Dynamic identification-model updating-seismic performance assessment of stone arch bridges

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ABSTRACT: Modernization of Samsun- Kalin railway line which is 378 km long has been undertaken by Turkish State Railways. Due to their historical significance, 41 stone arch bridges on the line were decided to be preserved. Samsun-Kalin line passes through North Anatolian Fault, resulting in high seismic demand on bridges. In this study, seismic assessment of the bridges was carried out by Finite Element Analysis; however, masonry structures such as stone arch bridges have significant uncertainties in terms of material properties, boundary conditions and modeling assumptions. Therefore, it becomes almost unavoidable to perform dynamic identification tests to validate Finite Element Models (FEM).

Along this line, dynamic properties of the bridges were identified by Enhanced Frequency Domain Decomposition method. Vibration measurements were collected under ambient conditions, impact loading and train passage. Based on identified modal parameters, FEM of the bridges were updated to obtain actual values of Young's modulus and soil spring values. FEM updating procedure was performed by minimizing the difference between experimental and analytical modal values.

Seismic performance assessment of the bridges was performed by pushover analysis. Nonlinear models were created by MIDAS software. Macro modeling approach was followed to develop homogenized behavior of stone and mortar. It was found that capacity of the bridges was affected mostly by the arch length. Structural deficiencies were observed on spandrel wall for bridges with wider arches and higher seismic demand. Analytical investigation of reinforcement of spandrel walls with mortars including glass fiber mesh was found to be adequate.

1 INTRODUCTION

Many assumptions are assumed for FEM's of structures because of uncertainties in structural parameters. Particularly, the number of uncertainties is higher for the masonry structures when compared to other type of structures. Therefore, dynamic identification tests are inevitable methods in order to minimize uncertainties of masonry structures and create proper FEM's for static and dynamic analysis.

Many studies were conducted related to model updating, assessment, and retrofitting of masonry structures. Fanning et al., (2000) studied the performance 3-D modeling of three masonry arch bridges by comparing the loading test results with the results determined from the FEM's. The consistency of the test results with the ones acquired from the simulations indicated that modeling of masonry bridge was satisfactory. One important outcome of the study is that the transverse bending may induce cracking in the arch barrel which can alter the response of the bridge. Aoki et al., (2007) carried out a series of dynamic, non-destructive and destructive tests were carried in visual inspections, material tests on stones and mortar, inspection of inner cavities with radar and fiberscope, and inspections of submerged foundation by camera were the non-destructive and destructive tests in order to clearly define the structural characterization of 89.3m long a stone arch bridge. Dynamic properties of the bridge were conducted during micro-tremors and traffic excitations. In the initial FEM, identified young's modulus of the stone and mortar were used whereas the young's modulus of the fill material was assumed as 1/10th of the one of mortar. The boundary conditions were assumed to be fixed at two piers and both abutments. The inverse Eigen - Sensitivity method was utilized for modal updating procedure. Pela et al., (2009) investigated the seismic performance of two masonry arch bridges, a stone masonry bridge with brick-made vaults and a stone masonry bridge with concrete made vaults. The structural capacity, which was obtained through pushover analysis, was compared with the demand of the earthquake ground motion described by an inelastic response spectrum. The importance of the choice of control node was examined by selecting the control node from the top of the bridges, their mass centers and energy equivalent displacement. In the study, core tests allowed the determination of the characteristics of stones and mortar. Dynamic ambient vibration surveys resulted in the tuning of the elastic modulus, unit weight and poison's ratios of the masonry materials in bridges. Costa et al., (2015) carried out modal updating of three masonry arch bridges based on the modal parameters obtained from operational modal analysis. The material properties of the initial FEM's consisted of the properties obtained from the experimental tests on material samples taken from the bridges, or by assigning properties representative of the experimental tests of previous studies. Even though large amount of material properties was obtained through laboratory tests, there were still some differences between the analytical and identified modal properties. Therefore, at the final step, the numeric models were tuned by adjusting the material properties or soil conditions. Zampieri et al., (2015) examined seismic performance of two different structural configurations of multi – span masonry arch bridges: a three span and a five span masonry arch bridge. Pushover analysis results showed that the pier base reached its maximum capacity and cracks were created indicating a collapse mechanism. However, shear stresses were lower than the strength of structure at pier base. Moreover, analysis results show that increasing arch length and pier slenderness ratio increased the probability of creation collapse mechanism due to bending failure. On the other hand the probability of shear failure occurrence is small for low piers' slenderness.

