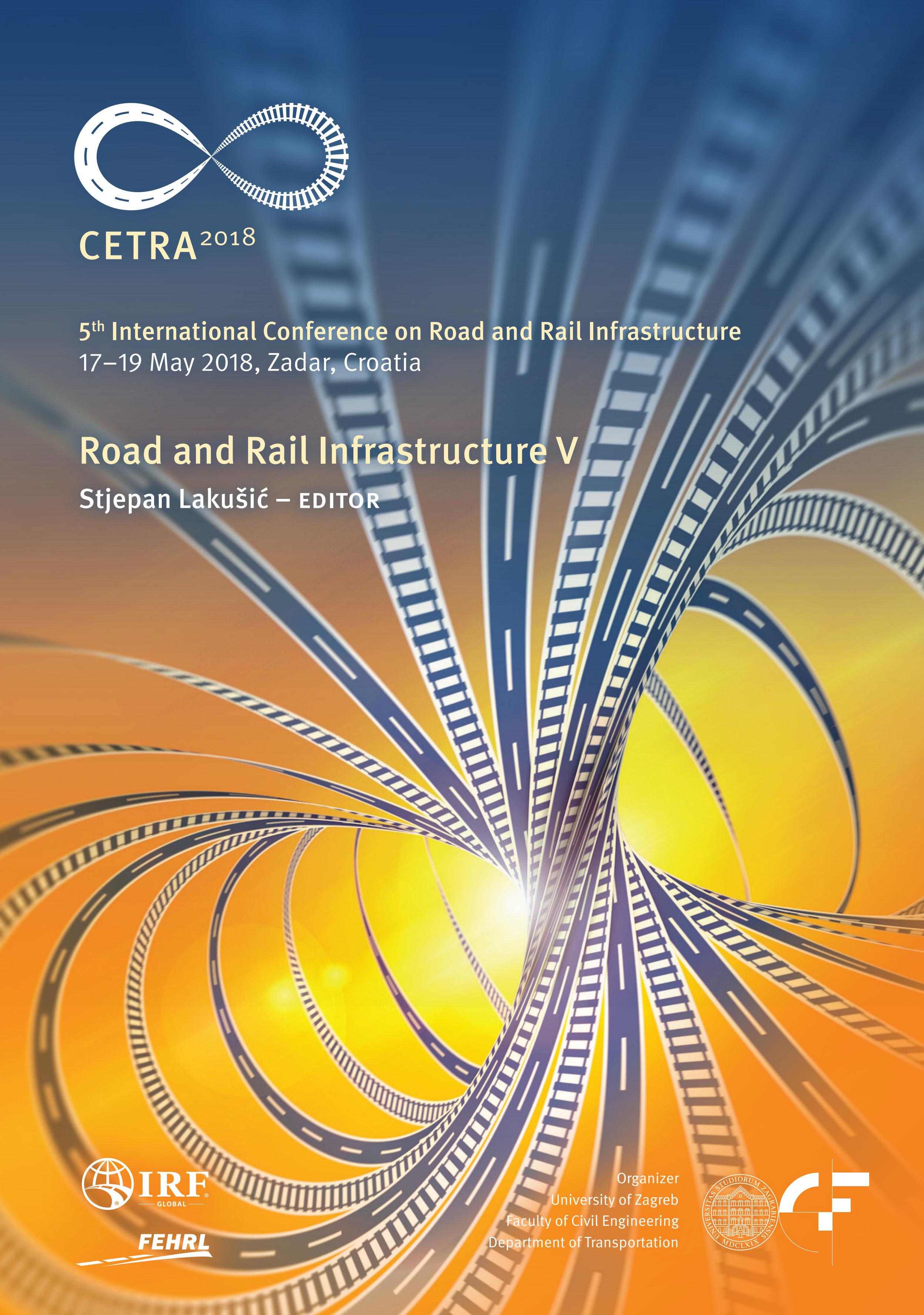

CETRA 2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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OPERATIONAL MODAL ANALYSIS OF TWO IDENTICAL SINGLE SPAN ROAD BRIDGES

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Abstract

Identification of modal parameters using response only measurements on the two identical single span road bridges is presented. The main advantage of output – only measurements is that it is not necessary to have information about excitation applied to the investigated structure. This technique is known as Operational modal analysis (OMA) as it uses ambient excitation, in this case heavy trucks passing over the bridge multiple times. Furthermore, 3D finite element numerical model of the bridge superstructure was constructed, and results were compared to the measured ones. Overview of modal parameters (natural frequencies, modal shapes and damping ratios) determined on two identical road bridges using Operational modal analysis and their comparison to the results calculated within numerical model are given. Experimentally determined modal parameters can be used for damage detection and assessment of health condition of the structure as damage, i.e. and structural deterioration causes changes in these parameters. Finally, the aim was to validate a cost effective and time saving procedure of modal parameter determination.

