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Finite element model calibration of a steel railway bridge via ambient vibration test

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Abstract. This paper presents structural assessment of a steel railway bridge for current condition using modal parameter to upgrade finite element modeling in order to gather accurate result. An adequate monitoring, such as acceleration, displacement, strain monitoring, is important tool to understand behavior and to assess structural performance of the structure under surround vibration by means of the dynamic analysis. Evaluation of conditions of an existing steel railway bridge consist of 4 decks, three of them are 14 m, one of them is 9.7 m, was performed with a numerical analysis and a series of dynamic tests. Numerical analysis was performed implementing finite element model of the bridge using SAP2000 software. Dynamic tests were performed by collecting acceleration data caused by surrounding vibrations and dynamic analysis is performed by Operational Modal Analysis (OMA) using collected acceleration data. The acceleration response of the steel bridge is assumed to be governing response quantity for structural assessment and provide valuable information about the current statute of the structure. Modal identification determined based on response of the structure play significant role for upgrading finite element model of the structure and helping structural evaluation. Numerical and experimental dynamic properties are compared and finite element model of the bridge is updated by changing of material properties to reduce the differences between the results. In this paper, an existing steel railway bridge with four spans is evaluated by finite element model improved using operational modal analysis. Structural analysis performed for the bridge both for original and calibrated models, and results are compared. It is demonstrated that differences in natural frequencies are reduced between 0.2% to 5% by calibrating finite element modeling and stiffness properties.

Keywords: steel bridges; operational modal analysis; structural safety

1. Introduction

A structural assessment is a procedure used to examine the adequacy, structural integrity and reliability of structures and their components. Assessment of a structure is done by visual inspection, non-destructive testing and dynamic analysis. The dynamic response of an existing structure is usually based on deterministic analysis, such as finite element analysis. Finite element analysis is a powerful tool to evaluate behavior of the structures. However, finite element modeling of an existing structure may not reflect or imitate structure as it is, due to elements exist on the structure that are not assumed as a structural components, but have some effect on behavior of the structure, boundary conditions, material properties, and any damages and/or deteriorations (Jaishi *et al*. 2007, Huang *et al*. 2008, Benedettini and Gentile 2011, Ni *et al*. 2012, Ribeiro *et al*. 2012). Old steel railway bridges are such structures that they were deteriorated due to environmental effects, some components were added/removed/changed for maintenance purposes, some components were strengthened for safety reasons, and connection components, such as rivets, bolts, and welds were weakened during operational life. Therefore, dynamic analysis may not reflect the actual behavior of the bridge because of the assumptions made in process of developing the finite element model and not able to reflect all details in the structure (Au *et al*. 2003, Jaishi and Ben 2005, Bayraktar *et al*. 2009, 2010, Türker *et al*. 2009, Altunisik *et al*. 2011, Ding *et al*. 2016). There are many approaches to upgrade finite element model, the most widely used method is experimental measurement. Therefore, finite element modeling should be calibrated in order to present actual behavior of the structure using experimental measurements. Experimental measurements are supposed to be non-destructive and based on determination of the certain properties of the structure, such as modal or stiffness properties. Modal parameters, especially natural frequencies and mode shapes are basic parameters to determine the dynamic response of the structures. They are also used to calibrate finite element modeling in respect to present actual behavior. The main purpose of the model calibrating procedure is to minimize the differences between the analytically and experimentally determined dynamic characteristics by changing some parameters such as material properties and/or boundary conditions.

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The process of determination the dynamic parameters of a system by testing are known as system identification (Ewins 1984, Ljung 1987). In modal field testing, basically, there are two different methods to identify the dynamic characteristics of a structure: experimental modal analysis (EMA) and operational modal analysis (OMA is also known output only modal analysis or ambient modal analysis) (Zang 2013). EMA is classical vibration test that the structure is excited by known forces (or accelerations) such as shakers and responses of the structure are measured. OMA is more practical testing method that the structure is excited by unknown forces such as traffic, wind, and ambient vibrations and responses of the structure are measured. In this study, the seismic response (basically acceleration measurements) of the steel railway bridge is evaluated by using OMA, and natural frequencies and modal shapes of the bridge are determined. Acceleration measurements may be conducted any time in operational condition under different environmental loading. The equipment consists of 18 uniaxial accelerometers and 18-channel 24 bit data accusation box. The acceleration data collected from bridge is processed using ARTeMIS® (ARTeMIS 2004) computer program to determine natural frequencies of the bridge.

2. Research significance

This study is performed due to necessity of upgrading the bridge to the possible changing in railways operation regulations in near future in Turkey. Although structural assessment was performed for current load requirements, the results might be used to assess the reliability of the analysis method. This study indicates that even for very simple structural system without complex components the elastic analysis does not reflect the actual behavior. The analysis method should be validated by experimental data.

