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Evaluation of material properties by NDT methods and FEM analysis of a stone masonry arch bridge

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ABSTRACT

Masonry is the oldest building technique that still finds wide use in today's building industries. The variety and natural availability of the materials that is needed for masonry combined with the easiness of the construction, has resulted in usage of masonry for thousands of years. The lack of research and underdeveloped codes in masonry results in poor applications of masonry technique which causes invaluable loss of lives of people in earthquakes. Today modeling of stone masonry structures is still very difficult because of unknown material properties. This study focuses on estimation of the material properties by destructive testing methods (DT) and non-destructive testing methods (NDT) and analysis of a historic stone masonry arch bridge. After visual investigation, the geometry of the structure is determined and 3D model of the structure was generated and meshed for Finite Element Method (FEM). For evaluation of material properties, NDT methods such as; impact-echo and ultrasonic pulse velocity testing methods were used. Schmidt hammer test was applied for estimation of the hardness of the stones. Fallen stone and mortar samples from the bridge were taken to the laboratory and destructive tests applied on them to determine the properties of masonry components. The test results for the materials obtained from the DT and NDT methods were compared with each other. Using these results mechanical properties of the masonry were estimated using standards and codes. The gathered material properties were assigned to FE model and the model was analyzed.

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1. Introduction

Modeling of masonry structures is still very difficult because of unknown material properties. In this study a historic stone masonry arch bridge in Urla, Zeytinler village was studied. This study focuses on estimation of the material properties by destructive testing methods (DT) and non-destructive testing methods (NDT) and analysis of this bridge. First, visual investigation established and the geometry of the structure is determined. For testing of material properties for finite element method (FEM) model, NDT methods such as; impact-echo and ultrasonic pulse velocity testing methods were used. Stack imaging of spectral amplitudes based on impact-echo (SIBIE) technique was applied to evaluate the inner structure of the bridge. Schmidt hammer test was applied for estimation of the hardness of the stones by an L type Schmidt hammer. The uniaxial compressive and indirect tension tests were applied to samples taken from the bridge to determine the strength and modulus of elasticity of the masonry components. The test results for the materials obtained from the DT and NDT methods were compared with each other. Using these tests' results a macro model of the masonry was created by homogenization approach for the FE model. Then, the masonry bridge was analyzed under static loads.

2. Mathematical Model

The structure is 3 spanned stone masonry arch bridge and is located in Urla Zeytinler village. It is on the road

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to Çeşme crossing a river. The bridge is not in use since new İzmir–Çeşme (Tepekahve) road opened in 1950's. The bridge has a 42.5 meters length 6.15 meter width and has 7 meters long 3 spans (Fig. 1). The spandered walls and the arches have 1.00 meter and 0.65 meter thickness, respectively. There is rubble stone filling concrete between spandrel walls. The stones used in the masonry are grey and pink andesite. After visual investigation, 3D model of the structure was generated and meshed for Finite Element Method (FEM) (Fig. 2).

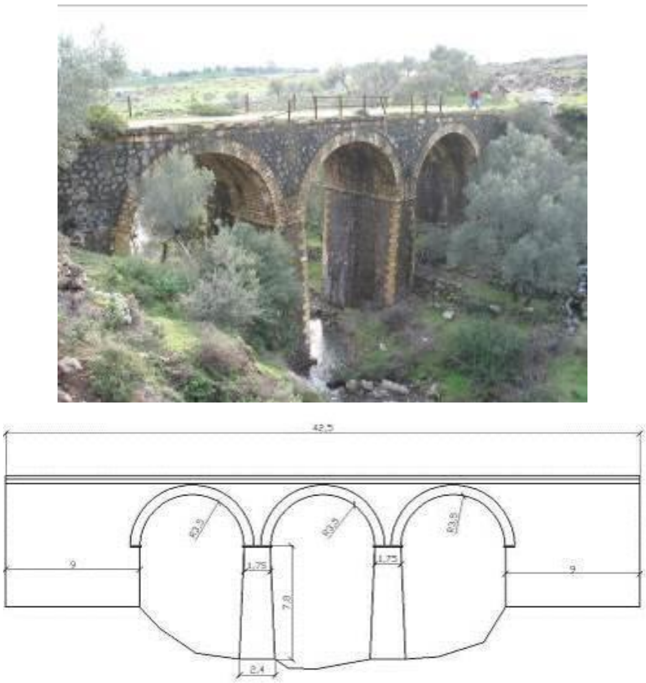

Fig. 1. Stone masonry arch bridge in Zeytinler.

