Finite element model calibration of Babak bridge by dynamic load tests

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Abstract
Masonry bridges are an important asset of Iranian railway infrastructure. Their health monitoring is vital due to their long life in service. Also, there is a growing demand for higher traffic which requires the passage of higher axle loads over such bridges. Feasibility study of applying an increased axle load of 25 tons to an old masonry bridge is presented. Babak bridge is located in north western zone of Iranian railway network and has been in service for more than 70 years. The bridge is consists of stone segments, and has three long spans of 21.5 meters, 7 spans of 10 meters, and a total length of 270 meters. A finite element model of the bridge is developed in Abaqus software. Modeling the exact behavior of masonry bridges is difficult due to their complex structures, added the age of bridges which could not be integrated in numerical models. In this respect, field tests of Babak bridge have been designed to monitor the response of bridge subjected to predefined loading scheme by 17 sensors including deflection meters and accelerometers. A total of 37 tests are carried out on Babak bridge, and the results are used to calibrate the numerical model of the bridge. The numerical model is then used to determine the weak spots of bridge due to subjection of higher axle loads for a possible strengthening procedure.

Keywords: Masonry arch bridge, Field tests, ABAQUS, F.E. model.

Introduction
Aiming at increasing the throughput of the network, railway administrators seek out new solutions such as increasing the axle load or operational speed of trains to allow more trains in the network. One major obstacle in doing so is the limited capacity of existing structures in the network such as bridges. In this regard, evaluating the performance of such structures subjected to different loading schemes and operational speeds seem to be the prerequisite of increasing the axle load. Iranian railway organization has started a project of increasing the axle load of its railway network from the current 20 tons to 25 tons. One major problem is the existence of old masonry bridges in the network such as Babak bridge that is a masonry arch bridge built more than 70 years ago. The problem with evaluating the performance of such structures is the complexity of their behavior, which has been of great debate during recent years.

There are a number of methods proposed for the evaluation of load carrying capacity of masonry bridges, including empirical methods such as MEXE [1997], yield design based methods [Havay, 1988; Clemente et.al, 1995], fiber beam elements method [Felice, 2009], and those employing a scaled model of the bridge [Prentice and Ponniah, 1994; Cancelliere et.al, 2010].

Recently a number of studies have successfully assessed the load carrying capacity of masonry bridges by 2D and 3D finite elements models [Bayraktar et.al, 2010; Chandra et.al, 2013; Marefat et.al, 2004; Oliveira et.al, 2010; Caglayan et.al, 2012; Brenchich and Sabia, 2007]. Caligyan et.al [2012] have conducted static and dynamic tests on a concrete arch bridge and used test results to calibrate the 3D model of the bridge. Marefat et.al [2004] have conducted static tests on a decommissioned masonry railway arch bridge. They concluded that despite initiation of cracks on the bridge structure, the bridge sustained loads much higher than the service load. Brenchich and sabia [2007] have conducted dynamic tests on a bridge with 18 spans of 10 meters. They used the test results to determine mode shapes and natural frequencies of the bridge and concluded that multiple spots on the bridge have to be instrumented in order to determine the mode shapes of the bridge by dynamic tests.

This paper aims at presenting the result of field tests carried out on one of the oldest masonry arch bridges of Iranian railway network to determine whether it is possible to increase the currently 20 tons axle load applied to the bridge. For this purpose, a 3D finite element model is developed in ABAQUS software and calibrated to conform to test results.

Bridge Characteristics
Babak bridge is a masonry arch bridge built more than 70 years ago in north western part of Iranian railway network. The bridge consists of 3 long spans of 21.5 meters, and 7 spans of 10 meters, totaling a length of 270 meters. The bridge carries a single rail track, which allows for an axle load of 20 tons. The superstructure consists of U33 rails, wooden sleepers, and K fasteners. Maximum allowable speed on the bridge is 60 km/h. Figure 1 shows a view of Babak bridge.
In order to have the characteristics of the material used in building the bridge, a series of tests have been conducted. Cores from different segments are taken to a lab and tested to determine the compressive strength of the material. According to test results, compressive strength of stone segments is 12 Mpa. Using the equations stated in UIC 778-3 and assuming a compressive strength of 5Mpa for mortar, a compressive strength of 3.8 Mpa is calculated for masonry, as follows:

$$f_{\text{masonry}} = 0.5f_{\text{stone}}^{0.65}f_{\text{mortar}}^{0.25} = 0.5 \times 12^{0.65} \times 5^{0.25}$$

**Eq.1**

### Bridge instrumentation

The aim of field tests is to determine the response of Babak bridge to the passage of the test train. For this purpose, vertical deflections and vibrations of three 21.5 meters spans and a 10 meters span are monitored. Since Babak bridge is of heritage value, all sensors are mounted on plastic frames glued to the bridge surface, and later taken off.

Deflection of arch is supposed to be recorded with a frequency and accuracy of at least 10 Hz and 100 µm, respectively. In order to record the deflection of any spot on the arches of bridge with such standards, a reference point is needed on which the deflection meter is fixed, and any displacement relative to the reference point is recorded. For this purpose, a type of deflection recording sensor called 'Deflected Cantilever Displacement Transducer', or simply put 'DCDT', is used. DCDTs come with a cable that is fixed to a reference point. A steel sleeper is placed beneath the span and DCDT's cable is fixed to the sleeper, as shown in figure 2. DCDT sensor is capable of recording the displacement in a range of 25 mm with an accuracy of 10 µm.

