

DETERMINATION OF LINEAR BEHAVIOUR OF AN HISTORIC STONE ARCH BRIDGE WITH A DEVELOPING FINITE ELEMENT CODE

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SUMMARY

A finite element code named FEMMAS-L (Finite Element Analyses of Masonry Structures-Linear Approach) has been developing by the first and second authors to solve general plane stress problems with limited finite element types. The code can be run on MATLAB environment. Validations of the code were done on the second authors' PhD thesis. In this paper, a sample stone arch bridge (Bas Arch Bridge) is selected as a case study. The bridge is located in the centre of Aksaray city in Turkey. It was remained from Seljuk period. The sample arch bridge has been restored about a year ago. Detailed information about the developing code is given in this paper. Linear analyses are performed using both with FEMMAS-L and LUSAS software respectively. Results are compared and discussed from both finite element analyses. Some restoration illustrations are also given with useful discussions.

Keywords: *FEMMAS-L, stone arch bridge, Aksaray, restoration, Finite Element Code*

1. INTRODUCTION

Historical arch bridges are the most invaluable cultural heritages from past civilizations for our future. It is very difficult to understand and retrace the past civilizations., These heritage structures have been badly damaged, and most of them are totally collapsed due to many manmade factors such as treasure hunters, wars, excessive loadings, and etc. In Turkey, during these kinds of historical structures are being restored, constructors are not pay attention about the structural behaviour of them. Mostly structural analyses of the mentioned structures have not been performed. As a result, the restoration does not fit the purpose.

Certainly, stone arch bridges are one of the most valuable heritages in many countries. These structures have an important role to create a strong link between the past and the present. They all reflect the social and architectural characteristics of the constructed period. The first examples of arches were seen in the underground tombs of the Sumerians in Mesopotamia around the year 3000 BC [1]. The ancient Romans used

stone arches for large bridges and aqueducts, and the traditional of building bridges in stone continued in medieval and Renaissance Europe.

The finite element method is used to solve physical problems in engineering analysis and design. The physical problem typically involves an actual structure or structural component subjected to certain loads. The idealization of the physical problem to a mathematical model requires certain assumptions that together lead to differential equations governing the mathematical model. Since the finite element solution technique is a numerical procedure, it is necessary to assess the solution accuracy. If the accuracy criteria are not met, the numerical solution has to be repeated with refined solution parameters such as finer mesh until a sufficient accuracy is reached [2]. The method is already described in many reference books such as Zienkiewicz and Taylor [3], Hutton [4].

2. ABOUT THE FINITE ELEMENT CODE

A finite element code named FEMMAS-L (Finite Element Analyses of Masonry Structures-Linear Approach) has been developing by the writers to solve general plane stress problems with limited element types. FEMMAS-L has been written on MATLAB [5].

MATLAB is a numerical computing environment and programming language. The program allows easy matrix manipulation, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs in other languages [6]. It is essential to verify the results by commercial software during preparing a finite element code. In this study, LUSAS [7] software has used for the verification of the results getting from FEMMAS-L. LUSAS software has not only to verify results of the code, but also used to preparing finite element data of the mathematical model. This cause when preparing the codes especially for the input data, the geometrical and material properties, loading and boundary conditions of models are formatted similar with LUSAS data file as far as possible. The considered structure first modelled with LUSAS and transfer the data file to the input file of the developing program. Afterwards, the program starts to analyse the model according to the input file.

2.1. Basic algorithm

The program is benefiting from the easy commands of MATLAB. Matrices are mainly used for the input data, pre-processing and post-processing stages. The basic algorithm of FEMMAS-L is given in the following Fig. 1.

[D] elastic material matrices must be constituted to determine the material characteristics of the elements. These matrices surely constitute various types of materials according to such as working space and isotropy, etc. The program is able to recognize both isotropic and orthotropic elastic matrices for 2D and 3D finite element problems. Stiffness matrices of all elements are calculated with the assistance of the shape functions.

