EVALUATING THE LINEAR AND NONLINEAR BEHAVIOUR OF A THREE SPAN STONE ARCH BRIDGE IN AKSARAY, TURKEY

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SUMMARY

Turkey is one of the oldest settlements all over the world due to its geographical location. Still existing historical structures in Turkey were commonly constructed with durable materials as cut stone. In this paper, the general information about stone arch bridges in Turkey is presented and a sample case study is performed on a Stone Arch Bridge (Nakkas Bridge) which located at Aksaray city centre. The bridge was restorated about a year ago. Restoration details and illustration photos are also discussed and presented. Finite Element Method is used for modelling of the bridge. Linear properties of the materials are used during self-weight analysis. Besides, nonlinear properties of the materials are used during nonlinear-static loading. Detailed information about restoration works and results from Finite Element Analyses are discussed and useful suggestions are given in the conclusion part.

Keywords: *Nakkas Bridge, Finite Element Method, stone masonry, restoration works.*

1. INTRODUCTION

Arches were used for passing openings for a long time in the history. Big sizes of arches were used for across the rivers such as bridges. Many civilizations were using different types of bridge geometry such as has Triangular, Corbel, Roman, Horseshoe, and Segmental arch etc. These heritage structures should protect from human damages and natural disasters. To protect them from mentioned hazards, it should be well known about their structural behaviours. Nowadays, some important studies on masonry stone arch bridges have been carrying out about their structural behaviours. Solla et al. [1], Riveiro et al. [2], and Bergamo et al [3] were studied on the health monitoring and non-destructive testing systems for arch bridges. Detailed FE modelling and assessment of some stone arch bridges were studied by Costa et al. [4], Bayraktar et al. [5], and Dimitri et al. [6].

Turkey has numerous historical structures due to the geographical location and rich cultural heritage. Turkish arch bridges, built in various periods, occupy an important place among historic engineering items. These bridges were built as a result of local funding and by the labours of the local inhabitants. The oldest arch forms take us back to 3000BC at the time of Sumerians in the underground tombs near Mesopotamia [7]. But the Romans utilize the arch form in the most amazing way.

In this paper, an historical stone arch bridge, which has three spans and located in the city centre of Aksaray, is evaluated under linear and nonlinear material assumptions. The name of the bridge is Nakkas Bridge. Three different analyses are performed on two different FE models which are represented both former case (FC) and after restoration cases (ARC).

Nakkas Arch Bridge is located in the city centre of Aksaray, which is one of the three historical stone arch bridges on Ulu river. It has three pointed arch spans. Two of small arch spans were remained under the soil during the rehabilitation of the river. Original length of the bridge was about 27.42 m, width was 4.2 m according to the survey projects. Main arch has about 10 m, and the other small arches has around 7 m spans. Arches, buttresses, and spandrel walls were built with cut-stones. Cut-stones were volcanic origin tuff and they were obtained from near the province of Aksaray such as Selime and Ihlara valley. The date of construction of the bridge is not actually known. One of ancient photo about Nakkas Bridge, which was taken by Gertrude Bell in 1907 (Fig. 1) exhibited in the archive of New Castle.

Fig. 1. *Former photo token by Gertrude Bell in 1907 [8].*

The bridge was used for the city transportation due to its location. Reinforced concrete slab with some beam elements was applied on the top of the bridge in order to help urban traffic. Hot bituminous asphalt was applied for covering the RC slab to the top. Besides, some extra cantilever slabs were constituted for the pedestrian traffic. These later additions were negatively effect on the load carrying capacity of the arch bridge.

2. FORMER STATE OF THE BRIDGE

The masonry units are tuff stones as stated above. According to the Compressive Strength tests that performed by the Ministry of Transportation, the mean compressive strength value of the stone units obtained about 13.8 MPa. RC slab application can be seen from Fig. 2a and Fig. 2b. Also fill application during the rehabilitation of the river can be seen from Fig. 2c. drinking water line of the city was installed to the bridge for passing the river. The application can be seen from the Fig. 2d. It should be pointed out that, this application damage the top of the buttresses (Fig. 2d).

