Structural Investigations on Justinianus Bridge in Sakarya City of Turkey

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Abstract Turkey having a great civilization history inherited many cultural heritage structures such as mosques, bridges, baths and madrasahs. Historical bridges constitute a significant part within these heritages and most of such structures were constructed as masonry stone arch bridges and so the preservation and transferring them to the next eras becomes an important issue. To contribute protection and rehabilitation of stone arch bridges in structural way, historical Justinianus Bridge, situated on the Sakarya River of Turkey and made of stone arch form, was investigated structurally. It is heritage from ancient Roman Era. Several damage, deterioration, deficiencies are observed on the structural system in the current state. 3D structural modeling of the bridge was performed by Finite Elements Modeling (FEM) through DIANA software. Separate modeling of arches, spandrel walls and backfill were considered with different material properties to consider interaction between such members. Modal characteristics were investigated by modal analyses. Structural analyses were carried out under self-weight/dead loads, live loads and seismic loading. Structural response and behavior of the bridge were investigated and discussed in terms of normal and shear stress distribution, mode shapes as well as displacements. It was aimed to analyze these damages which have occurred under gravity and lateral loading with engineering methods and to evaluate results of analysis for restoration in this study. The bridge has experienced many earthquakes since it was built, besides environmental and aging effects. Currently, various such as stone and masonry cracking, material loss and vegetation have been observed on the bridge.

Keywords: Historical structure, Stone arch bridge, Justinianus Bridge, Finite Element Modeling.

1 Introduction

Turkey hosted several civilizations including Roman and Ottoman Empires. Owing to this inheritance, several structural heritages exist across the board of the county such as mosques, bridges, churches. Substantial part of such heritages is bridges. Recently, numbers of surveying, restitution and restoration projects on historical building has been performed and still many of ongoing project exists. Beside, restoration projects on historical bridges are still limited compared to the buildings. Most of the existing historical bridges, like 1682 out of 1772, are masonry stone arch bridges according to current inventory of General Directorate of Highways (KGM) that is the foundation that is responsible for historical bridges via Division of Historical Bridges in Turkey. In between years of 1950 and 2003, 110 of historical bridges were restored; 58 of them also were repaired/restored during years 2003~2008 by KGM. Several restoration projects on historical bridges currently are in progress. Most of the remaining bridges await for intervention or restoration and most of them is masonry.

To perform an appropriate restoration project for these historical bridges, the important task is to understand a realistic structural behavior, since such masonry structures has complex geometry and structural behavior. Several researchers have investigated the issue in their studies such as Lourenço and Milani [1], Gedik et al. [2], Oliveira et al [3], Sevim et al [4], Korkmaz et al [5], Cavicchi et al [6]. The present study focuses on evaluating structural and seismic behavior of stone arch bridges to prepare a basis for structural part of restoration works for such bridges. The research work, Justinianus Bridge from the Byzantine era over the Sakarya River of Turkey and constructed in 6th century was investigated.

The bridge have been experienced many earthquakes since it was built. Several damages such as masonry cracks, vegetation, material loss and degrading are observed that likely are caused due to past earthquakes and environmental time-dependent effects. Structural model of the bridge was prepared in 3D by Fx+ DIANA software. Structural and seismic analyses were performed. Structural behavior of Justinianus Bridge was evaluated and discussed considering results obtained such as modal shapes, displacement values and normal and shear stresses.

2 Justinianus Bridge

The bridge was built in between years of 553-561 A.D within 6th century. The Emperor Justinianus of East-Roman Empire ordered construction of the bridge. The bridge takes place over the Sakarya River, in Sakarya city of Turkey that located on the north-west region of Anatolia (Figures 1, 2 and 3). The bridge was erected to connect Constantinople, the capital of the Empire, and east provinces.

