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Assessment of seismic behavior stone bridge using a finite element method and discrete element method

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Abstract. Seismic behavior of Osmanli and Senyuva stone bridges was addressed in this study. A combination of FEM and DEM was employed for getting closer to the real behavior of the bridge. One of the unique features of this combinational method is simulation close to reality. Modal numerical analysis was also used to verify the modeling. At the end of earthquake, a part of two lateral walls of Osmanli bridge was broken. The growth of arch cracks also increased during the earthquake. A part of right-hand wall of Senyuva Bridge was destructed during the earthquake. The left-hand side of the bridge wall was damaged during the earthquake but was not destructed.

Keywords: FEM; earthquake; bridges; simulation; seismic

1. Introduction

Historical bridges have artistic and architectural importance in human societies. Natural disasters such as flood and earthquakes have threatened these historical structures (Hacıefendioğlu and Koç 2016). Proposed project for structure retrofit and modification of bridge base soil has resulted in improvement of seismic behavior of Bosset Bridge. After the powerful earthquake in 2014 in Cephalonia Island, not damages have been seen in Bosset Bridge; therefore the seismic performance of the bridge was satisfying after the reinforcement and reconstruction process (Rovithis and Pitilakis 2016). Palu earthquake components which happened in 1978, was used for seismic analysis of Palu Bridge. The bridge was weak along the arch-perpendicular direction, therefore for investigation of seismic behavior, dynamic load of the earthquake was applied in the direction vertical to the bridge arch (Gonen *et al*. 2013). For real scale stone bridge analysis Non-Smooth Contact Dynamic (NSCD) method was employed. NSCD is a discrete element method. In (Rafiee and Vinches 2013) reverse analysis method was used for investigation of stone bridge damages. Reference (Conde *et al*. 2016) applied GPR method for obtaining the information and investigation of the internal features of arch bridge. The Derived information could be helpful for engineers and researchers. In (Solla *et al*. 2012) several numerical strategies were proposed for investigation of the nonlinear behavior. A non-commercial code and commercial software of FE was used for nonlinear analysis of the bridge. In (Reccia *et al*. 2014) the effects of stone bridge reinforcement were investigated by finite element method. Bridge reinforcement by polyurethane can distribute the train load better; therefore it can reduce the pressure on the arch. This method is a proper technique for stabilization of stone bridge (Thomas *et al*. 2015). Stone bridge is an important part of road and railways in Mediterranean regions. The maintenance costs of stone bridges are relatively higher than steel and concrete bridges. High weight of stone bridges can reduce the strength of the structure; finally, for making sure on the safety of the stone bridges, numerical analysis was used (Bergamo *et al*. 2015). Through application of FEM and DEM numerical methods, the load bearing capacity of the stone bridge was investigated. Modal experimental studies were used for verifying the validity of the numerical method (Costa *et al*. 2015). To reconstruct a stone bridge in Spain, photogrammetry earth technology was employed. Several FEM models were also applied for investigation of the real behavior of the bridge. Results showed that the reason for arch damages is the increase of forces and displacements in bridge support (Stavroulaki *et al*. 2016). Although this bridge was constructed 100 year ago, it is still working, in this regard, it is one of the important components of transportation. Human societies have reconstructed stone bridges. Experimental tests were used for investigation of the integrity in a reconstructed bridge in Turkey. FEM method was used for investigation of bridge behavior (Cakir and Seker 2015). To evaluate the seismic behavior of the stone arch, non-smooth contact dynamics method was employed. NSCD method was also used for simulation of seismic behavior of Arles aqueduct (Rafiee *et al*. 2008b, 2008a) Stone bridge is composed of walls and base. Due to complexity of bridge's material and geometry, it is not possible to obtain the accurate dynamic properties from the numerical methods. In this regard, modal experimental analysis was used for obtaining the dynamic features of

