CONDITION ASSESSMENT OF STEEL ARCH BRIDGES BASED ON AMBIENT VIBRATION TESTING

A. Bayraktar, A.C. Altunışık, T. Türker

Karadeniz Technical University, Department of Civil Engineering, Trabzon, TURKEY.

e-mails: alemdar@ktu.edu.tr, ahmetcan8284@hotmail.com, temelturker@hotmail.com

SUMMARY

The paper presents condition assessment of steel arch bridges based on ambient vibration testing. The bridge selected for the application is named as Borçka Bridge, which was built in 1936 on Çoruh River in the town center of Borçka, Artvin, Turkey. Total length, width and arch height from the bridge deck of the riveted bridge are 114m, 5.30m, 16.30m respectively. For the condition assessment, firstly, in-situ structural investigations on the bridge are implemented. Then ambient vibration tests are carried out on the bridge in order to determine the experimental dynamic characteristics called as the natural frequencies, mode shapes and modal damping ratios. The measurements are performed under the environmental effects of pedestrian movement and wind-induced vibration by using uniaxial seismic accelerometers. The initial finite element model developed according to the bridge survey data is updated by using the test results. The updated finite element model of the bridge is analysed for the different load cases including dead, moving, wind and earthquake loads.

Keywords: *Ambient vibration test, steel arch bridge, structural health monitoring, finite element model updating, condition assessment.*

1. INTRODUCTION

Structural condition assessment of old bridges is very important because of the fact that some bridges have been damaged or destroyed in the world every year. To investigate the damage reasons of the bridges, Wardhana et al [1] studied over 500 failures of bridge structures in the United States between 1989 and 2000. The most frequent causes of bridge failures were attributed to floods and collisions. Flood and scour, contributed to the frequency peak of bridge failures almost 53% of all failures. Bridge overload and lateral impact forces from trucks, barges/ships, and trains constitute 20% of the total bridge failures. Other frequent principal causes are design, detailing, construction, material, and maintenance.

There are some studies on the steel bridges in the literature. The studies are on the load rating, deterioration assessment, monitoring, model updating, dynamic response, rehabilitation and strengthening, estimation of the remaining fatigue life, reliability estimation and performance evaluation [2-26].

The study presents in-situ investigations, Ambient Vibration Tests, finite element model updating and safety assessment of an old riveted arch steel bridge.

2. BORÇKA STEEL ARCH BRIDGE

The investigated bridge is located in the Borçka district of Artvin Province, Turkey, and it has steel arch structural system. The bridge, built in 1936, is on the Çoruh River in the town center of Borçka. Total length and width of the bridge are about 114m and 5.30m, respectively. The main structural system of the bridge has 16.30m arch height from the bridge deck. The bridge abutments are made of stone masonry walls. The structural elements (arches, pillars, decks, wind connections etc.) are made of steel with riveted connections. Bridge is closed to vehicle traffic, it is open only to pedestrian traffic. Some views from Borçka Steel Arch Bridge are given in Fig. 1.

Fig. 1. *Views from Borçka Bridge.*

Fig. 2. *Longitudinal and transverse cross members.*

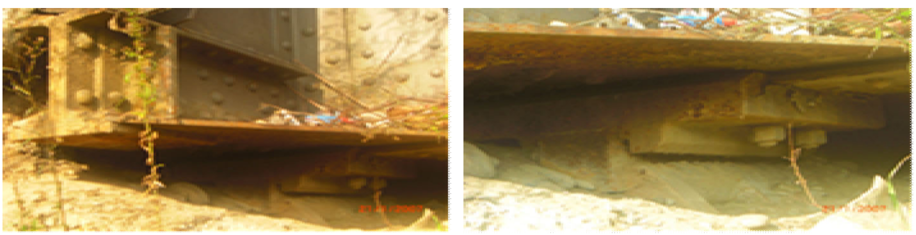


Fig. 3. *The supports of the bridge.*

It can be generally stated that there are important corrosion problems, especially under the deck elements, in the bridge (Fig. 2). Besides, serious support problems are observed during the investigations (Fig. 3). However, loose and tearing was not observed in the riveted joints (Fig. 4).

Fig. 4. The capped rivet connections.