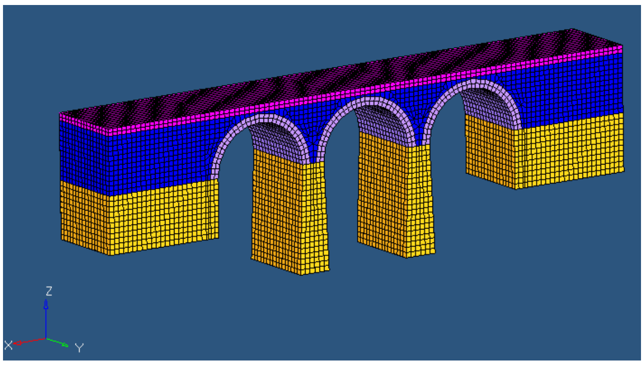

Fig. 2. 3D FE model of the bridge.

2.1. Material tests on stone and mortar

In order to determine the parameters needed for finite element modeling, material nondestructive and destructive tests were applied on constituents of masonry.

For the destructive tests fallen stones from the structure were taken. Stone samples which were strong enough to cut out core samples of diameter 54 mm were selected. Fallen stones were taken to the laboratory and cylinder core samples of diameter 54 mm were drilled out (Fig. 3). The heads of samples were cut with "cut of machine". Test samples for indirect tension test (Brazilian test) with height of 27-54 mm and samples for uniaxial compression test with height of 108-120 mm were prepared (TS 699, 1987; Ulusay et al., 2001). The heads of the cylinder core samples were grinded in order to have appropriate cylinder samples in emery machine (TS 699, 1987). After samples had been prepared, uni-axial compression and indirect tension tests were applied as shown in Fig. 3. The loading rate was 0.2 mm/minute which satisfies the failure time 1 to 10 minutes (TS 699, 1987). The average results are shown in Table 1.

Fig. 3. Drilling out core samples, uni-axial compression and Brazilian test.

For the nondestructive tests, before taking the samples to the laboratory, L type Proeq Schmidt Hammer was used to find surface hardness values of the stone samples. Schmidt Hammer test was also applied to the stones of the whole structure (Fig. 3). The compressive strength was calculated from the scheme of Ulusay et al. (2001). In the laboratory before indirect and uniaxial compression tests were applied to the stone samples, ultrasonic wave velocity tests had been conducted by CNS Farnel Electronic's Pundit type equipment (Fig. 4). The modulus of elasticity values of stone samples were also determined by Eq. (1) (ASTM 1997, C597).

Table 1. Test results of stone.

Sample	Number of Samples	Density ρ (g/cm^3)	Rebound Value, R	σ_c from R (MPa)	UAC f_c (MPa)	E (GPa)	Tensile Strength f_t (MPa)	Ultra Velocity (m/sec)	E from U.V. (GPa)
Stone	20	2,49	51.89	80	50.35	11.40	5,89	4010	34.88

Fig. 4. In situ Schmidt test and ultrasonic wave velocity test on stone samples.

$$E = V^2\rho(1+m)\frac{1-2m}{1-m}, \qquad (1)$$

where V, ρ, and m are ultra sonic pulse velocity, density and Poisson's ratio, respectively. The Poisson's ratio is taken as 0.21 for the Andasite stone. The estimated modulus of elasticity values from ultra velocity tests are higher than the values obtained by destructive tests (Table 1).

The mortar samples were weak and too small for drilling so only point load tests could be applied on arbitrary shape samples. By use of the point load index, the uni-axial compressive strengths of mortars were estimated. The average estimated uni-axial strength of mortars was calculated to be 11.95 MPa from point load tests. Tensile strength and modulus of elasticity of mortar was also estimated from literature by the help of point load test results. Tensile strength and modulus of elasticity σ_t, 1.11 MPa and E, 180 MPa are taken, respectively. The density of the mortar was calculated ρ = 1.80 gr/cm^3.

2.2. Impact-echo on the stone masonry arch bridge

Impact-echo is one of nondestructive testing methods for concrete based on multiple reflections of an acoustical wave between the test surface of concrete and an interface between materials with different mechanical impedances. An impact load is applied at the surface of the concrete and vibrations caused by this impact are recorded by a receiver. As a result, a waveform is built up in the time domain. In the traditional impact-echo analysis, this waveform is transformed into the frequency domain by applying FFT. Peak frequencies are identified in the frequency spectrum and corresponding depth is calculated by the given formula where C_p is longitudinal wave velocity, f is the measured frequency and d is the corresponding depth (Sansalone and Streett, 1997; Sansalone, 1997).

$$d = C_p/2f\,. \qquad (2)$$

However, in most of the practical applications, due to the complex information existing in the data, it is difficult to interpret the frequency spectrum. Consequently, SIBIE (Stack Imaging of spectral amplitudes Based on Impact-Echo) procedure has been developed to improve impact-echo method. Impact-echo has been applied for evaluation of masonry structures. In this study, a stone masonry bridge was tested by applying impact-echo and SIBIE.