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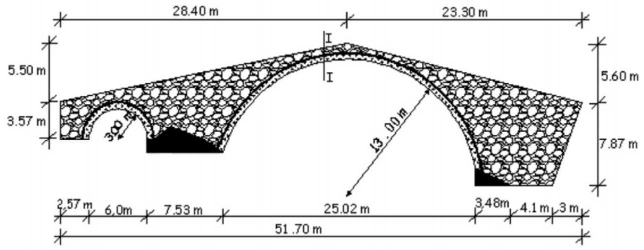

Fig. 1 Stone arch bridge geometry osmanli (Sevim *et al.* 2011)

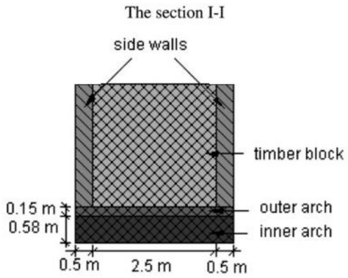

Fig. 2 Stone arch bridge geometry osmanli (Sevim *et a*l. 2011)

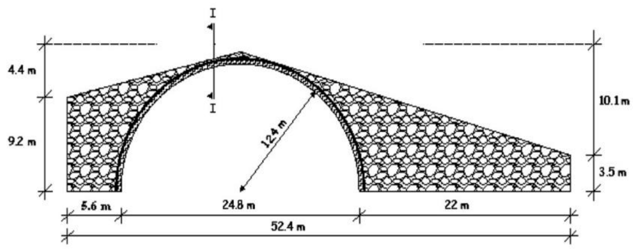

Fig. 3 Stone arch bridge geometry senyuva (Sevim *et al*. 2011)

stone bridges. EFDD and SSI methods were used for modal experimental analysis of the bridges (Bayraktar *et al*. 2015).

2. Stone arch bridge geometry

Osmanli Bridge is situated near Black Sea, it has two arches with 25.2 m and 6 m. the total length of the bridge is 51.7 m. The bridge is composed of lateral wall and timber block with the sizes of 0.5 and 2.5 m, respectively (Figs. 1 and 2). Senyuva Bridge was constructed in 1696 with the length of 52.4 m. the thickness of lateral wall and timber block is 0.5 and 2.5 m, respectively (Figs. 3 and 4). Both bridges were made out of the same materials, Table 1 (Sevim *et al*. 2011)

3. Finite element model calibration of the osmanli Arch Bridge

Two numerical and experimental methods were used for investigation of the seismic behavior of the stone bridge. Environmental vibrations were used to reach to the vibrational state (Sevim *et al*. 2016). In this study, it was tried to provide an accurate modeling of Osmanli Bridge. Calibration of the finite element model with the experimental results can result in validity of numerical methods. Experimental modal analysis of the bridge by SSI

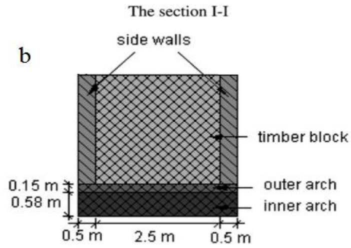

Fig. 4 Stone arch bridge geometry senyuva (Sevim *et al*. 2011)

Table 1 Material properties

Material	Modulus of elasticity (N/m2)	Poisson ratio	Density (kg/m^3)
Stone arches	3.0E9	0.25	1600
Timber block	1.5E9	0.05	1300
Side walls	2.5E9	0.20	1400