Fig.1. Satellite View of the Bridge [7]

Fig.2. North Facade of the Bridge – Downstream and Pointed Shape Piers [8]

Fig.3. South Facade of the Bridge – Upstream and Semi-circular Wave [8]

2.1 Definition of the Bridge

The bridge has 12 spans, named A1 to A12 in Figure 4, with the total length of ~346.5m in plan. The width and the current maximum height of the bridge are 10m and 9m respectively. In current situation, 7 bays of the bridge that are A4 to A10 are exceeded by longer span main load bearing arches. Arches of A5 to A10 are supported by piers; where arch A4 is supported by a pier at one end and by soil at another. Other arches are directly supported by soil in the present situation. Arch A8 has the maximum span length of 22m. The span length of arches A4, A5, A6, A7, A9 and A10 vary in between 18m to 20m. Other arches have smaller spans with ~3m to 9.5m. All arch forms are semicircular. Arches A4 to A10 constructed as double-vault. The thicknesses of main load bearing arches vary in between 600 mm to 1650 mm. The bridge has 7 piers in total. It is understood that significant portions of the piers remained under alluvium deposit layer in time.

The plan section layout of piers has pointed shaped at the north façade and semicircular shape at the south façade (as seen in Figure 4). These plan protrusions of piers were planned to be used as flood splitter.

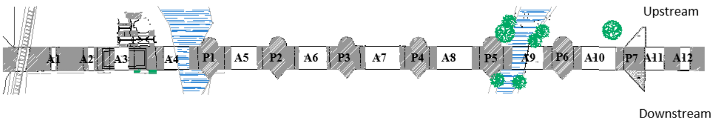

Fig.4. Plan View [9]

Fig.5. South Façade View [9]

Likely due to the past earthquakes as well as environmental and time-dependent effects, damages such as structural cracks, vegetation, material loss and degrading and surface contamination of masonry are observed on the bridge. Overall stability and integrity of the structural system is well yet.

2.2 Material Properties of the Bridge

Masonry units of the bridge are mostly made of limestone blocks. Rubble masonry blocks with brick dust mortar were used as backfill material in between exterior spandrel walls (See Figure 6). A part of the slab at the north side of the bridge is determined as concrete according to survey project prepared by General Directorate of Highways that likely attached to the bridge during a past restoration.

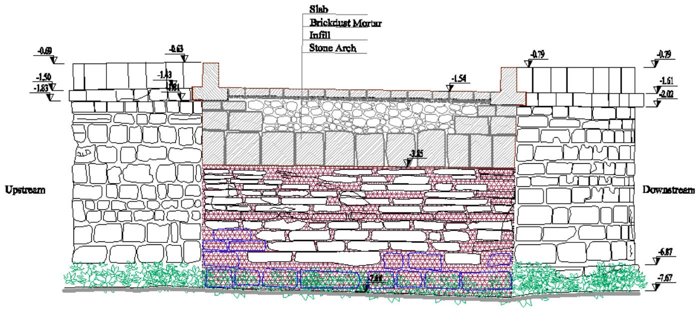

Fig.6. Cross section of the arch numbered 7 [9]

2.3 Soil Condition and Seismicity

The bridge is located on near the Northern Anatolia fault zone and is it is classified as the 1st degree seismic zone (See Figure 7) according to Seismic Zone Map of Turkey [11]. Geotechnical survey reports supplied by General Directorate of Highways shows that the soil group is determined as group C; and Local Site Class of the bridge is defined as Z3 class correspondingly, according to current Turkish Seismic Code released in 2007 named “Specifications for Buildings to be built in Seismic Zones”.

Fig.7. Seismic Zoning Map of Sakarya, Turkey [10]

3 Finite Element Modelling

Masonry stone arch bridges consist of stone units and binding mortars and have a complex geometry. Therefore, modeling them becomes a complicated task. To simplify the modeling, masonry is modeled by a composite macro-modeling approach [12] and unique parameters are assigning for whole masonry. Considering masonry unit material and literature survey on such structures, analyses parameters are assigned as given in Table 1. 3D model of the bridge is prepared in DIANA software using solid elements. Numbers of solid, surface and node used in the model are given in Table 2. The direction of stress, displacements as well as global x, y, z directions are indicated in Figure 8. 3D model view of the bridge a typical transverse cross section of the bridge at arch A8 are given in Figure 9.