3. AMBIENT VIBRATION TEST OF THE BRIDGE

Ambient vibration tests were carried out on Borçka Steel Arch Bridge in order to determine the dynamic characteristics called as the natural frequencies, mode shapes and modal damping ratios. The measurement was performed under the environmental effects of pedestrian movement and wind-induced vibration by using uniaxial seismic accelerometers. The accelerometers were placed to the bridge deck in both the vertical and horizontal directions as shown in Fig. 5 in order to measure bridge responses.

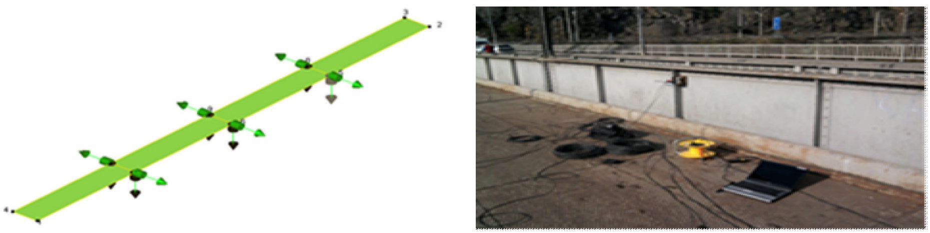


Fig. 5. The accelerometers location and placements in the bridge.

The spectrums obtained from Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) techniques are shown in Fig. 6. The first seven natural frequencies and modal damping ratios of the bridge are given in Tab. 1. The frequencies obtained from the SSI and EFDD techniques are close to each other.

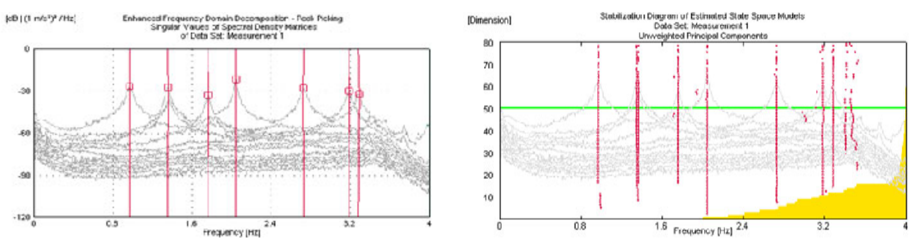


Fig. 6. The spectrums from EFDD and SSI techniques.

Table 1. The first seven natural frequencies and modal damping ratios of the bridge.

Mode No	Natural Frequencies [Hz]		Modal Damping Ratios [%]	
	EFDD	*SSI*	*EFDD*	*SSI*
1	0.970	0.968	2.185	1.801
2	1.352	1.348	0.736	0.926
3	1.761	1.758	0.962	0.817
4	2.042	2.041	0.459	0.401
5	2.726	2.725	0.764	0.707
6	3.183	3.189	0.432	0.395
7	3.279	3.281	0.543	0.685

4. MODEL UPDATING AND ANALYSES OF THE BRIDGE

Borçka Steel Arch Bridge was modelled by SAP2000 program to perform static and dynamic analyses. The dead, moving, wind and earthquake loads were considered in the analyzes. Elasticity modulus, poisson ratio and density of the steel members are taken as 2.1E11 N/m^2, 0.3 and 7850 kg/m^3, recpectively. The bridge arches, pillars, decks, main beams, beams with transverse and longitudinal stability of latitude were modelled as frame elements and the deck sheet was modeled as plane elements as shown in Fig. 7.

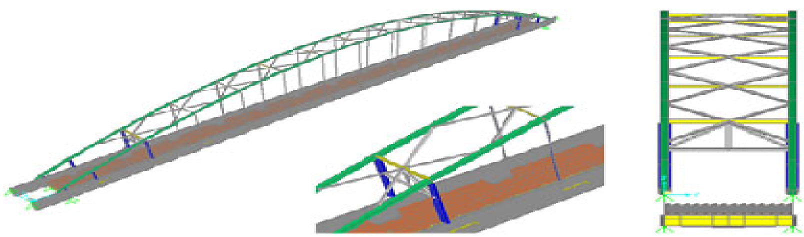


Fig. 7. The initial finite element model of the bridge.