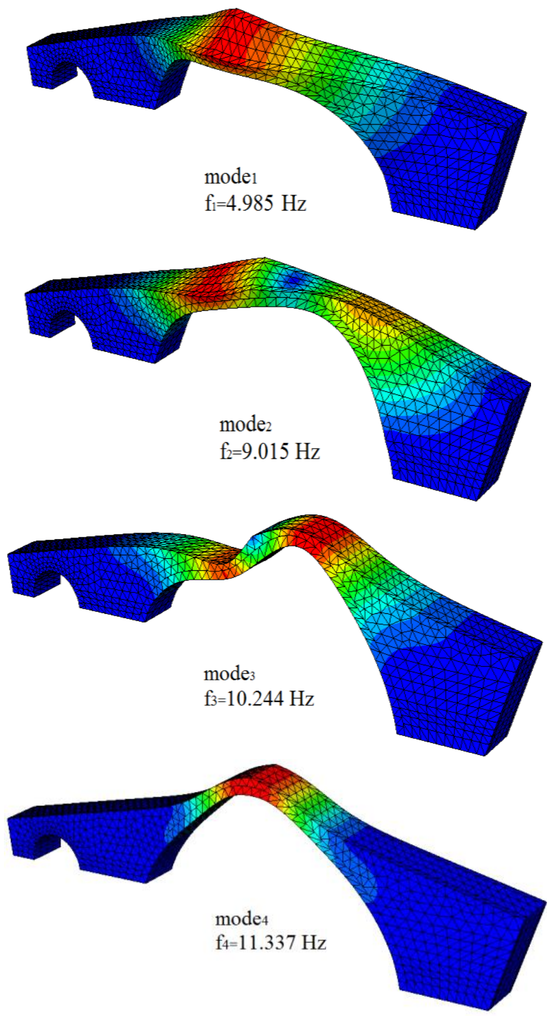

Fig. 5 Five mode calibrated frequencies of the osmanli Arch Bridge

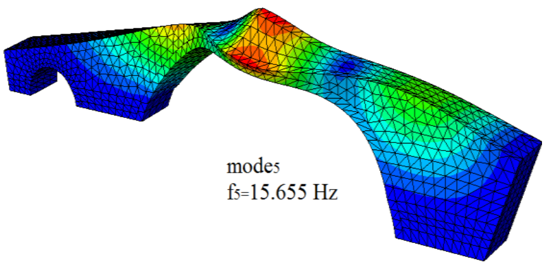

Fig. 5 Continued

Table 2 Analytical and experimental natural frequencies of the osmanli Arch Bridge after model calibration

Mode Number	Calibrated Analytical frequencies (Hz)	Experimental frequencies (Hz) EFDD	SSI	Max. difference After Calibrated
1	4.985	4.640	4.642	7%
2	9.015	8.094	8.325	8%
3	10.244	9.879	9.735	3.5%
4	11.337	12.340	11.910	4.8%
5	15.655	15.840	15.420	1.5%

and EFDD method was performed by Sevim Baris et al. for validation of the FE model; the experimental results of Sevim Baris et al were used. 86437 elements C3D10 was used for modeling Osmanli Bridge. The boundary conditions were considered constant. After updating of the FE model, the obtained natural frequencies were close to the natural frequencies obtained from the experimental method Fig. 5. After calibration of the finite element model, the maximum difference between the numerical and experimental model was less than 8%, therefore the created FE model is reliable, Table 2.

4. Finite element model calibration of the Senyuva Arch Bridge

To evaluate the seismic behavior of Senyuva Bridge and making sure on the accuracy of the modeling, it is necessary to compare the numerical results with experimental ones. In this regard, vibrational test results of the bridge was employed. Finite element model was made by application of ABAQUS software. The bridge model was created from 74752 C3D10 elements. After calibration of FE model, natural frequency ranged between 3.9-11.917 Hz. The validity of the model was verified through comparison of experimental and numerical results. Fig. 6. After updating of finite element model, the maximum difference between the numerical and experimental results was 6.23% which is acceptable, Table 3.

5. Seismic analysis of Arch Bridge

5.1 Earthquake

In this study, Erzincan earthquake (1992) was used. The east-west component of the earthquake was used for

Table 3 Analytical and experimental natural frequencies of the Senyuva Arch Bridge after model calibration

Mode Number	Calibrated Analytical frequencies (Hz)	Experimental frequencies (Hz) EFDD	SSI	Max. difference After Calibrated
1	3.91	4.045	4.066	3.3%
2	7.96	7.750	7.960	0.0%
3	8.3	8.020	8.044	3.18%
4	10.73	10.000	10.100	6.23%
5	11.917	12.160	11.750	1.9%