2.2.1. SIBIE Procedure

Based on the inverse scattering theory in elastodynamics (Nakahara and Kitahara, 2002), the SIBIE procedure has been developed at Kumamoto University (Ata et al., 2007; Ohtsu and Watanabe, 2002). This is an imaging technique for detected waveforms in the frequency domain. In the procedure, first, a cross-section of sample is divided into square elements as shown in Fig. 5. Then, resonance frequencies due to reflections at each element are computed. The travel distance from the input location to the output through the element is calculated as (Ohtsu and Watanabe, 2002),

$$R = r_1 + r_2\,. \qquad (3)$$

Resonance frequencies due to reflections at each element are calculated from,

$$f_2' = \frac{C_p}{R_2} \;\text{ and }\; f_R = \frac{C_p}{R}\,. \qquad (4)$$

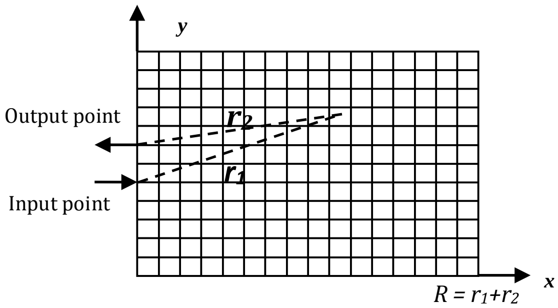

Fig. 5. Spectral imaging model.

Spectral amplitudes corresponding to these two resonance frequencies in the frequency spectrum are summed up at each mesh. Thus, reflection intensity is estimated as a stack image at each element. The minimum size of the square mesh for the SIBIE analysis should be approximately equal to $C_p\Delta t/2$, where C_p is the velocity of P-wave and Δt is the sampling time of a recorded wave.

2.2.2. Results of SIBIE

The stone masonry bridge tested is shown in the Fig. 6. The tests were carried out at several locations of the bridge. A hammer was used in the tests to generate elastic waves. Since the depth of the section to be tested was large, a hammer was used instead of a steel sphere to generate high impact energy. An accelerometer was used to detect surface displacements caused by reflections of the elastic waves. The frequency range of the accelerometer system was from DC to 50 kHz. Fourier spectra of accelerations were analyzed by FFT (Fast Fourier Transform). Sampling time was 4 μsec and the number of digitized data for each waveform was 2048. The cross-section of the bridge part tested was divided into square elements to perform SIBIE analysis. In this study, the size of square mesh for SIBIE analysis was set to 10 mm.

A result of SIBIE analysis of the impact applied above the center of the arch is depicted in Fig. 6(a). The SIBIE figure corresponds to the cross-section of the element that is tested. Here, red color zones indicate the higher reflection due to the interface between materials with different mechanical impedances. In the figure, impact and detection locations are indicated with arrows. The distance between impact and detection was selected as 5 cm. The depth of the section tested was 120 cm. The back wall reflection of red color zone is very clearly observed at the bottom of the SIBIE figure. The other red color regions are also clearly observed corresponding to the material interfaces. These reflections might be due to air existence between layers which means bonding between layers is not well.

There is another SIBIE result shown in Fig. 6(b). Impact-echo test location is different in this case. As can be seen from the figure the back wall reflection is very clearly observed. Other reflection is observed between two stones at the bottom of the section. The reason of existence of this reflection can be the existence of air between two layers. There are no other high reflections observed in the figure.