Fig. 2. *Former case, additions, and some damages of the bridge.*

3. RESTORATION WORKS

Restoration works were started by removing the RC slab parts from the bridge. Then, each arch was held with timber frames. After this operation, the infill part of the bridge was removed carefully. Some damaged cut-stone masonry units were replaced by the new ones according to the restoration project. The restoration works were ended with placing the new lightweight pozzolan-based filler for the infill part and completing the top of the bridge with cut-stones. Stages of the restoration works are given in the following illustrations (Fig. 3).

Fig. 3. *Restoration works of the bridge.*

4. FE ANALYSES OF THE BRIDGE

Different cases of FE analyses are performed in order to determine the structural behaviour of the bridge. All the analyses are performed using LUSAS [9] software, which able to solve linear and nonlinear structural problems. Two of FE models are created for representing the FC and the ARC. The first FE model is created considering the architectural survey projects, and second FE model is created according to the restoration project. 3d solid finite elements (HX8M) are used for the modelling. These element has 8 nodes and each node has 3 degrees-of-freedom. Number of 2311 finite elements, and number of 1676 nodes are used for the former case model. Besides, number of 2562 finite elements, and number of 1840 nodes are used for the ARC model. Created both finite element models can be seen from the following Fig. 4 and Fig. 5.

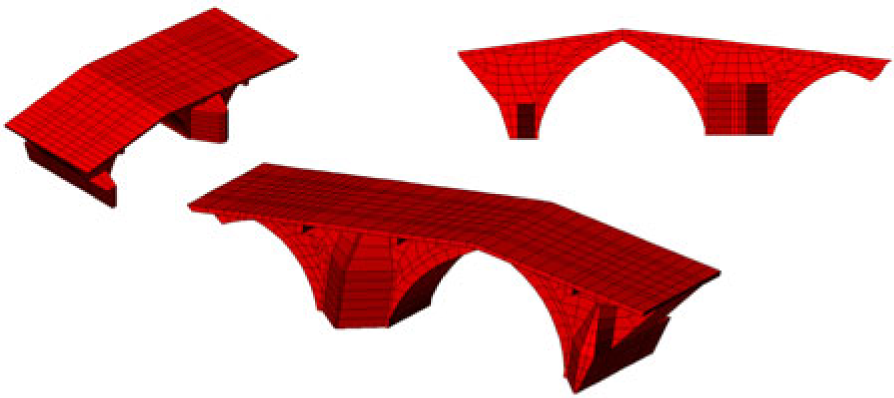


Fig. 4. *FC finite element model.*

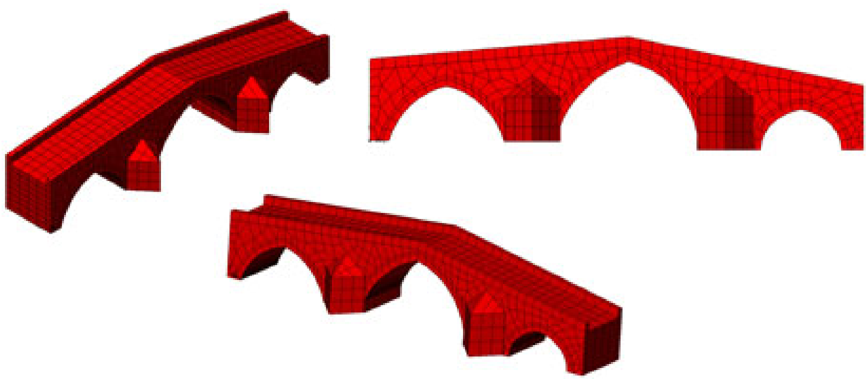


Fig. 5. *ARC finite element model.*

Masonry units were volcanic origin tuff and they were obtained from near the province of Aksaray such as Selime and Ihlara valley. According to the Compressive Strength tests that performed by the Ministry of Transportation, the mean compressive strength of the used stone units obtained about 8 MPa. Construction date of the Nakkas Arch Bridge is unfortunately unknown exactly. Some material parameters of the bridge for the both cases are collected into the following Tab. 1.

Table 1. *Material properties of the masonry units both former and after restoration cases.*

Cases	Parts of the bridge	Young Modulus [MPa]	Poisson's Ratio	Density [kg/m^3]
FC	Arch and spandrel walls	8000	0,3	1000
	Infill	7500	0,3	1800
	RC Slab	25000	0,2	2500
ARC	Arch and spandrel walls	16000	0,3	1600
	Infill	7500	0,3	1800

Drucker-Prager yield criterion is selected for the nonlinear material model. Cohesion (c) and friction angle (f) are the two parameters for the nonlinear behaviour according to the yield criterion. The most suitable values for these parameters are assumed from the literature [8] such as c = 2.80-3.70 MPa and ϕ = 25°-35°.