Many of the studies about old steel structures in the literature consider that the material properties of the steel would be as standard as it is manufactured. On the other hand, properties of the steel, especially strength of the steel, may be changed in the time due to some deterioration. In case of not able to testing the material, it is safe to assume the materials properties would not be changed. In this study, unlike other studies, aspect of changing in material properties is considered beside upgrading finite element model.

3. Description of the bridge

The evaluated bridge is located at +36.646 km of the Izmir-Usak railway line of TCDD (Turkish Public Railways) (Erol 2017). The bridge was built in 1950 (Fig. 1). The bridge has four spans, three of them are 14 m, one of them is 9.74 m (Fig. 2). Static model is given in Fig. 3, and the cross sections of 14 m and 9.74 m decks are different, and given in Fig. 4. Footings are reinforced concrete, and each opening is designed as simple beam. Most of the members of the bridge are built-in profiles, connections are created using rivets. The current condition of the bridge is poor, deteriorated, and need complete maintenance (Fig. 5). The railway line is under review changing to high speed line, maximum operational speed and load requirements are changed, assessment of bridge becomes a necessity. In this study, dynamic behavior of the bridge is evaluated in respect to stress capacity and displacements. Study is focused on calibration of finite element modeling of the bridge and collecting dynamic properties, and defining the behavior of the bridge according to information gathered.

4. Finite element modeling

Dynamic analysis of the subject bridge was performed

Fig. 1 Views of the evaluated bridge

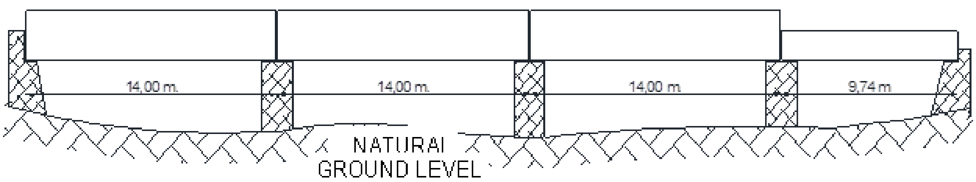


Fig. 2 The views of the evaluated bridge

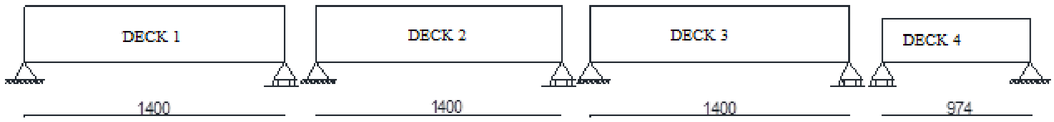
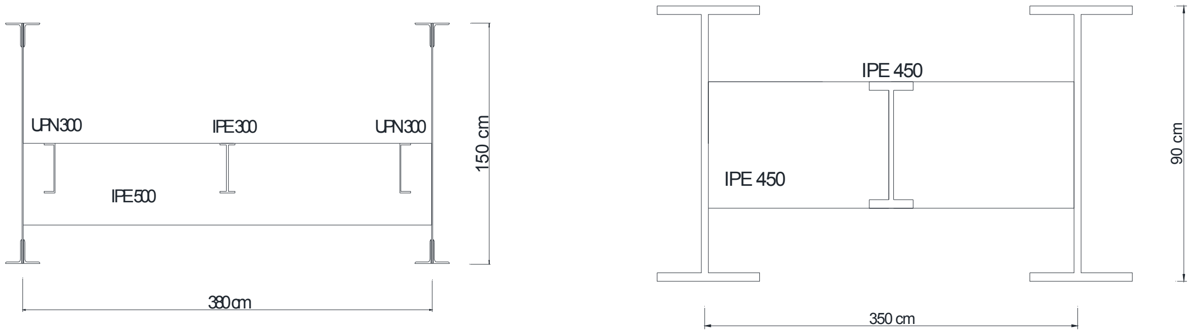


Fig. 3 Static model of the bridge (in mm)



(a) (b)

Fig. 4 Cross section of (a) 14 m part of bridge; (b) 9.74 m part of bridge

Fig. 5 Views from bridge

developing there-dimensional model in SAP2000 (SAP 2000). A global view of the model is given in Fig. 6. Steel deck is modeled as shell, all other members are modeled as beam. The material properties of the steel profiles used in analysis are given in Table 1.

Each bridge part is designed as simple beam. Adjacent bridge parts shared same abutment. Supports are designed as simple support. The bridge is analyzed under dead load only, dynamic properties are determined for only dead loads.