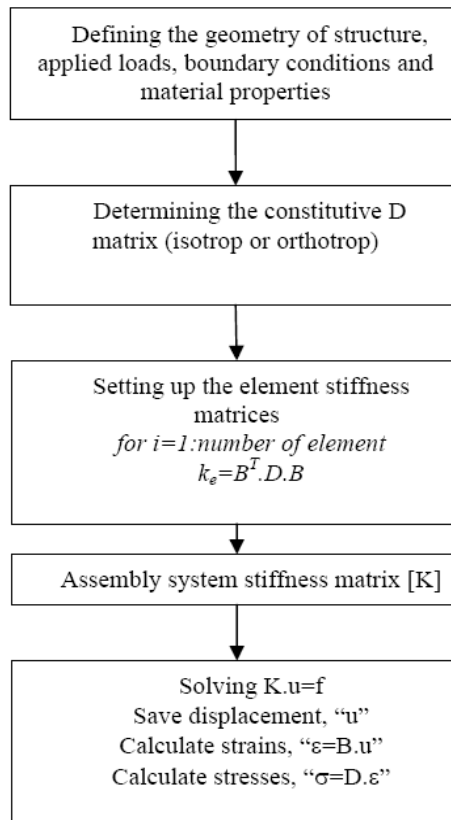


Fig. 1. Basic algorithm of FEMMAS-L.

3. A CASE STUDY: BAS ARCH BRIDGE

FEMMAS-L was applied to the Bas Arch Bridge for the case study. The bridge was restored approximately a year ago by Ministry of Transport, General Directorate of Highways, Director of Division of Historical Bridges joint with Aksaray University, Department of Civil Engineering. For the reliability, the bridge was modelled with also LUSAS software. Bas Arch Bridge is located in the city centre of Aksaray and it is one of the three ancient arch bridges on Ulu river. It has three arches in equilateral style. One of the small arches was totally and the other small arch was half filled with soil during former river rehabilitation works. According to the survey projects, original length of the bridge was around 36.8 m. and the width was around 6 m. Main arch has 10 m. span and the other small arches have 7 m. spans. While spandrel walls were built with rubble stone, other parts such as arch stones, buttresses and piers were built with cut stones. 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 9.1 MPa. Construction date of the Bas Arch Bridge is unfortunately unknown exactly.

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. These additions to the arch bridge can be seen from Fig. 2.

Another important fact about occurring damages on historical structures is vegetation. Plants can take their roots into the vertical and horizontal joints of ancient structures. As a result of this they cause terminating the adherence between mortar and masonry units, and cause some important cracks. Some vegetation on spandrel walls and buttress of the arch bridge can be seen from the same figure.

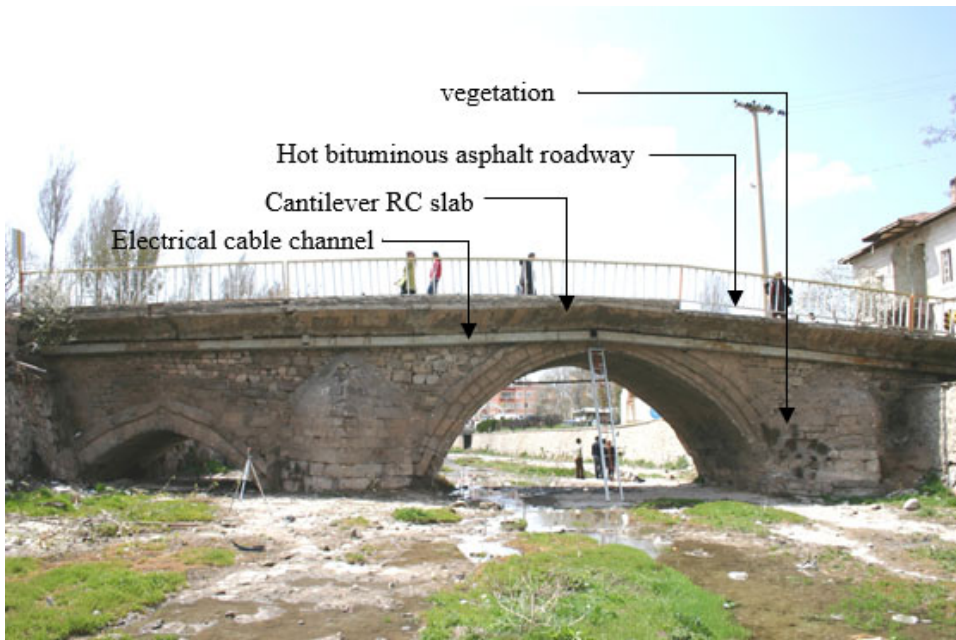


Fig. 2. Additions and vegetation on the bridge.