To determine the exact speed and location of test train on the bridge, a series of LVDT sensors and strain gauges are mounted on the rail, as shown in Figure 3. LVDT sensors are also used to record the crack deflection due to test train loads, as depicted in figure 4. Furthermore, bridge vibrations due to test train loads are recorded by 8 accelerometers. Overall, 17 sensors are mounted on S bridge as depicted in Figure 5. Data is recorded with a frequency of 2 KHz throughout the tests.
Three 6-axle locomotives and five 4-axle freight wagons are used to form the test train. Axle spacing and loads are presented in Figure 6, schematically. A total of 37 dynamic tests are carried out on the bridge, in which test train is passed through the test site in both directions with speeds of 15 to 60 km/h.

Field test results
Figures 7 present the response of the bridge in terms of vertical deflection of middle of first span in both northern and southern sides. Since no super elevation exists on bridge superstructure, DCDT signatures on both sides are almost identical. Figure 8 presents the maximum recorded deflections of all spans, due to the passage of test train with varying speeds. No observable trend between maximum deflection of spans and speed is perceivable. According to figure 8, 4th span has the minimum vertical deflection of all tested spans, which is explained by the fact that 4th span has a smaller span that results in a rigid behavior.

In order to compare the vibration levels in different spots of the bridge, root mean square of recorded acceleration signatures are calculated and presented in Figure 9. Figure 9 suggests that there is a positive correlation between RMS of acceleration signatures of all spans and speed of test train.

Crack monitoring test results suggest that maximum deflection of crack is less than 0.01 mm, which corresponds to the passage of axles. Deflection signature of crack is presented in figure 10. In this regard, the cracks could be omitted from the numerical model.
Figure 7: Vertical deflection signature of northern and southern sides of middle of first span, due to the passage of test train.

Figure 8: Maximum of recorded vertical deflection signatures of all spans, due to the passage of test train with varying speeds.

Figure 9: RMS of recorded accelerations in all spans of Babak bridge, due to the passage of test train with varying speeds.

Figure 10: Crack’s variation signature as a single locomotive crosses over the bridge.
Numerical model of Babak bridge
To study the possibility of increasing the allowable axle load of Babak bridge, a 3D finite element model of the bridge is developed in Abaqus software, as shown in figure 11. To make sure that the numerical model conforms to the response of Babak bridge, the numerical model is calibrated using results of field tests, as shown in Figure 12. The model is then used to derive the natural frequencies and modal shapes of the bridge, which are presented in Table 1 and Figure 13, respectively.
Assessment of tensions in service limit state

According to BD 91/04, the permissible compression tensions due to a loading scheme of \( D+1.2L \) in service limit state shall not exceed \( 0.5f_k \). Since \( f_k \) (compression strength of masonry) is 3.80 Mpa, compression tension shall not exceed 1.52 Mpa due to any loading scheme. Proposed loading scheme of 'UIC 776-1' with an axle load of 25 tons is presented in figure 14. Tensions in middle and quarter of first four spans of Babak bridge are calculated as loading scheme of 'UIC 776-1' is applied to the bridge and presented in Table 2. Table 2 suggests tensions in the middle of first three spans exceed the allowable values.

<table>
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<tr>
<th>Span ID</th>
<th>Position</th>
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<tr>
<td>1st Span</td>
<td>Middle Span</td>
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</tr>
<tr>
<td>1st Span</td>
<td>Middle Span</td>
<td>Bottom Fiber</td>
</tr>
<tr>
<td>1st Span</td>
<td>Quarter Span</td>
<td>Top Fiber</td>
</tr>
<tr>
<td>1st Span</td>
<td>Quarter Span</td>
<td>Bottom Fiber</td>
</tr>
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</tr>
<tr>
<td>2nd Span</td>
<td>Middle Span</td>
<td>Bottom Fiber</td>
</tr>
<tr>
<td>2nd Span</td>
<td>Quarter Span</td>
<td>Top Fiber</td>
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</table>

Conclusion

Results of field tests carried out on Babak bridge are presented in this paper. Having the bridge instrumented with 16 deflection meters and accelerometers, the response of bridge to test train is recorded. Test results suggest that the 4th span of the bridge has a more rigid behavior compared to other spans, which is explained by the fact that 4th span has a smaller span length. It is also shown that the RMS of all recorded vibration signatures have a positive correlation with train’s speed. To assess the possibility of increasing the allowable axle load of bridge, a 3D finite element model is developed in Abaqus software, which is calibrated using the results of field tests. Dynamic analysis are carried out on the numerical model of the bridge, and tensions in middle and quarters of first four spans of the bridge due to the subjection of an increased axle load of 25 tons are calculated. Results of dynamic analyses are then compared to allowable values stated by BD91/04 standard. Results suggest that tensions in middle of first three spans exceed the allowable value, and the bridge cannot sustain an axle load of 25 tons, unless strengthening methods are carried out on weak spots of the spans.

References