Table 1 Material and mechanical properties of steel bridge

	Modulus of elasticity (GPa)	Poisson ratio	Density (kg/m^3)	Yielding strength (MPa)
Steel profile	210	0.3	7.85	240

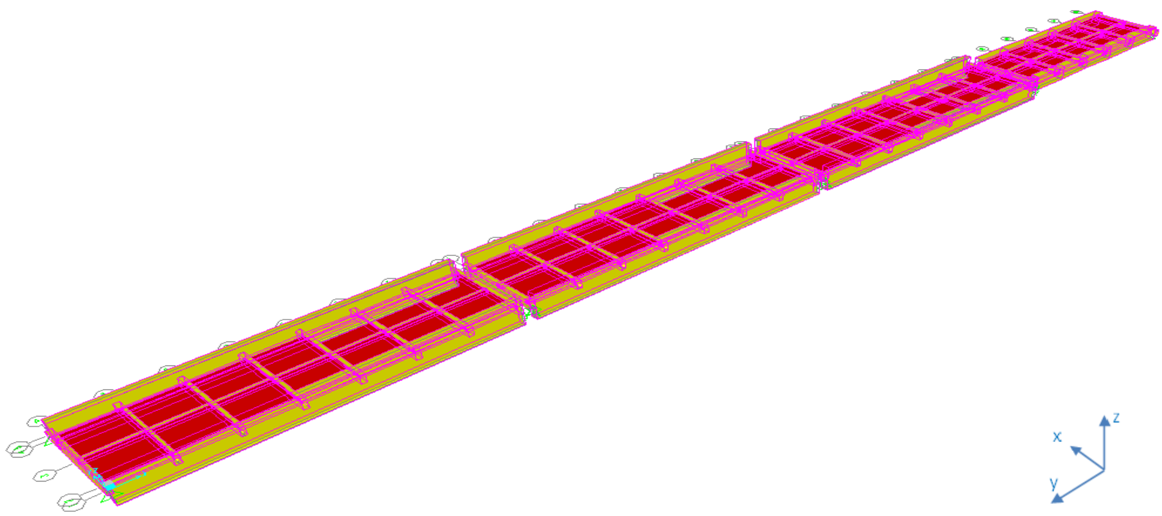


Fig. 6 Global view of the finite element model

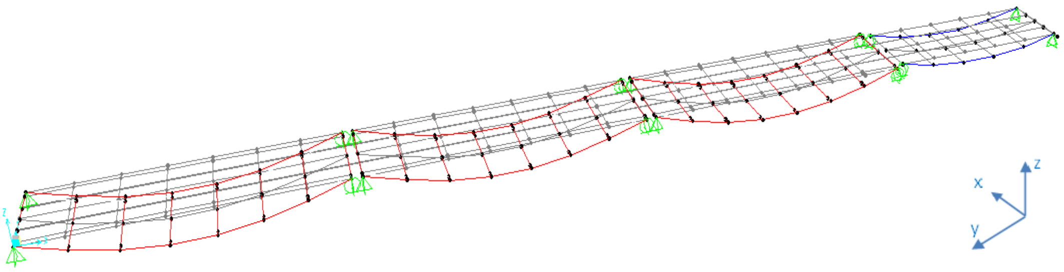


Fig. 7 Elastic behavior of the steel slabs

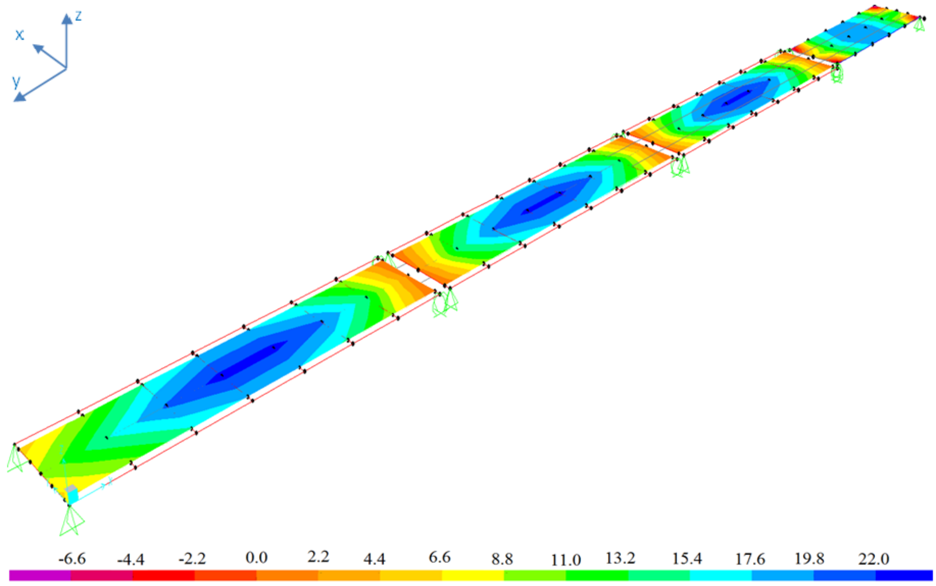


Fig. 8 Stress distribution the steel slabs (initial finite element model)