Some soil infills were present near the arch bridge, and they were absolutely affect the structural behaviour. Infills during rehabilitation of the stream can be seen from the Figure 3.

According to obtained photos, the former case of the bridge was in a bad condition in point of structural stability. Some explicit cracks on the lengthways of the arch were present on the main arch (Fig. 4). These cracks could be totally demolishing the bridge.



Fig. 3. Basic algorithm of FEMMAS-L.

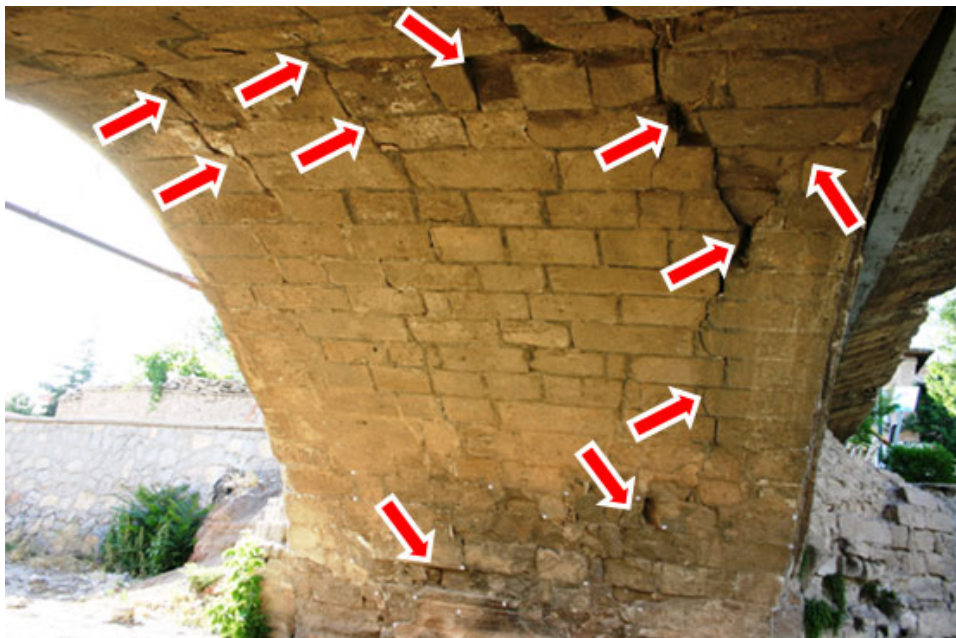


Fig. 4. Basic algorithm of FEMMAS-L.

Top RC slab was removed from the structure during the restoration works firstly. Some timber mouldings were applied for supporting the arches during the replacement of the masonry units. After this operation, new stone masonry units were placed and changed with deformed ones in spandrel walls, buttresses and arches. After forming the infill part of the structure, the restoration works were completed. These stages can be seen from the following illustrations (Fig. 5).



Fig. 5. Restoration stages of the bridge.

In the light of the LUSAS data file, two of input files were prepared. One of them was represent the former case, and the other was represent the case after restoration works of the arch bridge. Both of the models can be seen from the following Figure 6 both with LUSAS and FEMMAS-L.