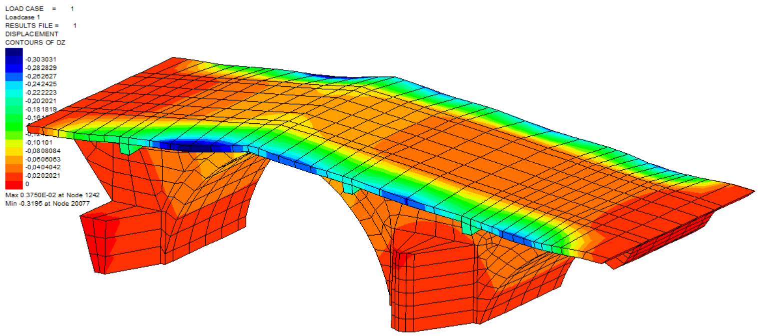
Analyses for determination of the structural performance of the Nakkas Bridge are performed both linear and nonlinear material assumptions. Three different analyses are performed for both cases such as; self-weight, flooding and transportation loadings. Analyse notations can be seen from the following Tab. 2.

Table 2. *Notations of the analyses cases.*

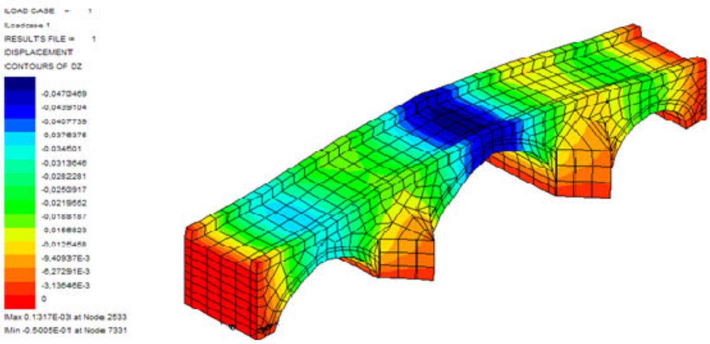
Cases	Self-Weight Analyses	Flood Analyses	Transportation Analyses
Former Case (FC)	FC-S	FC-F	FC-T
After Restoration Case (ARC)	ARC-S	ARC-F	ARC-T

Only self-weight is applied to the bridge for FC-S and ARC-S analyses. For the flood analyses, flowrate values are obtained from the Directorate of State Hydraulic Works, and static horizontal distributed loadings are calculated and applied to the upstream side of the bridge. For the transportation analyses cases, nonlinear transient analyses are performed using global distributed loading on the roadway of the bridge. Due to the limited page number of this work, only displacement contours of the analyses can be present in the following Fig. 6.

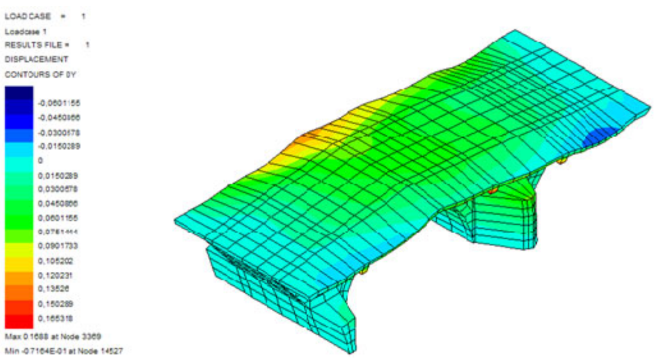
According to the results of the nonlinear analyses, maximum vertical displacements are occurred in the middle of the main arch span as shown on the following figures (Fig. 6e-6f).



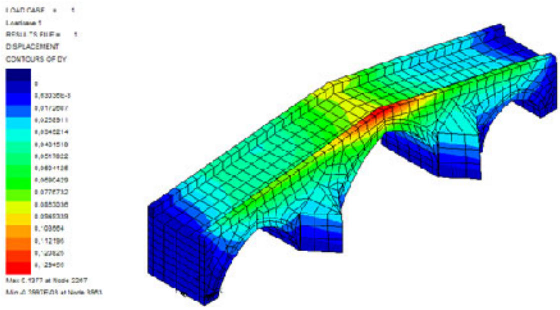
a) displacement contours of FC-S.