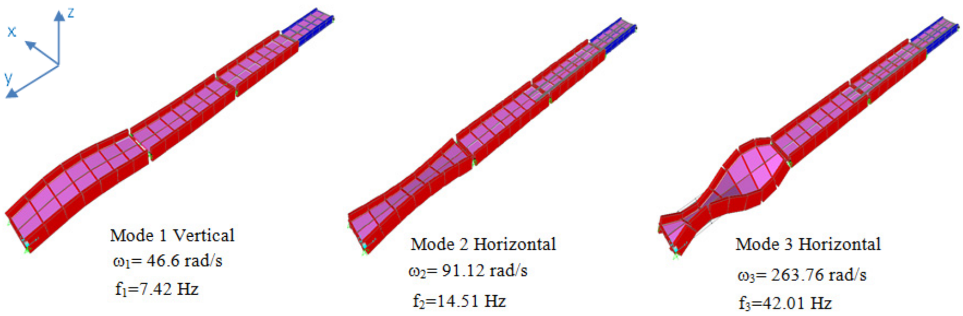


Fig. 8 Stress distribution the steel slabs (initial finite element model)

4.1 Numerical analysis

Because of simple nature of the design of the bridge, deformation, flexural stress capacities, and natural frequencies are collected as expected. Elastic behavior of the bridge is given in Fig. 7; flexural stress distribution on steel decks is given in Fig. 8. Maximum displacements, for 14 m length decks are 22.5 mm, for 9.74 m deck is 10.99 mm. Maximum flexural stresses, for 14 m length decks are 22.4 MPa, for 9.74 m deck is 17.8 MPa. Dynamic behavior of the bridge is also as expected. Since each part of the bridge is designed as simple beam, modal behavior of each deck with 14 m length is identical. Modal shapes for bridge are given for only one deck as seen in Fig. 9.

4.2. Experimental analysis

In order to calibrate finite element modeling for dynamic analysis, the dynamic properties of the structure should be determined. The dynamic properties, primarily natural frequencies and modal shapes, are determined by operational modal analysis method (Magalhaes *et al*. 2008, Schlune *et al*. 2009, Hoag *et al*. 2017) using vibration data collected from the bridge. In this method, vibration data is

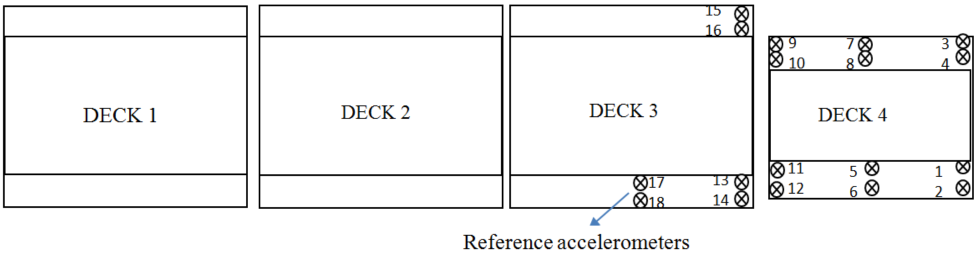


Fig. 10 Locations of accelerometers in deck 4

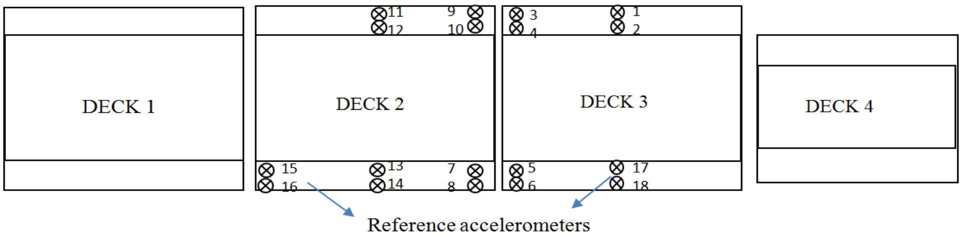


Fig. 11 Locations of accelerometers in deck 2-3

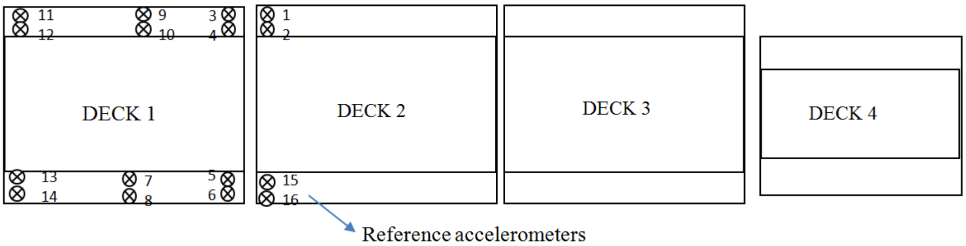


Fig. 12 Locations of accelerometers in deck 1-2

Fig. 13 Views of the accelerometers

collected when the structure is under its operating conditions (Ubertini *et al*. 2013). For this purpose, 18 uniaxial accelerometers with frequency range of 0-50 Hz. were used. Data acquisition was performed TESTBOX2010® system equipped with analog input modules with 24-bit resolution. The acceleration series were acquired over periods of 20 min, with a sampling frequency of 200 Hz and decimated to a frequency of 100 Hz. Data was collected in three steps, correlation of acceleration data between the decks was established accordingly and response of the decks were analyzed separately. The schematic locations of the accelerometers are given in Figs. 10-12, views from testing are given in Fig. 13.