Keywords: operational modal analysis, modal parameters, road bridges, natural frequency, modal shapes

1 Introduction

Development of modal analysis during last sixty years resulted in reliable techniques for determination of modal parameters [1, 2]. These techniques can be divided in two major groups: Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA). When EMA is implemented Frequency Response Function (FRF) is constructed using response and excitation signal measurements. That implies the need for controlled and measured dynamic excitation which is often problem in testing of large scale civil engineering structures. Controlled excitation can be applied by means of large drop weights or different types of heavy modal shakers together with adequate frequency signal generator. The use of excitation devices which can produce sufficient energy to excite the structure increases the costs of testing and deployment of such expensive and heavy equipment extends the setup and implementation time of experiment.

OMA uses ambient environmental and traffic excitation and there is no need for controlled dynamic excitation of the structure [3]. Unmeasured and uncontrolled ambient excitation is assumed to have the characteristics of Gaussian white noise process. This simplifies the testing procedure, especially for CE structures as only response measurement are required for determination of natural frequencies, modal shapes and damping ratios. Modal shapes determined by OMA techniques can't be scaled appropriately to the mass and therefore flexibility matrix can't be determined either [4].

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Experimentally determined modal parameters can be used for damage detection and assessment of the health condition of the structure as damage and structure deterioration causes changes in modal parameters which are global parameters of the structure [5, 6]. These methods are becoming widely used in determination of condition of CE structures, especially bridges. Today large number of bridges in Europe, USA and Japan due to their age and deterioration need rehabilitation [7]. Vibration based damage detection methods are implemented together with visual and localized experimental methods in order to determine safety and serviceability of these bridges.

In the last two decades more than 500 km of new motorways were built in Croatia. As a part of these motorways large number of new bridges were constructed. Croatian motorways are developing bridge management system which is mainly based on visual inspection. There is interest to upgrade and supplement bridge management system with methods of health condition assessment based on modal parameter determination. For the future maintenance and diagnostics of these bridges it is important to determine the initial modal parameters. In this paper authors evaluate procedure of in-sight testing, which implies shorter time of experiment preparation and execution, using reduced number of measured DOF's. The aim was to validate cost effective and time saving procedure of modal parameter determination. Two identical single-span concrete bridges were chosen and modal parameters for each bridge were determined using frequency domain decomposition methods.

2 Description of bridges

Two concerned bridges, bridge at chainage 47+315 km and bridge at chainage 50,825 km, were constructed as a part of motorway A9 which forms Istrian Y road system together with motorway A8. They were built according to the identical design and constructed by the same contractor, bridges are located at the distance of approximately 2,5 km and mechanical parameters of foundation soil are similar. Both bridges were built in 2010. Experimental testing was performed before they were commissioned into service.

Structure of two concerned bridges is a semi-prefabricated construction made of reinforced concrete over 18,0 m span. They consist of eight prestressed RC longitudinal T-shaped girders 125 cm high, with flange width of 170 cm placed at axial distance of 173 cm. Cross girders over supports were concreted at the site as well as RC deck slab whose average thickness is 20 cm. Total width of the bridges is 13,9 m. At abutments each girder is supported over elastomeric bearing (200 x 400 mm). Concrete quality of prefabricated elements is C40/50, and elements made "in situ" are C30/37 quality. Steel quality for all elements is B500.