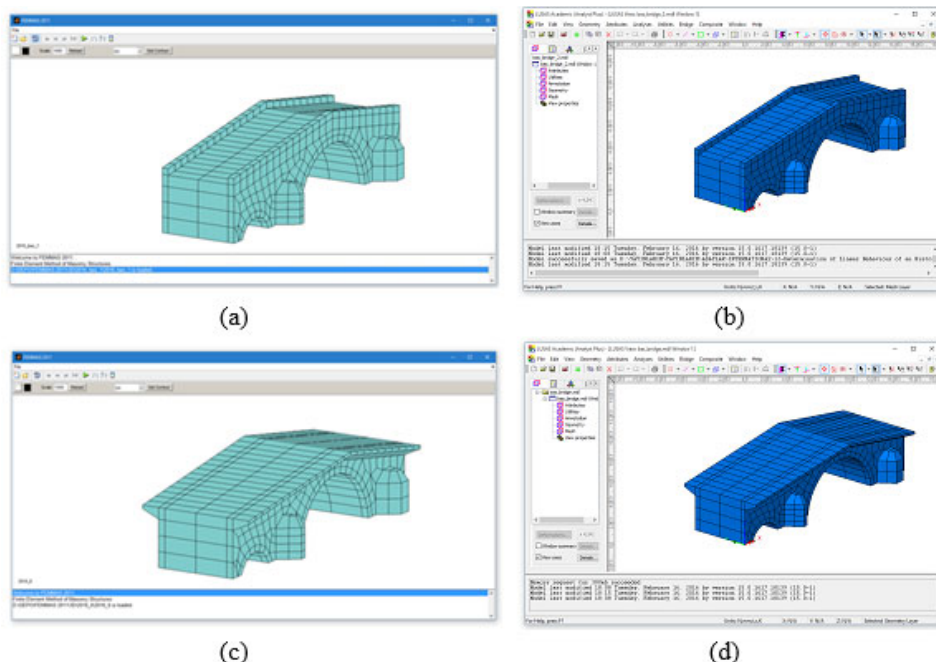


Fig. 6. FE Models of the bridge: a) FEMMAS-L, b) LUSAS models of the former case, c) FEMMAS-L, and d) LUSAS models of the after restoration case.

One difficulty on restoration works is determining the material properties of structures. However, it was not difficult for this bridge. Some sample stones were taken from the bridge and performed some material tests such as compressive strength. Besides, Young's Modulus and Poisson's Ratio were also determined from those material samples. Determined properties of the materials used for the bridge are summarised in the following Table 1.

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

	Former Case		After Restoration Case	
	Young's Modulus [N/mm ²]	Poisson's Ratio	Young's Modulus [N/mm ²]	Poisson's Ratio
Arch	4500	0,3	5000	0,3
Spandrel walls	4500	0,3	5000	0,3
Infill	2500	0,3	2500	0,3
RC slab	25000	0,3	-	-

Finite element models were considered in linear-elastic material behaviour. Only one linear static analysis was performed for this paper as under self-weight loading because of the page limitation. Results were collected on the following Table 2 from both LUSAS and FEMMAS-L with both cases.

Table 2. Results from the analyses.

	Former Case		After Restoration Case	
	LUSAS Results	FEMMAS-L Results	LUSAS Results	FEMMAS-L Results
u_x (mm)	0.012	0.016	0.019	0.02
u_y (mm)	0.009	0.019	0.009	0.018
u_z (mm)	0.079	0.076	0.085	0.072
σ_x (N/mm ²)	0.04	0.06	0.06	0.05
σ_y (N/mm ²)	0.029	0.02	0.03	0.02
σ_z (N/mm ²)	0.06	0.05	0.08	0.05
σ_{xy} (N/mm ²)	0.007	0.01	0.004	0.01
σ_{yz} (N/mm ²)	0.01	0.02	0.014	0.02
σ_{zx} (N/mm ²)	0.02	0.05	0.03	0.05
ϵ_x	0.5E-5	1E-5	8.4E-6	9E-6
ϵ_y	2E-6	9E-6	5.2E-6	8E-6
ϵ_z	1.2E-5	1.2E-5	1.5E-5	1.1E-5
ϵ_{xy}	2.2E-6	7E-6	2.5E-6	7E-6
ϵ_{yz}	6E-6	1.7E-5	7.4E-6	1.5E-5
ϵ_{zx}	1.3E-5	2.9E-5	1.7E-5	2.8E-5

Some main results such as displacement, normal and shear stresses, and strains are shown in the above table which are from both finite element packages. These results shows that, both finite element packages work fine and present similar results.