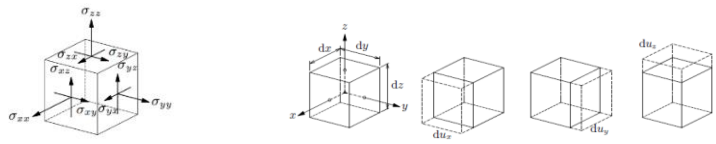

Fig.8. Cauchy Stresses and Displacements [13]

Table1. Material Physical Properties

Material Property	Stone Arches	Spandrel Walls	Piers	Infill	Slab	Concrete Slab Part	Parapet
Elastic Modulus, E (Mpa)	3000	2500	3000	500	2000	20000	2000
Poisson Ratio, ν	0.25	0.25	0.25	0.05	0.25	0.3	0.25
Density (kN/m^2)	16	14	16	12	12	20	12

Table2.Element Property and Number in Finite Element Model

Element Property	Element Number
Solid Elements	284,321
Surface Elements	224,560
Nodes	320,621

Fig.9.3D Model, Downstream (Left)**,** Typical Transverse Cross Section (Right)

4 Method for Structural Analyses

Structural analyses are carried out under dead (G), live (Q) and earthquake loads (E) including G+Q and G+Q+E combinations. Live load was considered as $5kN/m^2$. No vehicle traffic was assumed on the bridge. For seismic loading, the response spectrum analyses along with modal combination method was performed according to current Turkish Seismic Code named “Specification for Buildings to be Built in Seismic Zones” that inured in 2007 [11]. The elastic spectrum includes soil characteristics as well as seismic region of the structure. It is an elastic spectrum and basically defined based on local site condition. The parameters of Effective Ground Acceleration Coefficient (A_o), depending on the seismic zone, are 0.40 and Spectrum Characteristic Periods of T_A and T_B, depend on soil condition, and are 0.15 and 0.60 respectively for the bridge [11].

5 Results of Analyses and Discussion

To determine modal characteristics and behavior, free vibration analyses were carried out. The first free vibration period of the bridge is T_1=0.121sec. It is a small value, since the structural stiffness is quiet significant. The periods for higher modes 2 to 5 are T_2=0.117sec, T_3=0.114sec, T_4=0.113sec and T_5=0.112sec (See Table 3). Mode shapes of 1st, 2nd, 3rd and 4th modes are given in Figure 10. In mode shapes, responses localize on single arches in the first three modes. In the 4th mode, response expanded through longer spans with a mix of transverse and torsional behavior.

Table 3.Mode Shape Frequency & Period Values

Mode No	Frequency (Hz)	Period (s)
Mode 1	8.26293	0.121
Mode 2	8.57470	0.117
Mode 3	8.74186	0.114
Mode 4	8.85282	0.113
Mode 5	8.88582	0.112

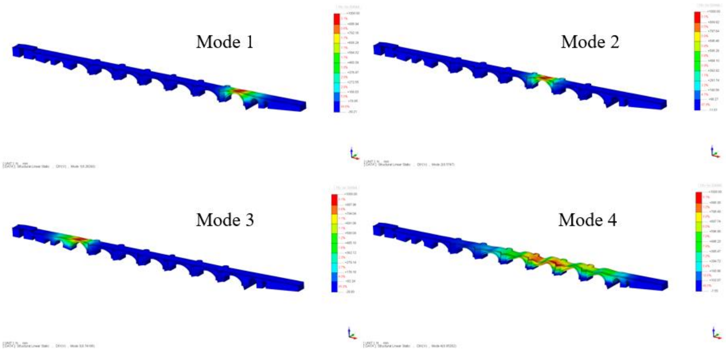

Fig.10. Mode Shapes

Maximum vertical displacement (DtZ) under G+Q loading was obtained as 3.0mm near keystone level of the A8, has the largest span. Maximum compression stresses occurred around the piers under self-weight as expected, maximum vertical normal stress (σzz) under G+Q loading reaches up to 0.8MPa in compression on the piers of arch A8. Tensile stresses were mainly localized about 0.10MPa near keystone level of the arches and flood splitters (See Figure 11).