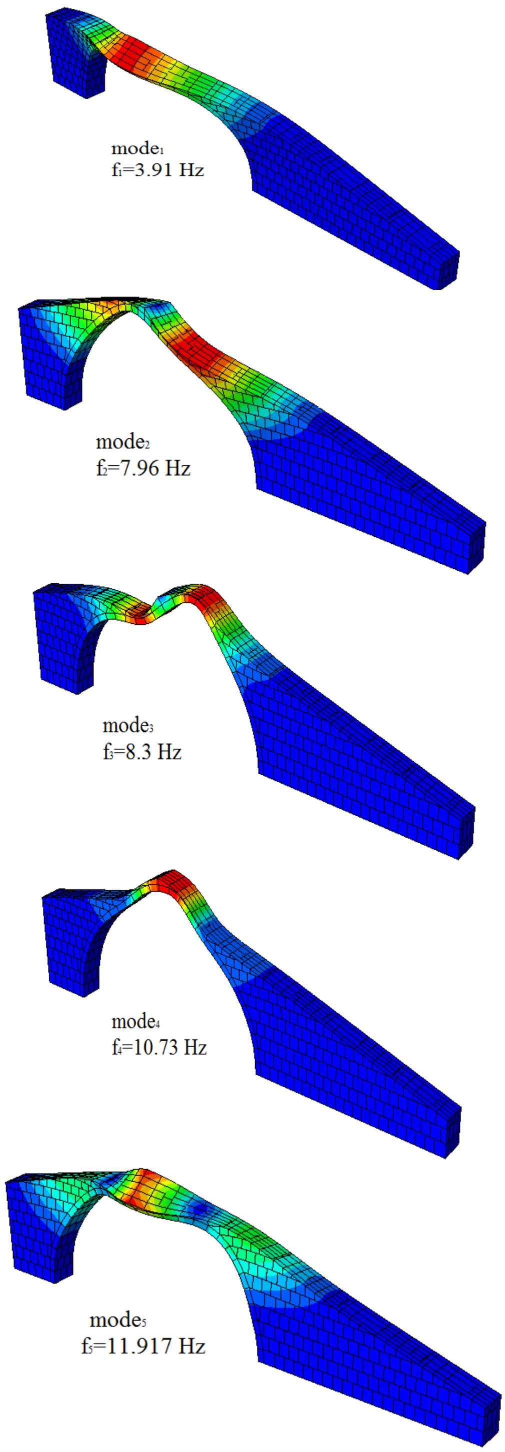

Fig. 6 Five mode calibrated frequencies of the Senyuva Arch Bridge

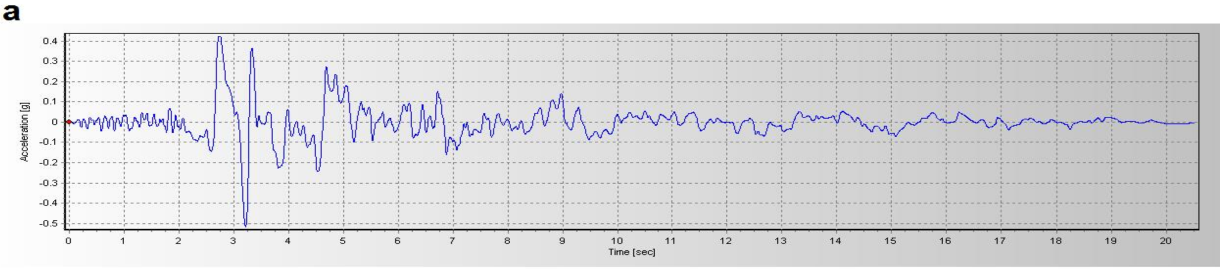

Fig. 7 Seismic acceleration

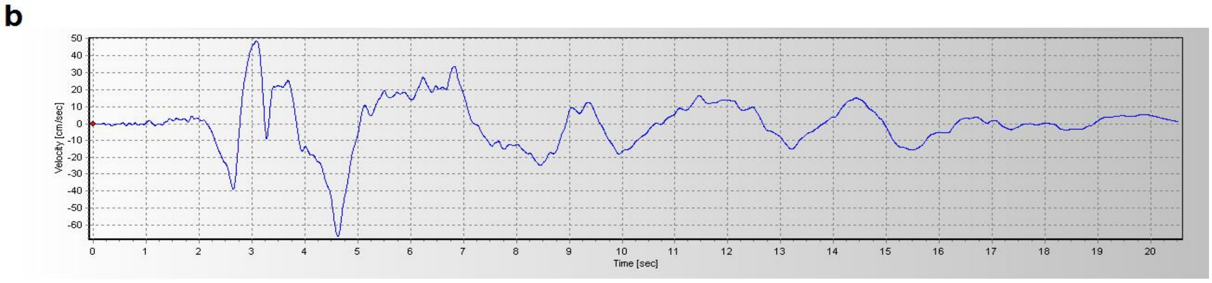

Fig. 8 Seismic velocity

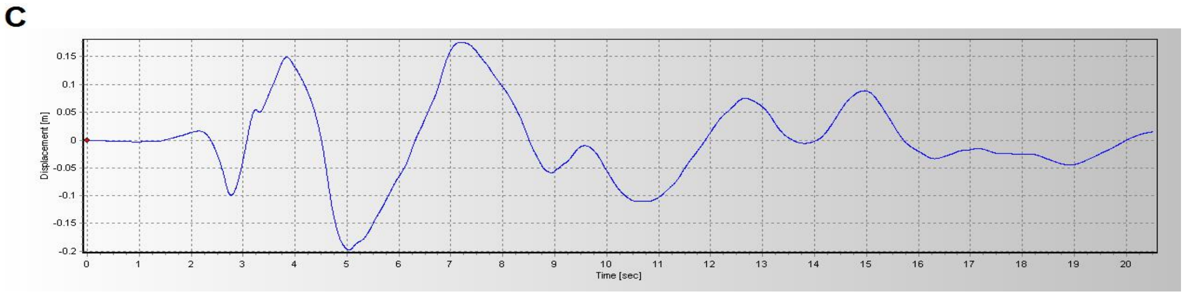

Fig. 9 Seismic displacement

dynamic seismic analysis. The seismic data was derived from siesmosignal software in which the earthquake acceleration was used. Due to weakness of the bridge along the arch-perpendicular-direction, earthquake loading was performed along the direction perpendicular to the arch; therefore, the destruction of bridge structure will be more than the other types of loading. Here, 7.6 s earthquake was used Figs. 7 to 9.

5.2 Seismic behaviors of osmanli Arch Bridges

In this study, it was tried to provide an accurate evaluation for seismic behavior of Osmanli Bridge. In this regard, authors tried to simulate the close-to-reality behavior of the bridge structure. Bridge simulation was performed by combination of FEM and DEM. Application of this combinational method provides information on damages and destructions of different parts of the structure. Recently, application of combinational method have been developed, for simulation of Osmanli Bridge, 86437 C3D10M elements were employed. Dry friction was also used to model the intra-block behavior. Friction coefficient of 0.7 was considered between the blocks. At the beginning of the earthquake, the right wall of the bridge cracked, at *t*=5.7 s, some of the blocks of right wall fell and finally some blocks of both walls destroyed, Fig. 10 is for