In this study, dynamic tests of 12 bridges located on Samsun-Kalin railway were carried out. These bridges were selected among 41 historical bridges on the railway route and they form a representative group of all the bridges in terms of masonry type, height, total length, span number and span length. In order to identify the dynamic properties of the bridges and create representative FEM's of bridges for performance assessment, dynamic tests were conducted. Modal parameters such as modal frequencies, mode shapes, and damping ratios were determined from vibration data recorded during ambient conditions, train passage, and impact loading and FEM's of bridges were updated based on identified modal parameters. Seismic performance assessment was carried out by pushover analysis due to its simplicity in computation time compared to non-linear time history analysis.

In the rest of the paper, just one of the bridges is focused to present the dynamic test, FEM updating, pushover analysis, and strengthening.

2 SYSTEM IDENTIFICATION

Modal identification allows obtaining dynamic parameters such as frequency, shape and damping ratio. These dynamic parameters were identified by Enhanced Frequency Domain Decomposition algorithm.

Vibration measurements were carried out under ambient conditions, impact and train passage (free vibration of the bridge after train passage were analyzed). These three cases represent broadband excitation of the bridge at different excitation levels. Modal frequencies and shapes were identified based on ambient vibration measurement. Damping ratios were obtained based on train passage and hammer impact loading as they give higher level of excitation.

2.1 Description of bridge and sensor layout

Figure 1 shows the overview of the bridge and Table 1 represents physical properties of the bridge in terms of span properties, total length, and height.

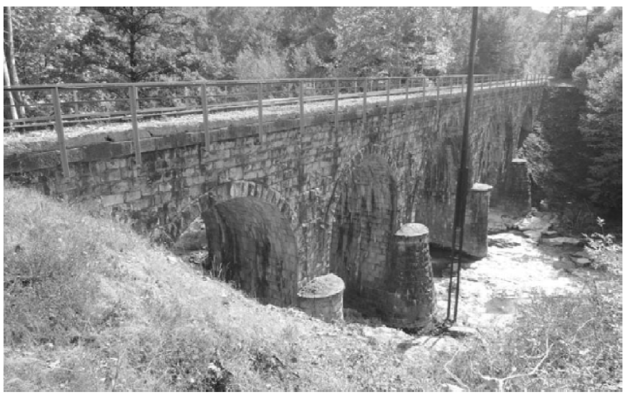

Figure 1. Overview of the bridge

Table 1.Pyhsical properties of bridge

Span (m)	Total Length (m)	Height (m)
2x6+2x10+6	38	12.30

Vibration data was recorded during ambient conditions, train passage, and hammer impact loading by using accelerometers in transverse, longitudinal, and vertical direction. Sensor layout was represented in Figure 2.

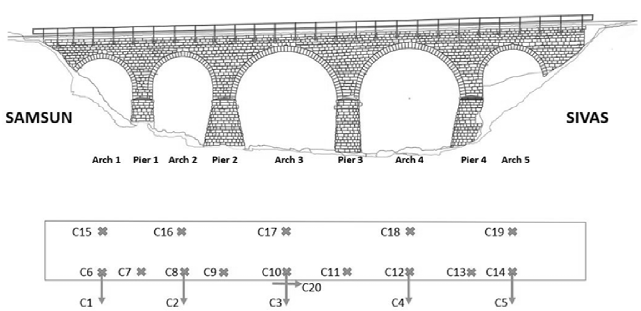

Figure 2. Sensor layout

2.2 Dynamic test results

These dynamic parameters were determined from vibration data by Enhanced Frequency Domain Decomposition algorithm. Figure 3 shows the power spectral density of the acceleration response and Figure 4 presents the mode shapes of the bridge. Modal frequencies and damping ratios were summarized in Table 2.