4.2.1 Modal parameters

Collected acceleration data was processed in stochastic subspace identification method (Jacobsen *et al*. 2006) that is available in ARTeMIS® operational modal analysis software application (ARTeMIS 2004) in order to determine mode shapes, natural frequencies, and damping ratios. Damping ratio was determined for only vertical motion. Frequency spectrum gathered from ARTeMIS® is given in Fig. 14. Natural frequencies and mode shapes determined by using operational modal analysis are given in Fig. 15. Damping ratio for vertical motion is 0.47%.

5. Finite element calibration

A finite element model is developed to represent a cracked beam element of length d and the crack is located at Calibration of a finite element model is to determine uncertain parameters, such as material and mechanical properties, stiffness properties, boundary conditions, etc. in

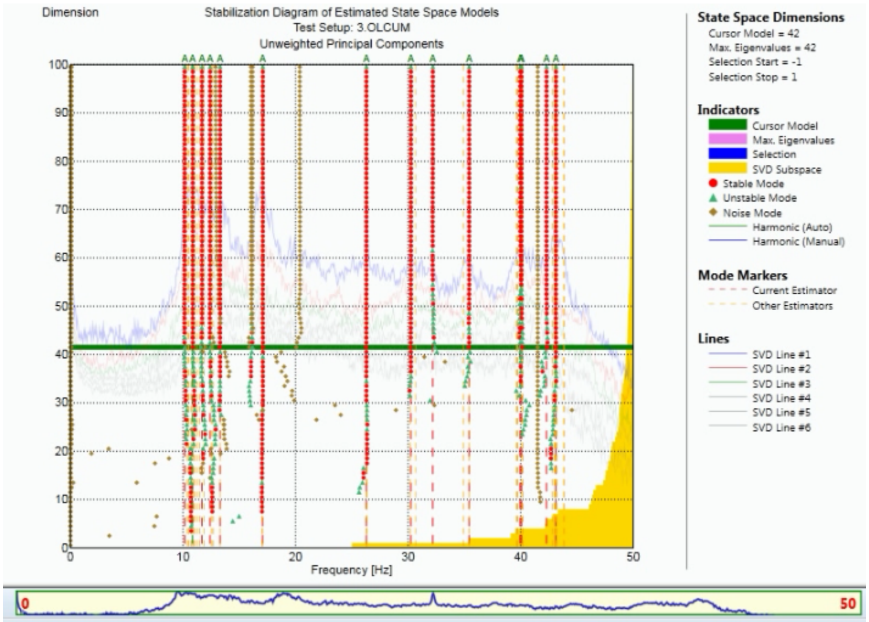


Fig. 14 Frequencies spectrum using stochastic sub-space identification method

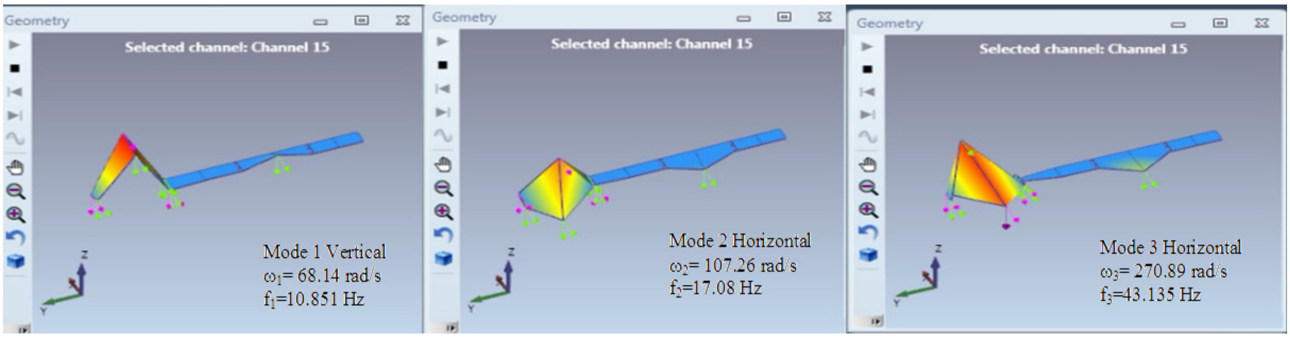


Fig. 15. Experimental mode shapes and natural frequencies

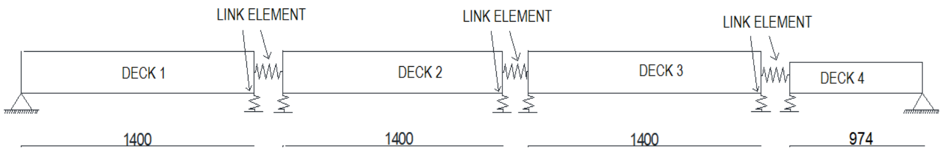


Fig. 16. Improved numeric model of the bridge (in mm)