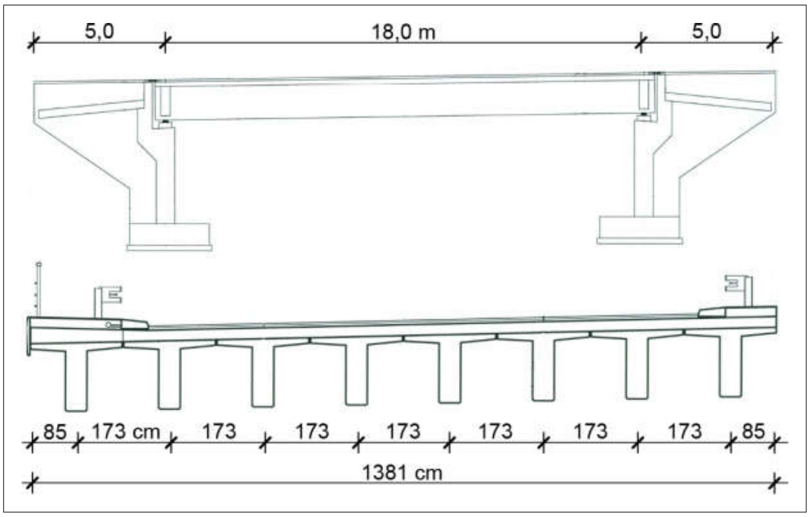

Figure 1 Bridge longitudinal and cross section

3 Numerical model

3D finite element numerical model of the bridge superstructure was constructed in Sofistik. Material properties and dimensions of bridge elements were modeled according to the project design. Numerical model was constructed prior to the experimental testing to give basic information about natural frequencies and modal shapes. This information was used in designing of the testing procedure. Numerical model was primarily used as a baseline for comparison to experimentally determined natural frequencies and modal shapes.
First five natural frequencies and modal shapes in the vertical direction from the numerical model are shown in figure 2. It should be noted that numerical modal analysis revealed some local modes that were dispersed between the vertical modes shown in the figure 2.

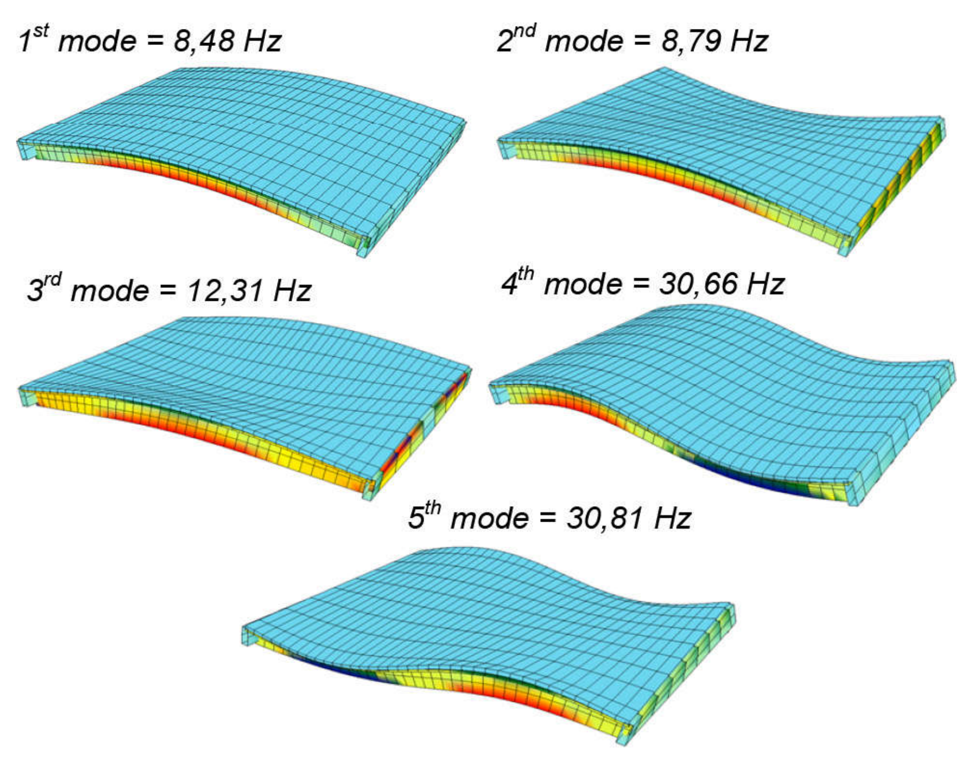

Figure 2 Modal shapes obtained from the FEM model

4 Identification of modal parameters

Identification of natural frequencies, modal shapes and damping ratios was conducted using methods of frequency domain decomposition (FDD). The procedure is based on singular value decomposition (SVD) of Power Spectral Density (PSD) matrix of the measured responses (Gyy). We have to assume that the loading is white noise process, the structure is lightly damped and close mode shapes are geometrically orthogonal. Result of SVD is:

$$\hat{G}_{yy}(\omega_i) = U_i S_i U_i^H \tag{1}$$

Equation (1) is known at discrete frequencies $\omega = \omega i$ where Ui represents unitary matrix of singular vectors, and Si diagonal matrix of singular values. At the discrete frequency of the resonance peak first singular vector is an estimate of mode shape [8]. Enhanced frequency domain decomposition (EFDD) identifies the Single Degree of Freedom (SDOF) PSD function around the peak by comparing vector at the peak with the vectors corresponding to discrete frequencies around the peak using Modal Assurance Criterion (MAC). If the MAC value is high enough the corresponding singular value is included in SDOF function. Inverse discrete Fourier transform of acquired SDOF function enables determination of damping ratio for that particular mode [9]. Curve-fit frequency domain decomposition (CFDD) technique is similar to EFDD but it applies curve-fitting to the SDOF function directly in the frequency domain [10].

5 Experimental testing and comparison of results

Response of the structure was measured by 5 Brüel & Kjær 4508 accelerometers. These accelerometers have a nominal amplitude range of 70 g, sensitivity of 100 mV/g and frequency range of 0,3 Hz to 8 kHz. Test setup consisted of 6 vertical DOF measured in two measurements by roving 1 accelerometer according to figure 3. Heavy steel plates were placed at the bridge deck and accelerometers were attached to them using magnets. Measurements were performed during traffic of heavy trucks over the bridge. Accelerations were recorded using Brüel & Kjær 5-channel portable data acquisition system type 3560 C. The sampling rate used for the testing was 1,000 Hz.

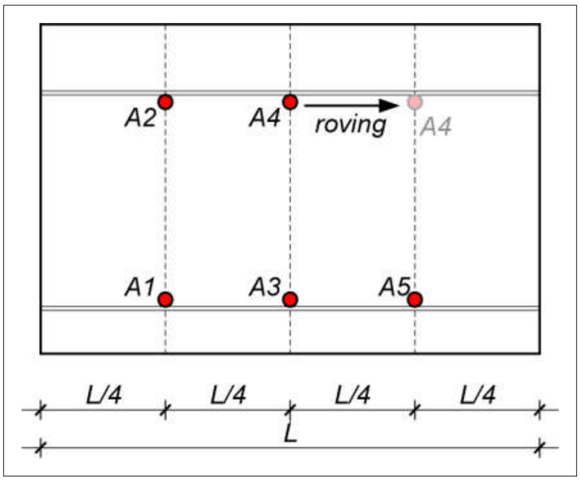

Figure 3 Position of accelerometers

Results of experimentally determined natural frequencies and their comparison to numerical results are shown in Table 1, together with results of experimentally determined damping ratios for first 5 modes.

Table 1 Experimental and numerical results

Mode	Experimental frequency [Hz]		Numerical frequency [Hz]	Damping ratio [%]	
	bridge km 47+315	bridge km 50+825		bridge km 47+315	bridge km 50+825
1	8,92	8,85	8,48	0,81	0,97
2	9,79	9,69	8,79	0,67	0,60
3	12,78	12,29	12,31	0,52	0,63
4	31,28	30,84	30,66	0,30	0,24
5	32,12	31,67	30,81	0,32	0,23

Figure 4 shows singular values of spectral density matrices and SDOF functions derived by curve fitting which were determined for both bridges [10]. Modal shapes were estimated as first singular vectors at the resonance peak.