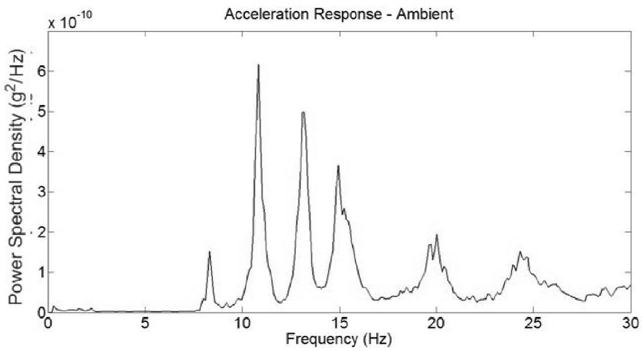

Figure 3. Power spectral density of ambient vibration response

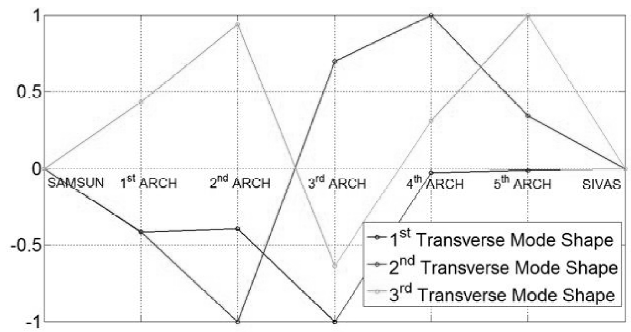

Figure 4. Identified transverse mode shapes

Table 2. Modal Frequencies and damping ratios

Mode	Shapes	Frequency (Hz)	Damping (%)
1	1st Transverse	8.31	1.40
2	2nd Transverse	10.84	1.97
3	3rd Transverse	13.18	2.04
4	1st Longitudinal	14.94	2.83
5	1st Vertical	20.02	2.89
6	2nd Vertical	24.32	4.82

3 FEM UPDATING

FEM updating procedure was performed based on minimizing the difference between experimental and analytical modal values. The main purpose of FEM updating was to obtain Young's modulus and soil spring constants of the bridges. Decoupling of modes in linear analysis demonstrated that the first three transverse modes and first two vertical modes produced significant portion of seismic force. Therefore, the first three transverse modes and the first two vertical modes were adequate to be considered in updating procedure. The weighing coefficients were chosen according to the modal participation factors of corresponding modes.

Young's modulus of the bridge materials and soil spring constants of non-updated model were 7.80 GPa and 75000 kN/m respectively. These values were chosen according to existing knowledge in literature. Identified, non-updated, and updated modal frequencies of the bridge and related material properties and soil spring coefficients were represented Table 3 and Table 4, respectively.

Table 3. Comparison of modal frequencies

Mode Shapes	Non-Updated Frequency (Hz)	Updated Frequency (Hz)	Identified Frequency (Hz)
1st Transverse	3.28	7.40	8.31
2nd Transverse	5.79	10.84	10.84
3rd Transverse	9.29	15.33	13.18
1st Vertical	12.95	23.38	20.02
2nd Vertical	13.80	25.64	24.32

Table 1. Non-Updated and updated FEM parameters

Parameter	Non – Updated Model	Updated Model
Material Modulus of Elasticity (GPa)	7.80	14.05
Vertical Spring Coefficient (kN/m)	75 000	Fixed
Horizontal Spring Coefficient (kN/m)	37 500	Fixed

4 SEISMIC PERFORMANCE ASSESSMENT

Seismic performance assessment of the bridge was carried out by pushover analysis. Based on FEM updating, stiffness values were determined as presented in Table 4. Based on material tests, tensile and compressive strength of mortar was obtained as 0.8 MPa and 56.4 MPa respectively. Unit weight of masonry was 25.4 kN/m^3. Material nonlinearity was considered to be elastic-perfectly plastic with tensile and compressive strength values given above.

Performance targets for the bridge were determined as ‘minimum damage performance level’ (no or very limited structural damage. It requires operational continuity for the structure or permits some minor structural damages which should be repaired in a few days) for D1 (50% probability of exceedance in 50 years) and ‘controlled damage performance level’ (limited and repairable structural damages after an earthquake. There can be operation interruption for a few days or a few weeks) for D2 (10% probability of exceedance in 50 years) earthquake levels.

The bridge structure was recorded in situ by means of 3D laser scanning devices for the purpose of generating orthogonal-photographic real images of the façades and plan views by utilizing special software. The ortho-photo images were inserted into AutoCAD drawing file in 1:1 scale to be used for geometrical information. The detailed analysis of the masonry arch bridge is performed by 3D structural modeling based on finite element method using the Midas Civil & Midas FEA computer software. The 3D image of FEM is given in Figure 5.

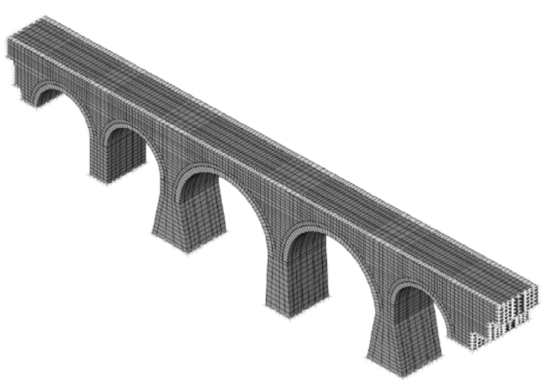

Figure 5. Finite Element Model of the Bridge

Seismic performance assessment of the bridge was carried out by means of mass proportional pushover analysis and control node was selected as the centre of mass at the upper level of the arch barrel. After obtaining pushover curve, bilinear relation was plotted as shown in Figure 6.