the initial model based on experimental results. The objective of calibration is to achieve a more suitable improved model of the structure (Au *et al*. 2003, Bayraktar *et al*. 2009, 2010, Altunisik *et al*. 2011). Improved models are used for the prediction of dynamic responses under new load scenarios of the system, as well as for damage identification and health monitoring. In this study, calibration of the numerical model is developed by calibrating stiffness properties of the initial finite element model by adding effect of blast materials, traversers, rails, pedestrian passage attached to the bridge, and deterioration in supports. Effects of mentioned factors are defined as "link element". Each link element has stiffness in three directions. The calibrated finite element model is shown in Fig. 16. Dynamic analysis needed to be repeated until the frequencies of numerical and operational modal analysis were overlapped. When only model was updated, the operational modal frequencies were not catch, then modulus of elasticity of the steel was also decreased in order to gather target frequencies. Assumption of decrease in the modulus of elasticity of steel is based on decrease in the strength of the steel over time due to deterioration in steel members and rivets, besides; changing in modulus of elasticity is also possible in temperature changing (Wilson 1984). By using improved finite element model shown in Fig. 16, and by assuming the modulus of elasticity to be 180 GPa, the natural frequencies determined from dynamic analysis are overlapped with the frequencies collected from operational modal analysis. The natural frequencies for calibrated model are as in Fig. 17. In calibrated finite

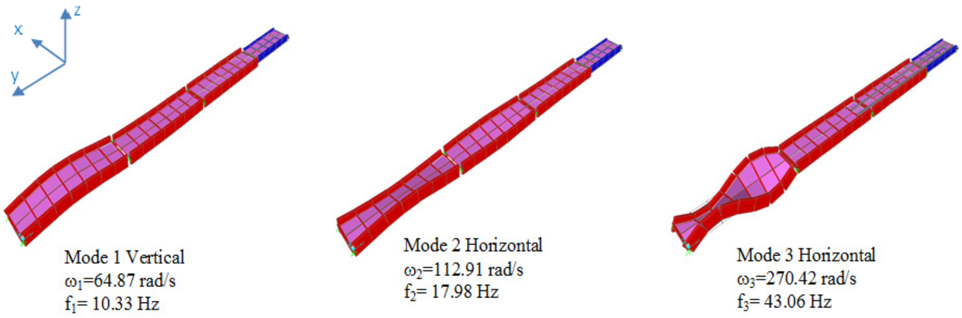


Fig. 17 Natural frequencies determined from improved numeric model of the bridge

Table 2 Comparison of frequencies (frequencies belong to Deck 1)

Modes	Natural frequency in initial finite element model (Hz)	Natural frequency in improved finite element model (Hz)	Natural frequency in operational modal analysis (Hz)	Difference in frequency between initial model and operational modal analysis (%)	Difference in frequency between improved model and operational modal analysis (%)
1	7.42	10.33	10.85	39	5
2	14.51	17.98	17.08	24	5
3	43.05	43.06	43.14	0	0.2

element analysis, each deck has different frequencies because of link elements between the decks provide the system responses together, yet not enough to response as a continuous system. On the other hand, mode shapes were not different, so that for comparison purposes, only largest frequencies are chosen and the frequencies also happen to belong to Deck 1.

The comparison of frequencies in initial and improved models is given in Table 2.

The dynamic analysis was repeated after calibration, displacement and stress distribution of the bridge were determined. The stress distribution for steel deck is shown in Fig. 18. Maximum displacements, for 14 m length decks are 12.13 mm, for 9.74 m deck is 8.62 mm. Maximum flexural stresses, for 14 m length decks are 14.4 MPa, for 9.74 m deck is 14.1 MPa. Comparison of the maximum displacement and stress distribution on the steel deck with respect to initial finite element model analysis and calibrated finite element model using operational modal analysis is given in Table 3. Differences in displacements and stress distribution indicate that the only finite element analysis results mislead understanding behavior of the structure. Any considerations made about structures, such as strengthening or reconstruction, becomes unreliable. Further studies supposed to be performed in order to improve initial finite element modeling.