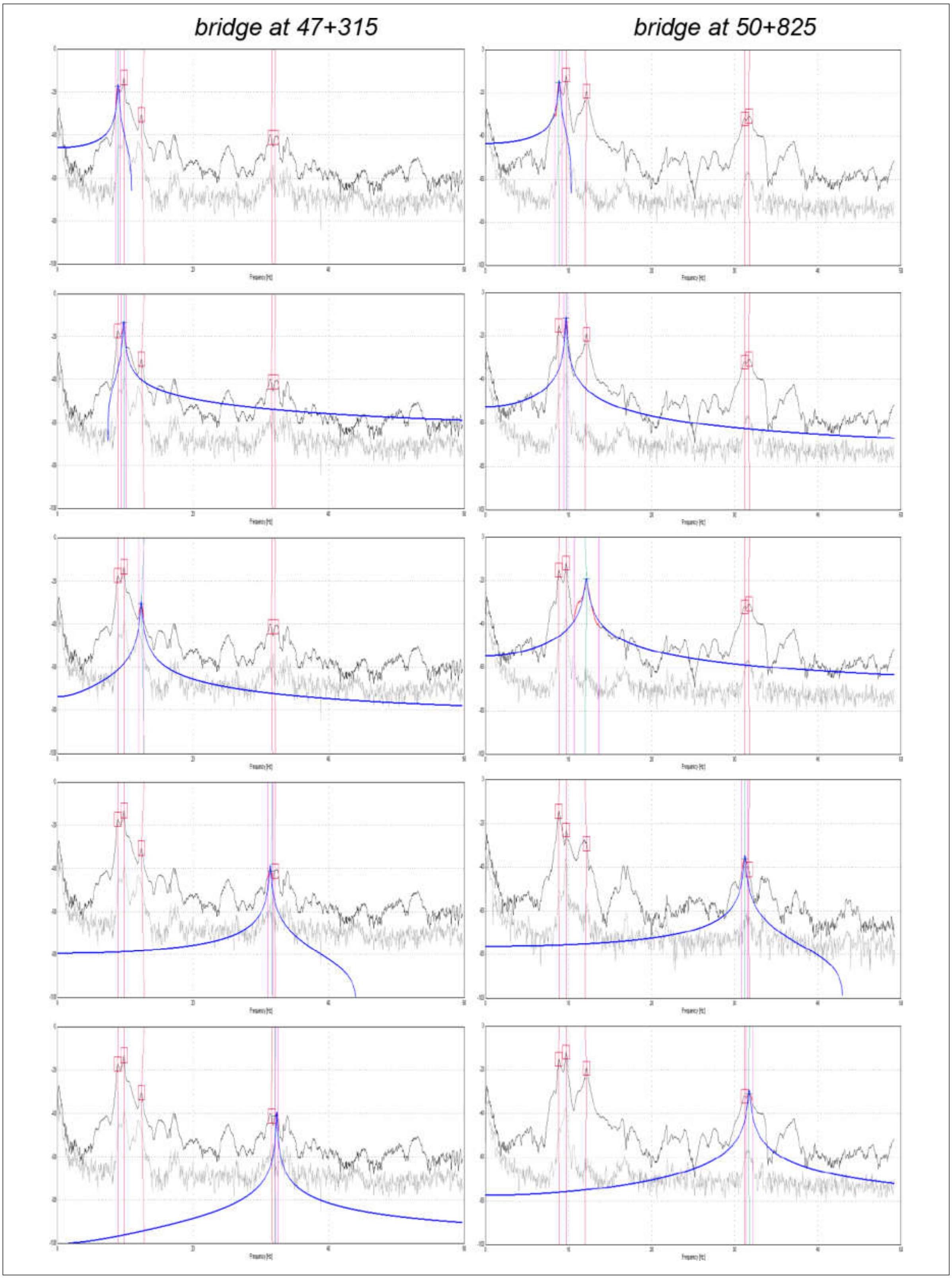

Figure 4 Singular values of PSD matrices

Damping ratios were determined by EFDD technique from PSD function of estimated SDOF systems using EFDD technique. These functions are transformed back to the time domain using IDFT, finally damping is determined from SDOF normalized correlation functions using logarithmic decrement [9]. Normalized correlation functions determined for first five modes of the bridge at chainage 50+825 km for first five modes are shown in figure 5. The same procedure was performed for both bridges.