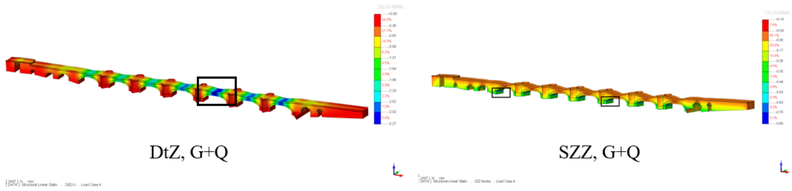

Fig.11. Vertical Displacement (DtZ) & SZZ Stress Distribution under G+Q Load Combination

Under G+Q+E_y load combination including seismic loads along transverse Y direction, the maximum vertical displacement, DtZ was determined as 7mm near keystone level of A8 which has the largest span. The displacement values in Y direction (DtY) were determined as 8mm in the same arch. Maximum compression stress of 0.70MPa was determined on the piers of arch A8. The maximum tension stress of 1.2MPa was determined on spandrel around arch A3 and A4. Morever, the highest tension values mostly localized around flood splitters attached piers (See Figure 12). In case of shear stress, the maximum value reaches about 0.8 Mpa for SZX were defined on arches with longer spans. Since the maximum values generally localized at a unique point or a limited area, discussion on the average distribution was also made. That shows the highest values having a meaningful area rather than a very local distribution. In this sense, maximums are around 0.5Mpa for compression and 0.4MPa for shear stresses.

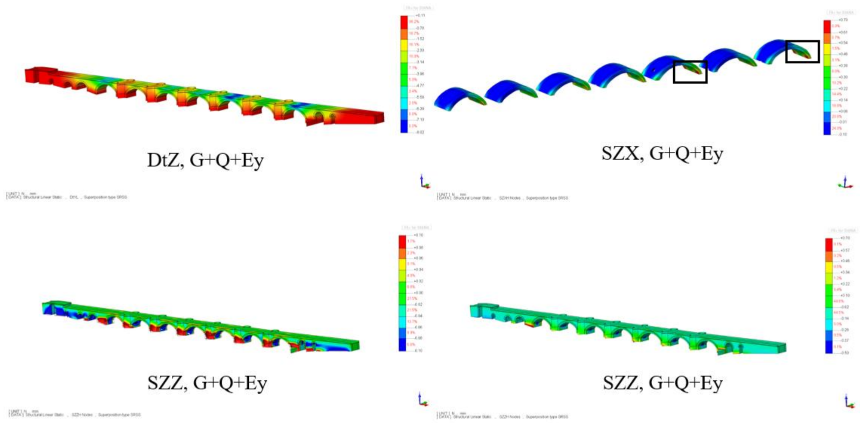

Fig.12. Vertical Displacement (DtZ) & Stress Distributions Under G+Q+Ey Load Combination

6 Conclusions

The main objective of this research is the assessment of Justinianus Bridge and to contribute its preservation and delivering to next generations safely in terms of structural behavior. To achieve that, 3D modeling of the bridge is prepared and structural and seismic analyses are performed. Mode shapes, stress and displacement values were evaluated to investigate the behavior. The results demonstrate that, the most critical part of the bridge is arch A8 having a span of 22m. Generally the highest values of responses are observes in the arches, A4 to A10, with longer span of around ~18m to 22m on the elements such as spandrels, piers and arches. The results demonstrate that, in some regions the stress values exceed than that of the strength limits which is acceptable for such stone masonry. For a possible severe earthquake, some damage or cracking may be expected on mentioned critical regions. It is considered that modeling and analyses are performed under composite masonry and linear-elastic approaches and thus only a general behavior of the bridge could be evaluated. For further studies on the bridge, detailed modeling of masonry and behavior beyond the elastic region would be considered.

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