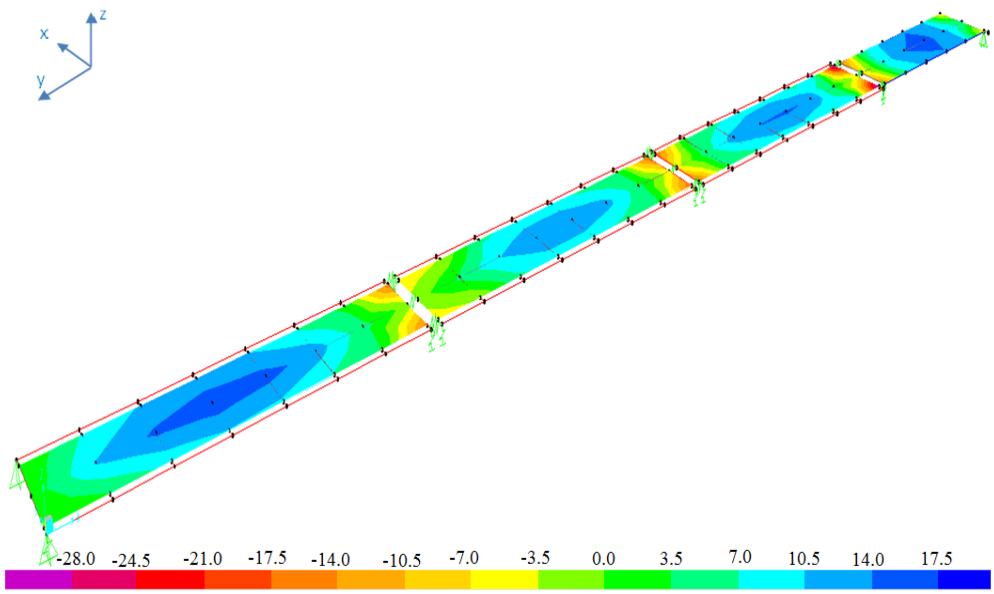


Fig. 18 Stress distribution the steel slabs (calibrated finite element model)

Table 3 Comparison of displacements and stress distribution

	Bridge parts	Before Calibration	After Calibration
Max. Displacement	14 m deck	22.5 mm	12.13 mm
	7.94 m deck	10.99 mm	8.62 mm
Max. Stress	14 m deck	22.4 MPa	14.4 MPa
	7.94 m deck	17.8 MPa	14.1 MPa

6. Conclusions

This paper presents structural assessment of a steel railway bridge based on finite element model validated by modal parameters. Structural analysis is performed using structural analysis software with finite element modeling; experimental validation of the numerical model is performed using operational modal analysis. The study consists of three parts: structural and dynamic analysis based on initial finite element modeling, operational modal analysis based on ambient vibration data and calibration initial finite element modeling according to modal and stiffness parameters, structural and dynamic analysis using calibrated finite element modeling. Calibration or improving finite element modeling is important to understand structural behavior, and to identify vulnerability of structure rationally. The results indicate that modeling and analyzing the bridge as it is, meaning that using material and mechanical properties, stiffness parameters and boundary conditions with certain assumptions, do not provide satisfactory results, the performance of the bridge does not reflect actual behavior.

In the study presented, the natural frequency of the initial finite element model of bridge (for one deck only) is 7.42 Hz (the period is 0.846 s) while the frequency is determined from operational model analysis is 10.33 Hz (the period is 0.608 s). Although the bridge studied is simple bridge without any complex components, the dynamic parameters determined by dynamic analysis using the finite element modeling with general assumption in material properties and stiffness parameters were not match with the ambient vibration test results. Difference between frequencies is caused by inaccurate material properties and stiffness parameters, poor approximation in boundary conditions and damping mechanism, and not to have proper modeling. Upgrading the modeling and calibrating the stiffness properties would provide sufficient enough converging to the true behavior of the bridge. However, because of the numbers of variables (the stiffness parameters, material properties, and modeling), effect of all these variable should be studied separately to be certain.

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References

Altunışık A.C. and Kalkan, K. (2016), "Investigation of earthquake angle effect on the seismic performance of steel bridges", *Steel Compos. Struct., Int. J.*, **22**(4), 855-874.

Altunisik, A.C., Bayraktar, A., Sevim, B. and Ates, S. (2011), "Ambient vibration based seismic evaluation of isolated Gülburnu highway bridge", *Soil Dyn. Earthq. Eng.*, **31**(11), 1496-1510.

ARTeMIS (2004), Ambient Response Testing and Modal Identification Software ARTeMIS Extractor Pro. Structural Vibration Solutions, A/S Aalborg East, Denmark.
URL: http://www.svibs.com (web page on 01/02/2017)

Au, F.T.K., Tham, L.G., Lee, P.K.K., Su, C., Han, D.J., Yan, Q.S. and Wong, K.Y. (2003), "Ambient vibration measurements and finite element modelling for the Hong Kong Ting Kau Bridge", *Struct. Eng. Mech., Int. J.*, **15**(1), 115-134.

Bayraktar, A., Altunişik, A.C., Türker, T., Karadeniz, H., Erdoğdu, Ş. and Angın, Z. (2009), "Modal Testing, Finite-Element Model Updating, and Dynamic Analysis of an Arch Type Steel Footbridge", *J. Perform. Constr. Facil.*, **23**(2), 81-89.