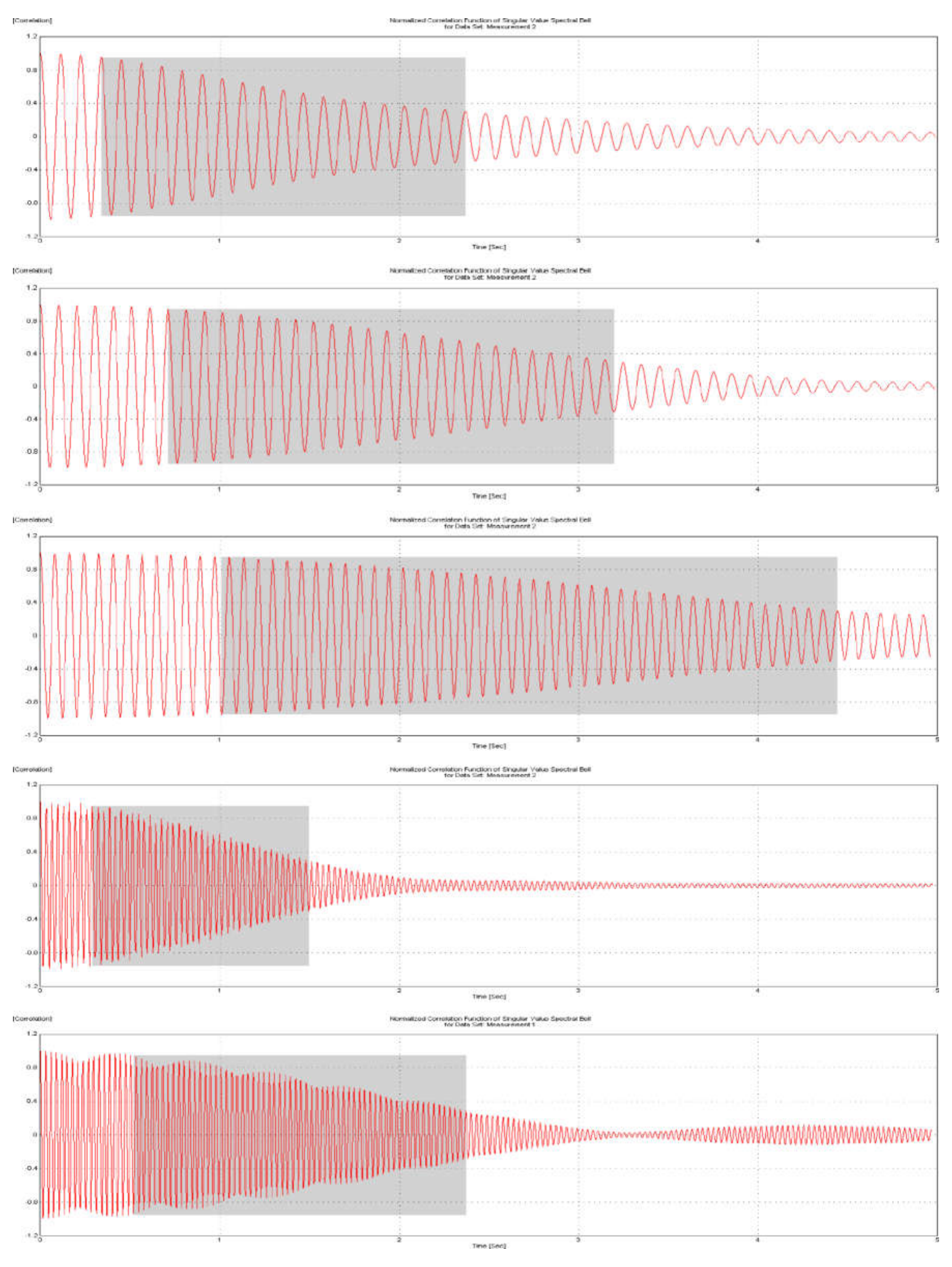

Figure 5 Normalized correlation functions for first five modes of bridge at chainage 50+825 km

Experimentally determined first five mode shapes for both bridges are shown in figure 6. Correlation analysis of mode shapes for two bridges was conducted using modal assurance criterion (MAC) which is essentially a squared, linear regression correlation coefficient. MAC is defined as a scalar constant relating the degree of correlation between modal vectors ϕc and ϕd for mode shape r.

