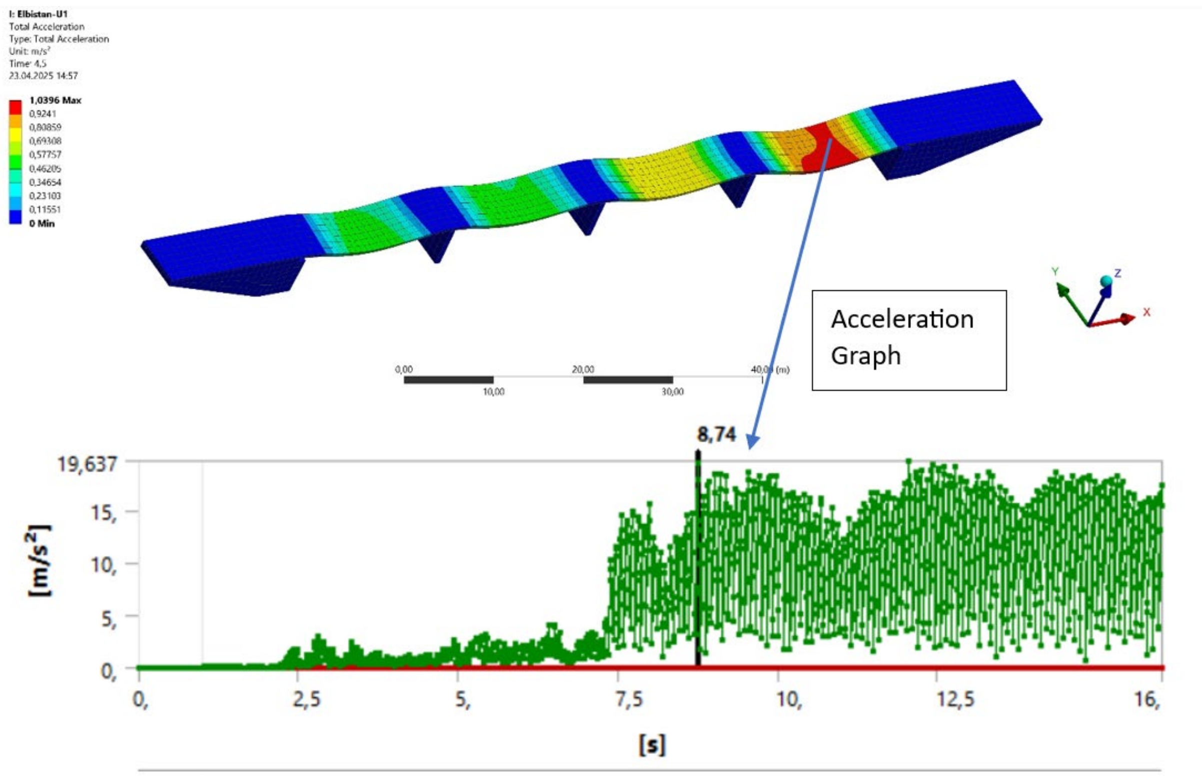


Figure 15. Response acceleration values and distributions caused by vertical earthquake

It has been concluded that partial damage may occur in the bending areas of the beams in the middle span of the bridge structure due to vertical earthquakes. It is expected that limited damage may occur in the column and support areas. It has been concluded that the tensile, compressive and in-plane shear stresses resulting from vertical earthquake effects are greater than the stress values resulting from horizontal earthquake effects.

4. Conclusions

In this study, a performance evaluation was made on the bridge structure of Kırkgözüler Bridge located in Horasan District of Erzurum Province, Turkey, in terms of whether it fulfills the expected economic, social and cultural interaction functions. In determining the performance of the bridge structure, time history analyses including vehicle load effect were applied. In the analyses, apart from the vehicle load effect, acceleration values of Erzincan earthquake were used for horizontal earthquake effect and acceleration values of Elbistan earthquake were used as vertical earthquake effect. The results obtained in the study are briefly summarized below.

- In the evaluation made in terms of tensile stresses formed in the bridge structure, it was determined that tensile stresses were concentrated in the main beams located in the middle span in both vertical and horizontal earthquake loadings. It was determined that maximum tensile stresses of 1.24 MPa and 11.03 MPa occurred in the main beams in horizontal and vertical earthquake loadings, respectively. It was concluded that tensile stresses of 0.3 MPa and 1.01 MPa occurred in the columns in horizontal and vertical earthquake loadings, respectively. It is expected that limited damage occurred in the bridge structure in horizontal earthquake loadings, but controllable damage may occur in the beams in vertical earthquake loadings.
- It was concluded that the pressure and in-plane stresses occurring in the vertical and horizontal earthquake loadings in the bridge structure can be safely resisted.
- It was determined that the vertical and horizontal response acceleration values occurring in the bridge structure were at a reasonable level to meet the earthquake effects. It was observed that the horizontal and vertical acceleration values were more pronounced in the decks at the side spans.
- It was concluded that the displacement values of the bridge structure under horizontal earthquake loading and the deflection values caused by vertical earthquake effects remained at a limited level.
- Vertical earthquake effects have created greater stress values than horizontal earthquake effects.

The time history analyses showed that the Kırkgözeler Bridge exhibits different performance characteristics under horizontal and vertical earthquake loads. While the bridge can generally withstand horizontal earthquake effects with limited damage, vertical earthquake loading induces higher tensile stresses in the main beams, potentially leading to controllable damage [4,9]. The compressive and shear stresses resulting from both horizontal and vertical earthquake loading were within acceptable limits [12]. To mitigate the risk of damage from vertical earthquake events, reinforcement of the main beams, such as jacketing or FRP wrapping, is recommended to reduce tensile stresses and acceleration values [13].

In the evaluations made on the transportation superstructure, it was determined that the bridge structure was generally at a controllable damage level. As a result of possible reinforcements (jacketing or FRP wrapping) to be made on the main beams in the middle span and side spans, it is expected that the tensile stresses and high peak acceleration values in the bridge structure will decrease and reach a limited damage level.

Nomenclature

AASHTO: American Association of State Highway and Transportation Officials
AASHTO LRFD: American Association of State Highway and Transportation Officials Load and Resistance Factor Design
EW: Horizontal Direction
UD: Vertical Direction
g: Gravitational Acceleration
GM: Model Frame with Geopolymer Mortar
LVDT: Linear Derivation Displacement Transducer
Mm: Milimeter
Mw: Magnitude of Moment in the Earthquake
N: Newton
PGA: Peak Ground Acceleration
Sae: Horizontal Elastic Acceleration Spectra

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This article was written within the scope of the master's thesis titled ‘Investigation of The Usability of Early Damage Diagnosis Techniques in Transportation Structures Before and After Earthquake: Kirkgözeler Bridge’.

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