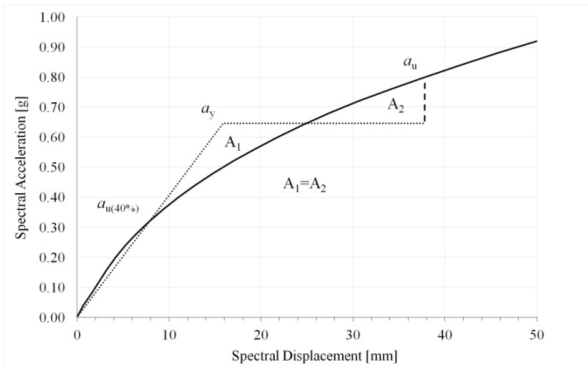

Figure 6. Bilinear representation of capacity curve

Figure 7 shows design spectra obtained based on seismicity of the site and soil class-class A. Design spectra were in compliance with the criteria set forth in Technical Earthquake Regulation Concerning Construction of Coastal and Port Structures, Railroads, Airports by the Ministry of Transport, Maritime and Communication, DLH-2008.

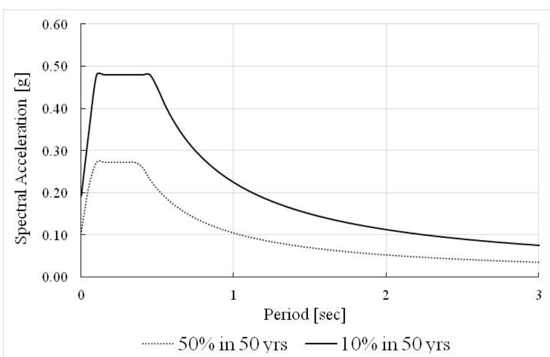

Figure 7. Design Response Spectra

After obtaining capacity and demand curves, performance point was determined based on these curves as shown in Figure 8.

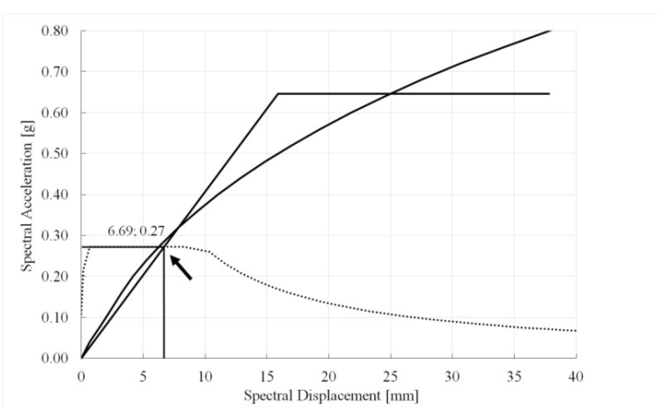

Figure 8. Determination of performance point

Following the determination of performance point, stress distribution throughout the structure along the global x and z directions, was checked to evaluate the condition of arch barrels, piers, abutments or spandrels. Based on these checks, stresses over tensile strength of mortar (dark regions in the figure) on the spandrel wall extends along the arch span which is expected to result with a partial failure from the bridge as shown in Figure 9. Therefore, the spandrel wall is assumed to be inadequate.