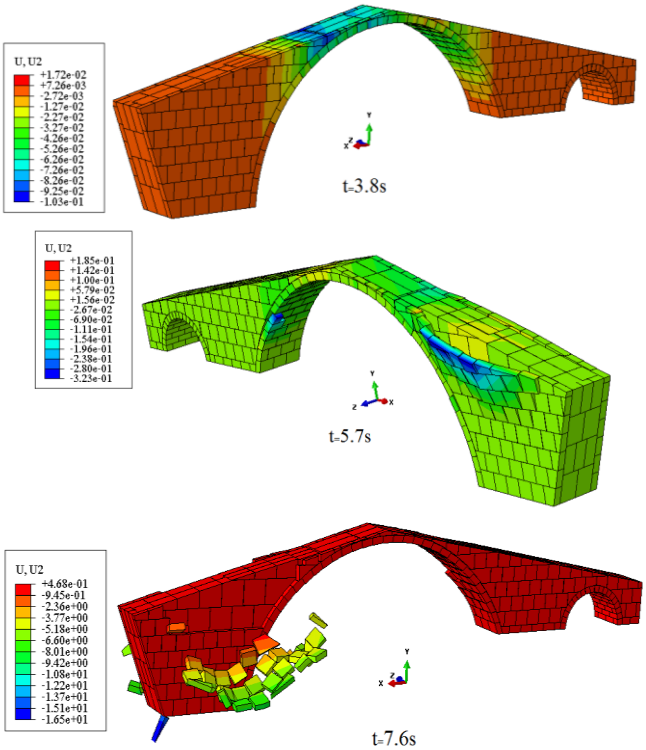

Fig. 10 Bridge deformation after the earthquake the past time

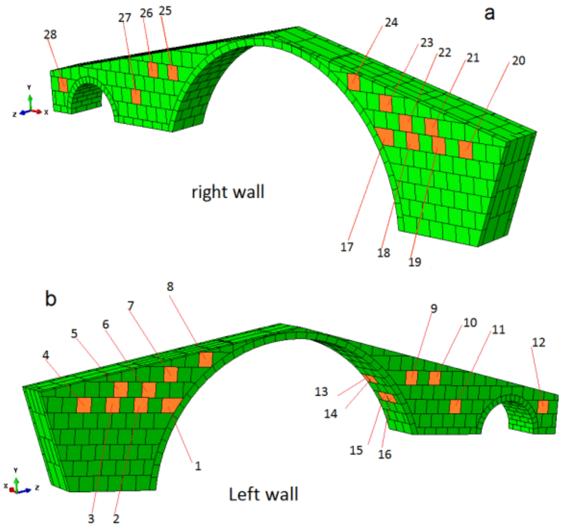

Fig. 11 Numbering block of osmanli arch bridge

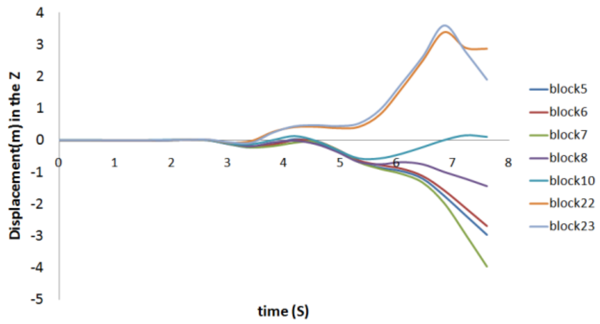

Fig. 12 Displacement(m) in the *Z* direction of the wall of bridge

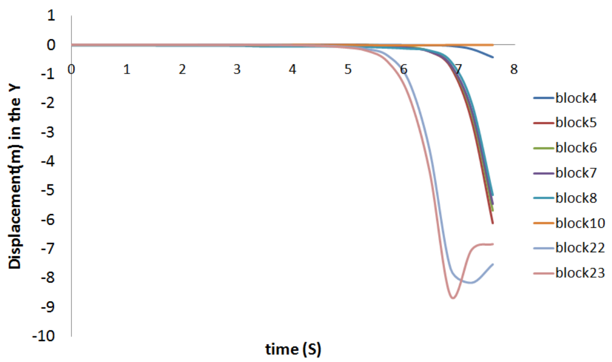

Fig. 13 Displacement(m) in the *Y* direction of the wall of bridge

evaluation of the results of the labeled blocks. Fig. 11 the blocks of the both sides were thrown to maximum distance of 4 m. Fig. 12 the beginning of bridge destruction was on *t*=5.7 s. some of the blocks fell. Fig. 13 some cracks were also created during the earthquake Fig. 14.