Bayraktar, A., Sevim, B., Altunişik, A.C. and Türker, T. (2010), "Effect of The Model Updating on The Earthquake Behavior of Steel Storage Tanks", *J. Constr. Steel Res.*, **66**(3), 462-469.

Benedettini, F. and Gentile, C. (2011), "Operational modal testing and FE model tuning of a cable-stayed bridge", *Eng. Struct.*, **33**, 2063-2073.

Ding, Y., An, Y. and Wang, C. (2016), "Field monitoring of the train-induced hanger vibration in a high-speed railway steel arch bridge", *Smart Struct. Syst., Int. J.*, **17**(6), 1107-1127.

Erol, O. (2017), "Calibration of finite element modeling of 39+646 steel railway bridge using operational modal analysis", Master Thesis; Ege University, Department of Civil Engineering, Bornova, Izmir, Turkey. [In Turkish]

Ewins, D.J. (1984), *Modal Testing: Theory and Practice*, John Wiley & Sons, Chichester, UK.

Hoag, A., Hoult, N.A., Take, W.A., Moreu, F., Le, H. and Tolikonda, V. (2017), "Measuring displacements of a railroad bridge using DIC and accelerometers", *Smart Struct. Syst., Int. J.*, **19**(2), 225-236,

Huang, M., Guo, W., Zhu, H. and Li, L. (2008), "Dynamic test and finite element model updating of bridge structures based on ambient vibration", *Front Archit. Civil Eng. China*, **2**, 139-144.

Jacobsen, N.J., Andersen, P. and Brincker, R. (2006), "Using enhanced frequency domain decomposition as a robust technique to harmonic excitation in Operational Modal Analysis", *Proceedings of the ISMA2006: International Conference on Noise & Vibration Engineering*, September, Heverlee, Belgium.

Jaishi, B. and Ren, W.-X. (2005), "Structural finite element model updating using ambient vibration test results", *J. Struct. Eng.*, **45**, 617-628.

Jaishi, B., Kim, H.J., Kim, M.K., Ren, W.X. and Lee, S.H. (2007), "Finite element model updating of concrete-filled steel tubular arch bridge under operational condition using modal flexibility", *Mech. Syst. Signal Process.*, **21**(6), 2406-2426.

Ljung, L. (1987), *System Identification: Theory for the User*, Prentice-Hall, Englewood Cliffs, NJ, USA.

Magalhães, F., Cunha, Á. and Caetano, E. (2008), "Dynamic monitoring of a long span arch bridge", *Eng. Struct.*, **30**, 3034-3044.

Ni, Y.Q., Xia, Y., Lin, W., Chen, W.H. and Ko, J.M. (2012), "SHM benchmark for high-rise structures: a reduced-order finite element model and field measurement data", *Smart Struct. Syst., Int. J.*, **10**(4), 411-426.

Podworna, P. (2017), "Dynamic response of steel-concrete composite bridges loaded by high-speed train", *Struct. Eng.*

Mech., *Int*. *J*., **62**(2), 179-196.

Ribeiro, D., Calçada, R., Delgado, R., Brehm, M. and Zabel, V. (2012), “Finite element model updating of a bowstring-arch railway bridge based on experimental modal parameters”, *Eng*. *Struct*., **40**, 413-435.

SAP 2000 (2000), Structural Analysis Program, Computers and Structures INC. USA.
USA: https://www.csiamerica.com/products/sap2000
(web page on 01/02/2017)

Schlune, H., Plos, M. and Gylltoft, K. (2009), “Dynamic finite element model updating of prestressed concrete continuous box-girder bridge”, *Earthq*. *Eng*. *Vib*., **31**, 477-485.

Toydemir, B., Kocak, A., Sevim, B. and Zengin, B. (2017), “Ambient vibration testing and seismic performance of precast I beam bridges on a high-speed railway line”, *Steel Compos*. *Struct*., *Int*. *J*., **23**(5), 557-570.

Türker, T., Kartal, M.E., Bayraktar, A. and Muvafik, M. (2009), “Assessment of semi-rigid connections in steel structures by modal testing”, *J*. *Constr*. *Steel Res*., **65**(7), 1538-1547.

Ubertini, F., Gentile, C. and Materazzi, A.L. (2013), “Automated modal identification in operational conditions and its application to bridges”, *Eng*. *Struct*., **46**(1), 264-278.

Walia, S.K., Vinayak, H.K., Kumar, A. and Parti, R. (2015), “Modal parametric changes in a steel bridge with retrofitting”, *Steel Compos*. *Struct*., *Int*. *J*., **19**(2), 385-403.

Wilson, F. (1984), *Building Materials Evaluation Handbook*, Van Nostrand Reinhold Company Publishing, New York, NY, USA.

Zang, L. (2013), “From Traditional Experimental Modal Analysis (EMA) to Operational Modal Analysis (OMA), an Overview”, *Proceedings of the 5th International Operational Modal Analysis Conference*, May, Guimaraes, Portugal.

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