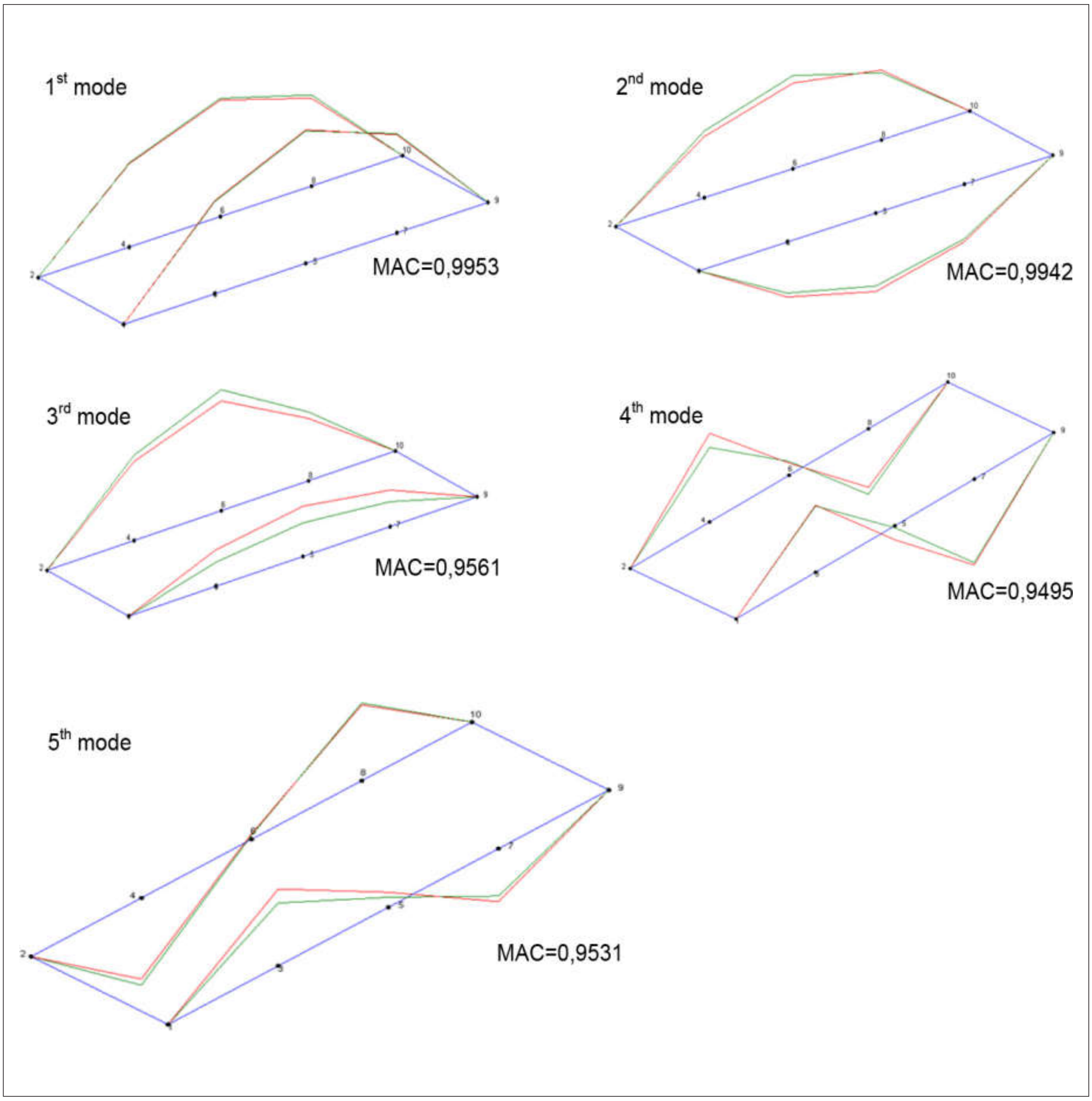

Figure 6 Experimentally obtained modal shapes of the bridges and MAC factor comparison

$$\mathrm{MAC}_{cdr} = \frac{\left|\phi_{cr}^{T}\phi_{dr}\right|^{2}}{\left\{\phi_{cr}^{T}\phi_{cr}\right\}\left\{\phi_{dr}^{T}\phi_{dr}\right\}} \tag{2}$$

A MAC value 1 indicates perfect correlation between two mode shape vectors, while a MAC value 0 indicates no correlation exists. MAC values are above 94 % for first five experimentally determined vertical mode shapes which is showing very good correlation.

6 Conclusion

Comparison of experimentally determined natural frequencies and mode shapes for two identical bridges shows very good correlation, as well as their comparison to numerical values obtained from FEM model. These results lead to conclusion that high precision of modal parameter estimation was achieved. High precision of modal parameter estimation is needed for the assessment of health condition of the structure in the future.

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