5.3 Seismic behaviors of Senyuva Arch Bridges

Through double-stage analysis, seismic behavior of stone bridge was addressed. At the first stage, static nonlinear analysis was compared with 84 nonlinear dynamic analysis. In the second step, control points were

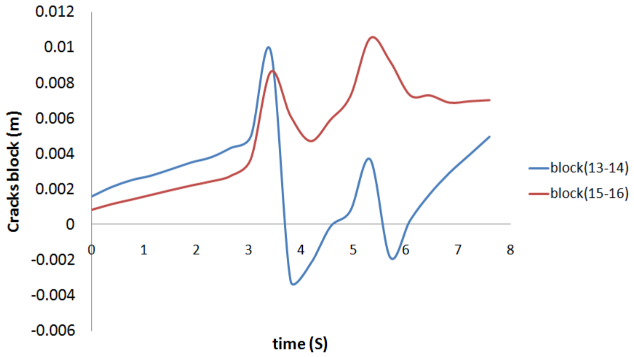

Fig. 14 Cracks (m) between the blocks

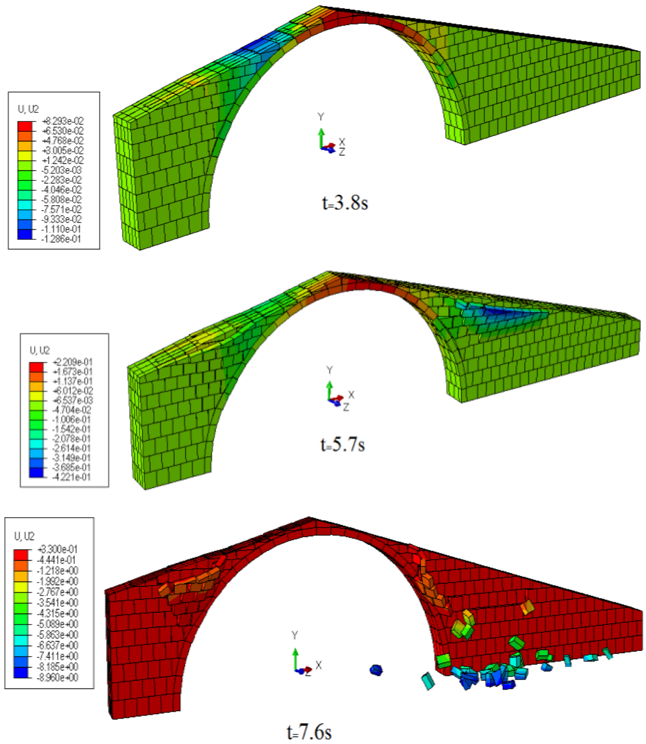

Fig. 15 Bridge deformation after the earthquake the past time

selected in the finite element for determination of bridge seismic capacity. (Pelà *et al*. 2013) for further investigation of seismic behavior of Senyuva Bridge, a combination of FEM and DEM was employed; whose advantage is accurate prediction of bridge seismic behavior. Overall, 74752 C3D10M elements were used for modeling the Senyuva Bridge. This element is A10-node modified quadratic tetrahedron type. Friction was used for modeling the behavior of the blocks. The friction coefficient was 0.7. After 5.7 seconds, a part of right wall of the bridge started to fall and the left wall damaged but was not destroyed. In Fig. 15, some of the lateral wall blocks and arch were labeled for further understanding of bridge seismic behavior. In Fig. 16, after 4 seconds from the earthquake, the lateral wall blocks were thrown in *z* direction. Fig. 17 some part of the right lateral wall had failure after *t*=5.6 s. in Fig. 18, observable cracks can be seen in the bridge arch the largest crack is about 5 cm Fig. 19.