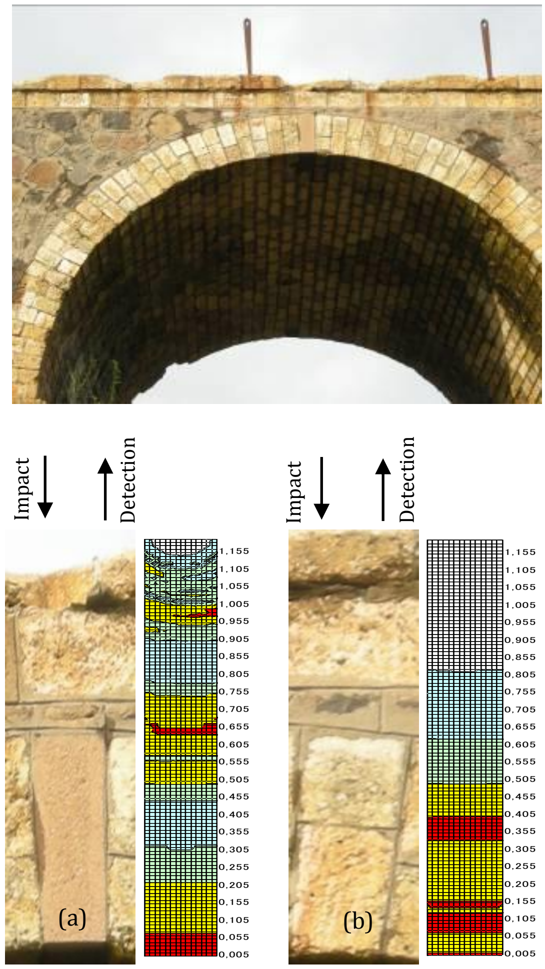

Fig. 6. SIBIE result of the bridge section above the center of the arch (a) and close to the center of the arch (b).

According to the test results it can be said that SIBIE procedure can be applied to stone masonry structures to evaluate the structure non-destructively. The discontinuities in the structure are appeared at the SIBIE results as relevant regions (red zones in this case). Here, by evaluating the results, the dimensions of the stones, thickness of the mortars and thickness of the spandrel walls can be estimated and also it can be said that there are some flaws between layers. These flaws decrease the strength of the material and thus affect the durability of the structure.

3. Finite Element Analyses of the Stone Masonry Arch Bridge

3.1. Determination of material parameters for FE model

The masonry is a composite and this composite material consists of two or more different constituent materials. By the use of homogenization approach, behavior of mortar and stone were assumed together so an overall behavior of the composite media has been taken into account. While determining the elastic parameters of masonry, the homogenization equations which depend on the strength parameters of constituents were used.

The compressive strength of masonry is determined by Eq. (5) (Eurocode 6, 1995).

$$f_k = K f_b^{0.65} f_m^{0.25} , \quad (5)$$

where K is a constant, f_b is the compressive strength of stone, f_m is compressive strength of mortar. K is in the range of 0.4 to 0.6 and depends on the morphology of the masonry (Eurocode 6, 1995). K was taken 0.5 in this study.

The modulus of elasticity of masonry was determined by the use of Eq. (6) (Lourenço, 2001).

$$E = \frac{t_m + t_u}{\frac{t_m}{E_m} + \frac{t_u}{E_u}} \rho , \quad (6)$$

where t_m, t_u, E_m, E_u are the thickness of mortar and height of the unit the coefficient ρ varies with the bond between mortar and unit and was taken 0.5 for this study (Lourenço, 2001).

The shear modulus can be taken as 40% of the modulus of elasticity (Eurocode 6, 1995). The tensile strength of masonry can be taken as 10% of compressive strength (Koçak, 1999).

The density of BM and fill were calculated as 2.1 kg/cm^3 and 1.75 kg/cm^3, respectively. The Poisson's ratio was taken as 0.17 for masonry (Koçak, 1999). Elastic material parameters of SM and Fill for finite element model are shown in Table 2.

Table 2. Material parameters of masonry for FE model.

	Stone Masonry	Fill
Compressive Strength (MPa)	11.88	9.49
Tensile Strength (MPa)	1.18	0.76
Modulus of Elasticity (MPa)	1164.3	600
Shear Modulus	465.7	240
Density (kg/m^3)	2100	1950
Poisson Ratio	0.17	0.05

4. 3D FEM Analysis of the Bridge

The data gathered from destructive and nondestructive tests were used for FE analysis of the bridge. Linear elastic self weight analysis of the structure was conducted in order to check the safety of the structure under its own weight. The stress results of the FEM analysis were very small compared to its allowable stress proving that the structure is safe.

5. Conclusions

In this paper, numerical analysis of a stone masonry arch bridge is presented and performed by means of a FEM. The material properties of the masonry were estimated by NDT and DT methods. By using SIBIE the inner parts of structure were identified and it can be said that SIBIE procedure can be applied to stone masonry structures to evaluate the structure non-destructively. By evaluating the results, the dimensions of the stones, thickness of the mortars and thickness of the spandrel walls can be estimated. According to the FE analysis structure is safe under its self weight. The results of a FEM analysis can be useful, in case of restoration of masonry arches.

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