Table 2. The theoretical and experimental natural frequencies of the bridge

Mode Number	Natural Frequency [Hz]		Difference [%]
	Theoretical	*Experimental*	
1	0.780	0.970	19.6
2	1.863	1.352	27.4
3	1.960	1.761	10.2
4	2.060	2.042	0.87
5	2.122	2.726	22.2
6	2.930	3.183	7.95
7	3.423	3.279	4.21

The modal analysis of the initial finite element model was performed and the natural frequencies were attained as given in Tab. 2. Also, the frequency values derived from the finite element analysis were compared with the experimental values. The differences between natural frequencies change in the range of 0.87-27.4%.

Experimental measurement results reflect the current state of the structure, so the initial finite element model was updated to reduce the differences. In the process of calibration of the bridge, some arrangements were made on the initial finite element model by taking into consideration the conditions encountered in the field views, such as the influence of corrosion in cross members, the support conditions, deck problems, the connection losses on the struts. Taking into account the above mentioned cases, the initial finite element of Borçka Bridge was updated and the updated natural frequencies were determined as given in Tab. 3. By the calibration process, the differences between the experimental and theoretical frequency was reduced up to the acceptable limits. The analytical and experimental first mode shapes of the bridge are shown in Fig. 8.

Table 3. *The updated natural frequencies of the bridge.*

Mode Number	**Natural Frequency [Hz]**		**Difference [%]**
	Theoretical	***Experimental***	
1	0.901	0.970	7.20
2	1.590	1.352	14.9
3	1.860	1.761	5.39
4	1.900	2.042	6.90
5	2.320	2.726	14.8
6	3.230	3.183	1.50
7	3.370	3.279	2.70

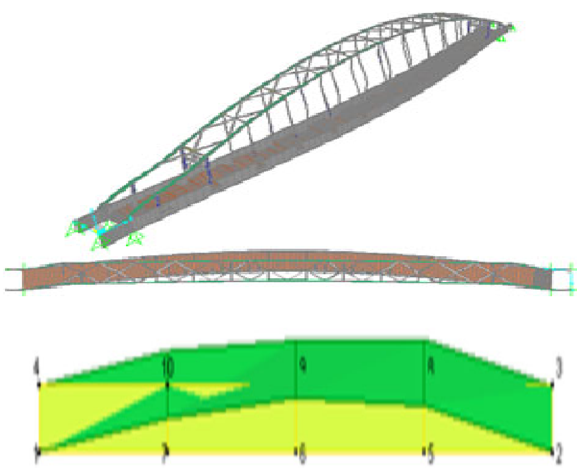


Fig. 8. *The first analytical (top) and experimental (bottom) mode shapes of the bridge.*

Borçka Steel Arch Bridge was analyzed using the updated finite element model for its own weight, moving loads (vehicle and/or pedestrian load), wind loads and seismic loads. Moving loads on the bridge deck was considered as 300kg/m^2 and the vehicle load was taken as 750kg/m^2. For earthquake load analysis, considering the region's seismicity, a spectrum was defined and used in the earthquake analysis. The four load combinations were considered in the evaluation. The maximum displacement was occurred in the mid-span of the projected point on the deck as 25.15cm (Fig. 9). The maximum normal force on the belts and decks beams was attained as 4350kN and 3420kN, the maximum shear force on the belts and decks beams was attained as 107kN and 760kN, and the maximum bending moments on the belts and decks beams was attained as 190kNm and 5350kNm, respectively (Fig. 10).