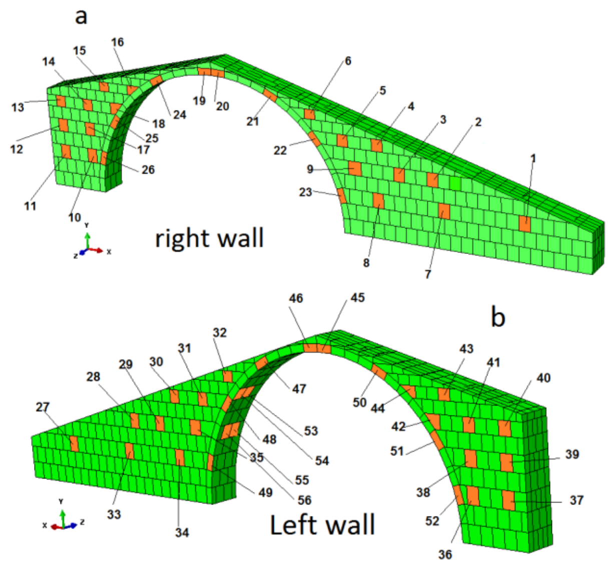

Fig. 16 Numbering block Senyuva arch bridge

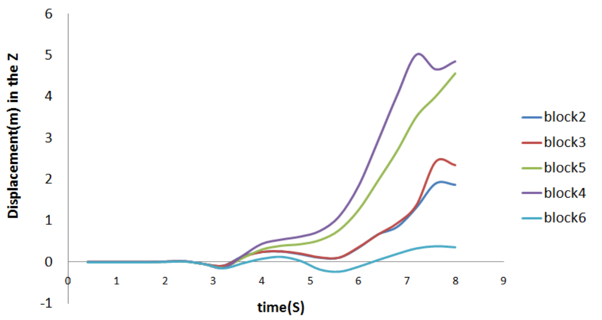

Fig. 17 Displacement(m) in the *Z* direction of the right wall of bridge

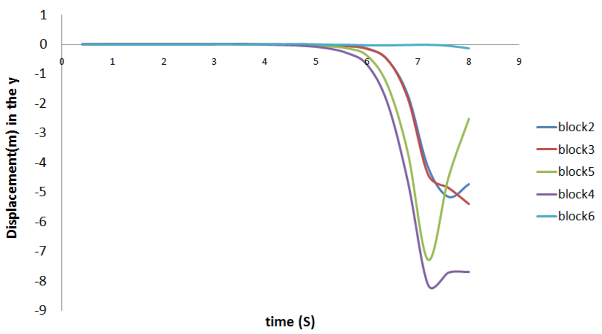

Fig. 18 Displacement(m) in the *Y* direction of the right wall of bridge

6. Conclusions

Protection and maintenance of the stone bridges are one of the most important programs in the societies which is impossible without precise evaluation of bridge structure. Therefore the aim of this study was to investigate the seismic behavior of the bridge. Nonlinear dynamic analysis was used for simulation of seismic behavior of the bridge. Regarding the complexity in mechanical features and geometry of the bridge, precise evaluation of seismic behavior is a difficult task. Therefore, experimental analysis

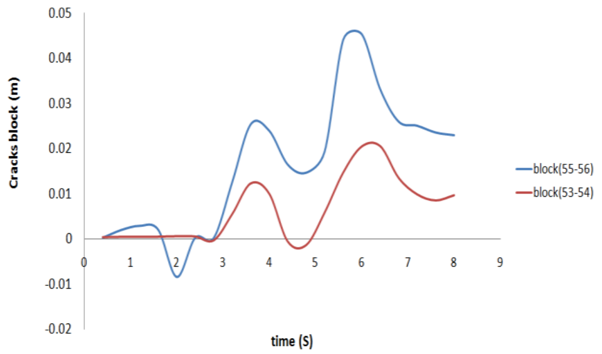

Fig. 19 Cracks (m) between the blocks

was used to increase the modeling precision.

• Bridge numerical modeling was used by combination of FEM and DEM. This combinational method is a powerful tool for crack and failure simulation. Friction was also used to increase the precision of analysis

• For accurate simulation of Osmanli Bridge seismic behavior, combination of FEM and DEM was used. After 5.7 s from the earthquake the creation of cracks started in both lateral walls. At the end of the earthquake, cracks were created in the arch which is about 1 cm. due to the applied acceleration. The blocks would be thrown away.

• Discrete simulation was used for simulation of Senyuva Bridge. A part of right lateral wall was destroyed during the earthquake. The left lateral wall also damaged but was not destroyed. The blocks of the right wall were thrown along z direction. The growth of arch cracks increased during the earthquake and the maximum crack had the side of 4.5 cm.

• According to the results of numerical studies, combination of FEM and DEM is an efficient technique. Seismic capacity of both bridges was determined based on the results of numerical studies. It is recommended to reinforce both bridges against the earthquakes.

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