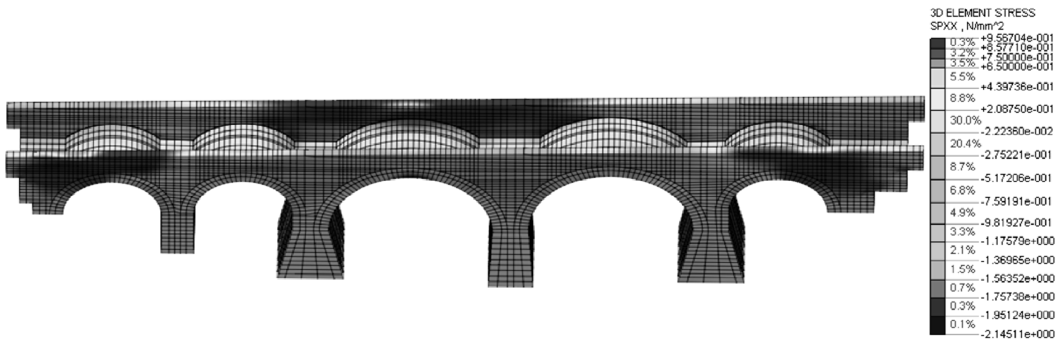

Figure 9. Stress distribution at performance point

5 STRENGTHENING

As shown in previous section, spandrel walls are exposed to tensile stresses at limit value with an influenced region that points out partial failure allowing displacement of the fill, although compressive stresses are within the limits. Therefore, inner face of spandrel walls were decided to be strengthened by a FRP reinforced mortar matrix considering it provides ductility and deformation capacity to the spandrel walls.

In the current phase of the project, only analytical investigation of strengthening methodology has been completed. Based on this conceptual study, strengthening at site will be performed as follows: after removing the fill, the spandrel walls will be injected by salt-resistant hydraulic binder based on lime and eco-pozzolan to consolidate the masonry. The inner face of the spandrels will be flattened and covered by cement-free pozzolanic mortar made from natural hydraulic lime. The mortar layer will be reinforced with alkali resistant glass fibre mesh which can be fastened in place with a connector using a chemical anchoring. This connector will help to prevent the strengthening strip splitting off the spandrels. The strengthening details will be applied along the spandrel walls with a thickness of approximately 4 cm and will be embedded at the abutments. The arches will be strengthened on the extrados and a layout of 50 cm strengthening strip will be required on the backing to provide anchoring.

Strengthening concept is based on the fact that tensile strength of glass fibre mesh will contribute the stability of the spandrels with the help of connectors. The tensile stress at the spandrel walls will be transferred to the composite material limited by the tensile strength of the material. The connectors will help the strengthening strip fasten to the spandrels and glass fibre mesh will keep spandrel walls in place in case mortar of the masonry suffers damage.

FEM of strengthened bridge was developed with the mechanical propertied of the FRP reinforced mortar. Afterwards, pushover analysis was carried out as explained before and stress distribution at the performance point was investigated. Figure 10 shows that any probable failure will not occur at the spandrel walls for the earthquake level D1. The assessment of the stress distribution at the strengthening strip supports the conclusion on the structural condition of the spandrels.

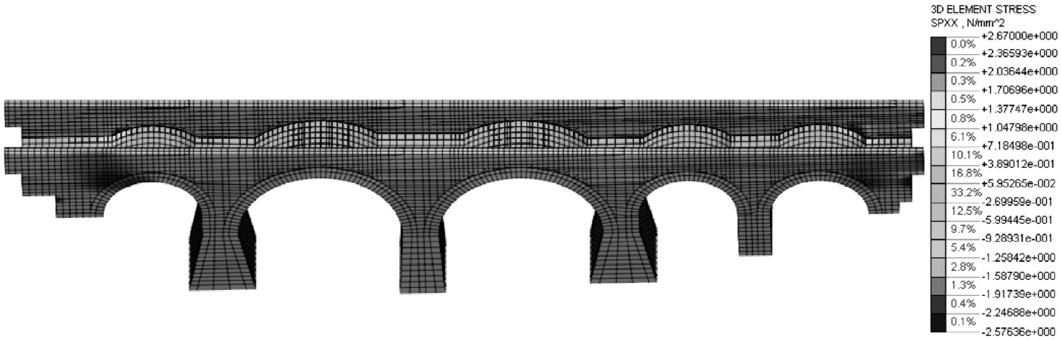

Figure 10. Stress distribution at performance point of strengthened bridge

6 CONCLUSION

This paper presents the summary of a comprehensive project on seismic performance assessment of historical stone arch bridges on Samsun – Sivas railway line. Stone arch bridges have significant structural uncertainties as other historical structures. It was seen that modal values based on material properties obtained from literature or material testing may give significantly different values than the actual ones. Therefore, dynamic identification and FEM updating of these bridges were carried out to obtain more representative FEM and carry out more reliable seismic assessment.

After obtaining updated FEM, seismic performance assessment of the bridges was carried out by pushover analysis. It was seen that there was no global structural deficiency i.e.no significant strength overcome on piers and arches of all bridges on the line. On the other hand, structural deficiencies were observed on spandrel walls for bridges with wider arches and higher seismic demand. In the project, 12 out of 41 bridges were in need of strengthening on their spandrel walls and this paper presents one of these bridges. For the bridges with structural deficiency, FRP reinforced mortar was chosen as the strengthening methodology.

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