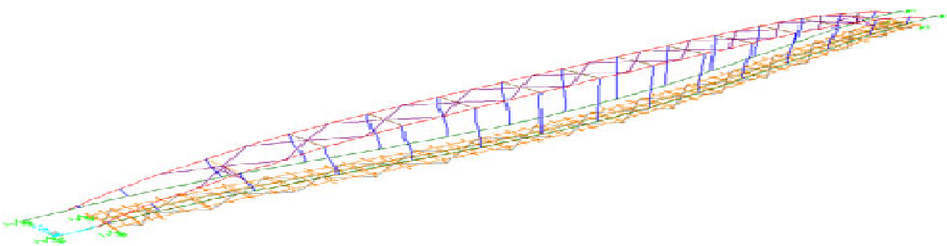


Fig. 9. *Maximum displacements for dead, moving and wind load case.*

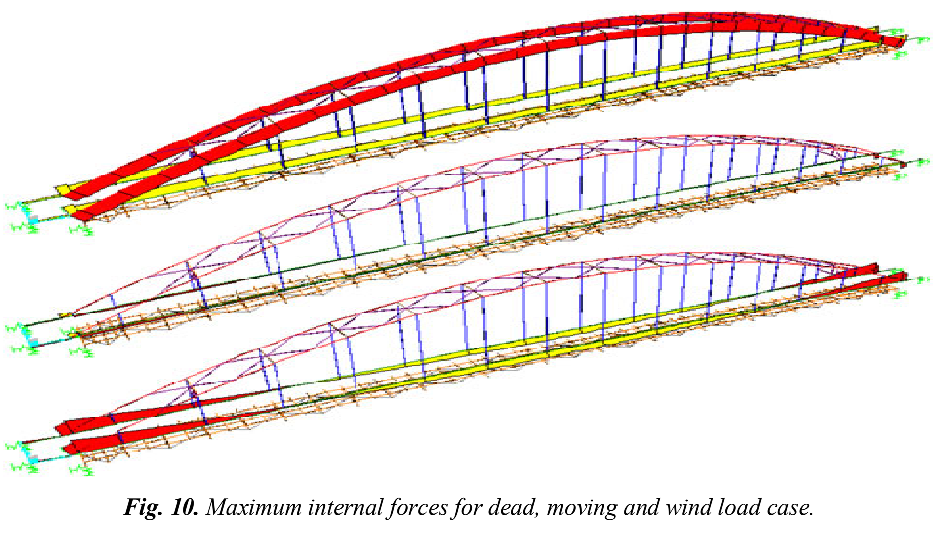


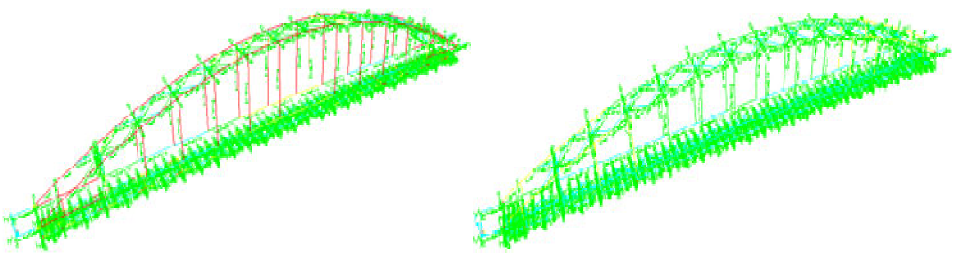
Fig. 10. *Maximum internal forces for dead, moving and wind load case.*

The member sections of the existing bridge were checked using AISC-ASD89 [27] code by considering own weight, live loads, wind loads and seismic loads. The results taking into account the own weight of the bridge remained below the limit values. In the other load cases, the results exceed the limit of the stresses (Fig.11a). Therefore, the bridge needs the repair and restoration.

Because the bridge is a registered historical bridge and closed the vehicle traffic, the strengthened suggestions to change the structural system were not recommended. Below repair and restorations are suggested for the bridge:

- The supports of the bridge need repairing or replacement.
- The connection losses on the struts and cross-sections need repairing or replacement.
- The repair or replacement is required in the high crosses.
- The repair or replacement of the deck is required.
- All elements need cleaning and painting with protective materials.

The verification according to the AISC-ASD89 [27] was carried out for the restored case by considering the own weight, live loads, wind loads and seismic load. The results of these verifications were given in Fig. 11b. It can be seen from Fig. 11b that the results of verification taking into account the own weight, moving load and wind load remained below the limit values.



a) initial case *a) restorated case*

Fig. 11. *The design check results for initial and restored cases.*

5. CONCLUSIONS

In-situ investigations, Ambient Vibration Tests, finite element model updating and safety assessment of Borçka old riveted arch steel bridge are implemented in this study. The results of the study can be drawn as below:

- The first seven experimental natural frequencies of the bridge are within the range of 0.968-3.281Hz. The results of the EFDD and SSI techniques are very close to each other. Damping ratios are generally obtained less than 2%.
- It is observed some differences between analytical and experimental dynamic characteristics. The updated natural frequencies of the bridge are determined in the range of 0.970-3.279 Hz.

- According to AISC-ASD89 code, the stress limit is exceeded for dead, moving and wind load cases in the existing bridge. However, after repair and restoration suggestions considered in the bridge model, the stress limit is not exceeded for dead, moving and wind loads in the restored bridge model.
- The measurements should be repeated after the restoration of the bridge to see the effect of restoration.

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