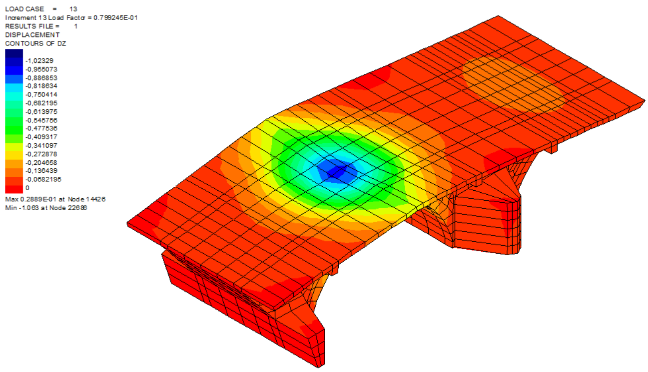
b) displacement contours of ARC-S.



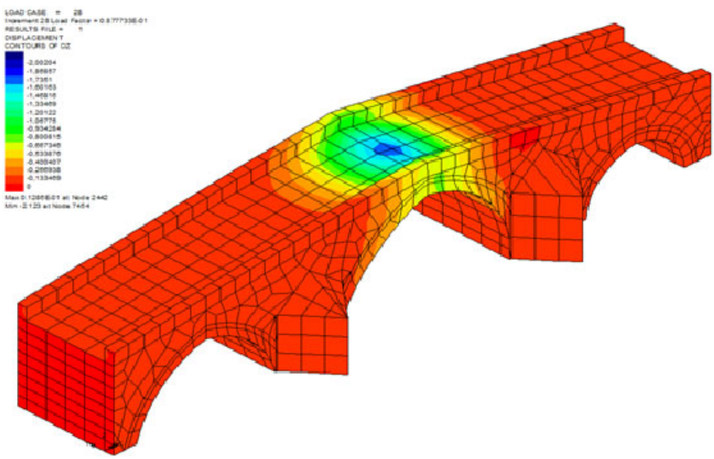
c) displacement contours of FC-F.



d) displacement contours of ARC-F.



e) displacement contours of FC-T.



f) displacement contours of ARC-T.

Fig. 6. *Some main result contours of the FE analyses.*

Table 3. *Material properties of the masonry units both former and after restoration cases.*

Case	Displ. [mm]	Stress [MPa]			Strain	
		Tensile	Comp.	Shear	Tensile	Comp.
FC-S	0.32 (Ver)	0.43	0.69	0.13	0.0000166	0.000029
FC-F	0.17 (Hor)	1.15	1.42	0.2	0.00004432	0.0000637
ARC-S	0.05 (Ver)	0.1	0.19	0.074	0.0000095	0.0000106
ARC-F	0.14 (Hor)	0.26	0.39	0.096	0.0000147	0.0000223

Though the bridge was carrying about 0.075 MPa for the former case, the load carrying capacity was becoming approximately 0.088 MPa for the after restoration case. Linear analyses results of the case studies are given collectively such as displacement, stress, and strain values.

According to the results of the finite element analyses; maximum compressive stresses are lower than the compressive strengths of the masonry units that used for the spandrel walls. Besides, there is no any problem with regards to the tensile stress and strengths excluding the FC-F model. This case shows that, the bridge would be damaged due to any flood disaster if it was not restorated.

5. CONCLUSIONS

Engineers or workers have been able to use a lot of repairing and strengthening techniques for historical structures. However, protecting the original form of the structures should be the most important mission of the constructors. Besides, if it is available, historical techniques used during the first construction of the structure should be well investigated and utilized by the workmen as well as possible to the original form of structure.

The Nakkas Arch Bridge is one of the most valuable historical structure, remained from Seljuk period, for the middle Anatolia region. It was restorated about a year ago by the General Directorate of Highways of Turkey. Restoration works were done considering the finite element analyses that subjected to this paper. Finite element analyses have to be done by the experts, and restoration works should be done under the lights of FE analyses results. Otherwise, some irreversible damages on these kind of structures occurs.

According to the analyses results and restoration works, the bridge will continue its life for a long time.

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