Similarly, only vertical displacement contours from both Finite Element Packages are shown in the following Fig. 7 for the former and the after restoration cases. According to the results, maximum vertical displacements are occurred at the mid span of the arches and approximately 0.07 mm.

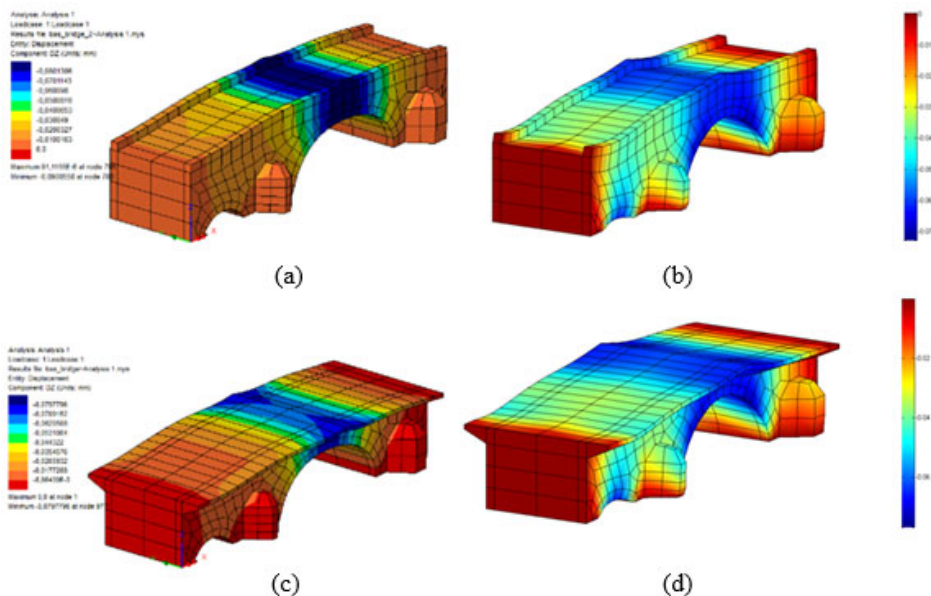


Fig. 7. Vertical displacement contour results: a) LUSAS, b) FEMMAS-L models former case, c) LUSAS, d) FEMMAS-L models after restoration case.

4. CONSLUSIONS

In Turkey, most of ancient arch bridges are remained from Ottoman Empire and most of them are in poor condition due to some climatic effects and manmade hazards. Transferring these heritage structures from past to the future generations have to main goal for us. In this study, an historical arch bridge, which was located in the city center of Aksaray, was taken into account for the structural analyses. The bridge was restored according to the results of the finite element analyses, which mentioned in this paper. For the restoration works, some extra analyses were also performed such as flood loading, earthquake loading. Besides the materials of the bridge was also considered as nonlinear behaviour. Some main conclusions drawn from the finite element analyses and sideseeing investigations are listed below.

The results of stream rehabilitation works carried out at various dates, one of the small arches was totally, and half of the other one was remained under the soil. These parts of the structure were bringing out during restoration works.

The stone arch bridge has been using because it is located in the city center. The application of RC slab on the bridge was contained great dangers to the bridge. Considering that the original material has been exhausted under self-weight loading during centuries, RC slab element gave about 150 tons extra loading to the bridge.

Two Finite Element Programs are used for the determination of the stone arch bridge. One of them is already used for commercial purposes, which named LUSAS, and the other one is currently developing using MATLAB environment by the first and the second authors of this paper, which named FEMMAS-L. According to the results of

analyses, both finite element programs gave us similar results. A few PhD students are working on FEMMAS-L software for adding new finite elements such as 2D triangular and 3D tetrahedral elements, and also they are working on some dynamic analyses procedures such as Eigenvalue and Time-History cases.

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